CHONDRULE FORMATION FROM EJECTA MELTS WITH ADAPTIVE MESH REFINEMENT.

M. L. A. Richardson[1], N. Ouellette[2], and M. Morris[2,3] [1]Department of Physics, University of Oxford: (Mark.Richardson@physics.ox.ac.uk). [2]Physics Department, SUNY Cortland. [3]School of Earth and Space Exploration, Arizona State University

Introduction: Understanding protoplanetary disks (PPDs) requires a synergy of astronomical observations and meteoritic analysis. While recent observations with e.g. *ALMA* are beginning to reveal the physical scale and thermal properties of PPDs, such millimeter measurements can only probe dust of limited size [1]. Meteoritic data, on the other hand, can be used to probe the nature of our Sun's PPD over a range of time and length-scales. Chondrules, small igneous inclusions found in chondrites, are a useful probe of the disk environment. While most chondrules formed roughly 2-3 Myr after the oldest solids (calcium-aluminium-rich inclusions, or CAIs) [2][3], those found in CH and CB chondrites are consistent with a formation time of 5-6 Myr after CAIs. Thus CH/CB chondrules allow us to study the nature of the changing disk environment.

We aim to understand the origin of CH/CB chondrules, gaining insight into the nature of our PPD 5-6 Myr after its formation. Our model considers melts in an ejecta fan resulting from the collision of small bodies at speeds near the local escape velocity. This ejected material will eventually disrupt through turbulence and condensation. Previous models of this scenario [4] use *Smoothed Particle Hydrodynamics (SPH)* methods, which have difficulty capturing the turbulent interaction between ejecta and the ambient disk, and are incapable of resolving low densities and small length scales. Recent simulations considered impacts between much larger, solid bodies as a formation method for the more common porphyritic chondrules [4].

Numerical Methods: We simulate the evolution of the ejecta fan resulting from the collision of a 30km radius object with a 100km radius target planetesimal. This collision occurs at twice the system escape speed. This collision was initially simulated using an SPH method [5].

To overcome the limitations inherent to SPH methods, we instead use the *Adaptive Mesh Refinement (AMR)* code `FLASH` for our simulations [6]. AMR is better able to model shocks, turbulence, and mixing [7], and can select regions for refinement to high resolution. AMR initial conditions are mapped from an SPH dataset, using methods previous employed for cosmological simulations [8]. The impact is modeled using the SPH method, which conserves angular momentum in the absence of artificial viscosity, and better accounts for the advection of the planetesimals. The results of the SPH simulation are mapped directly as initial conditions into the AMR simulation (see Top of Figure 1), which models the evolution of the resulting ejecta fan and the subsequent formation of *in situ* melts.

In the AMR simulation of the post-collision evolution of the ejecta fan, we only model the full hydrodynamics of the leading fan itself (see Bottom of Figure 1), and neglect the remnant body and in-falling debris. We evolve the fan with and without a non-hydrodynamic gravitational particle to determine the impact of the gravitational attraction of the remnant body on the final extent of the cooling ejecta fan.

Our simulations are first run without radiative cooling in the fan, for which a lower limit to cooling via adiabatic expansion can be determined. We are in the process of implementing radiative cooling modeled using the radiative transfer module in `FLASH`, where Rosseland mean opacities of basaltic dust were used to calculate radiation over all frequencies. A Levermore-Pomraning flux limiter, typical for these kinds of simulations, is used to respect causality and prevent radiation from escaping too fast [9]

Currently, we only consider a pure basalt fluid, but are working towards more complex fluids of multiple rock types. This multifluid treatment will also be accounted for in the radiative cooling work, using opacity tables for the range of materials.

Here we outline the preliminary results from our first ideal simulations.

Results and Discussion:

In Figure 1 we show slices of the gas density two hours after the collision at the moment it is mapped to AMR. The material is compact in height and at roughly 2000K. Our main simulation only evolves the material that is to the right of the planetesimal in the top image. This material (bottom panel, Figure 1) represents the region of the ejecta fan that is most unbound to the planetesimal. We find that regardless of whether we include the gravitational attraction of the planetesimal, the ejecta propagates to 3000km before reaching 1400K (see Figure 2). This is to be expected since the impact occurs above the escape speed. The gas is first mapped at almost 2000K, and then cools to 1400K in 25 minutes, suggesting a cooling rate on the order of 1000K/hr. This cooling time corresponds to a lower limit, as it derives from our non-radiative simulations.

The speed at which the fan disperses in AMR, occurring in 25 minutes compared with the two-hour evolution in SPH prior to the mapping, suggests that SPH may have difficulty capturing the full pressure scale height of the fan. Thus, we are in the process of modeling the collision itself in AMR, to compare results with those of the SPH and SPH-AMR hybrid runs. This dynamic process occurs in the high-density region of the planetesimal, leading to slow computing time, and is still on-going.

Conclusions: We present three-dimensional AMR simulations of an ejecta fan's evolution in a planetary nebula. For the case of adiabatic cooling, we find rapid cooling times of roughly 1000K/hr, and are pursuing fully radiative models to capture radiative cooling. Further, we are making efforts to compare with the entire evolution of the system using AMR.

We will ultimately treat the material composition more realistically by allowing for compositions more complex than uniform basalt. This improved model of the composition will be coupled with the ANEOS equation of state, which includes the change of phase, from solid through to vapour, and opacity tables that reflect the more complex composition. We will employ a source term to capture the formation of condensates in the cooling ejecta fan. This study will provide results needed to test the impact formation mechanism for CH/CB chondrite components, and will provide valuable information to further constrain our protoplanetary disk.

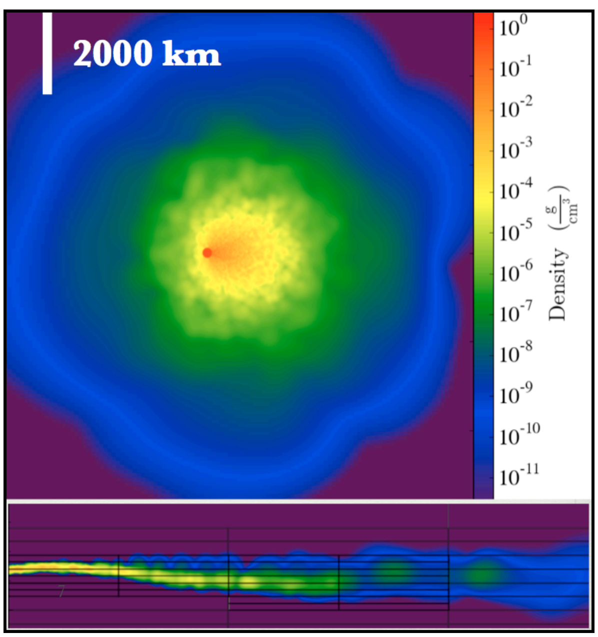

Figure 1: Gas density slices showing the mapping of the post-collision material and planet bodies. Top: Remnant body and full ejecta blanket, from above the system. Bottom: Slice through the fan for material to the right of the remnant. Black rectangles highlight different resolution levels, where each box contains 8x32x32 cells.

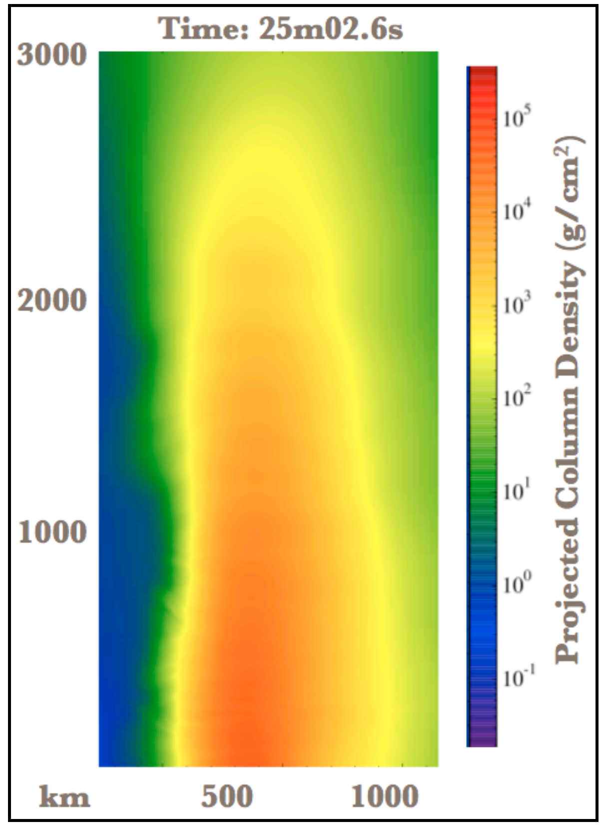

Figure 2: Projected density of the ejecta fan, which is initially ejected upwards in the figure orientation. As the fan propagates it also expands outwards, dropping in density and temperature. By 25 minutes the bulk has cooled to 1400K, having expanded out to 3000km and 1000km thick. This corresponds to a cooling rate of roughly 1-2 x 10^3 K/hr.

References: [1] Williams J. P. and Cieza L. A. 2011 *The Annual Review of Astronomy and Astrophysics* 49:67-117 [2] Kurashi E., Kita N. T., Nagahara H. and Morishita Y. 2008 *Geochimica et Cosmochimica Acta* 72:3865 [3] Villeneuve J., Chaussidon M. and Libourel G. 2009 *Science* 325:985-988 [4] Johnson B. C., Minton D. A., Malosh, H. J. and Zuber M. T. 2015 *Nature* 517:339-341 [5] Asphaug E., Jutzi, M. and Movshovitz N. 2011 *Earth and Planetary Science Letters* 308:369-379 [6] Fryxell, B., Olson, K., Ricker, P. et al. 2000, *The Astrophysical Journal Supplement* 131, 273 [7] Agertz O., Moore B., Stadel J. et al. 2007, *Monthly Notices of the Royal Astronomical Society*, 380:963-978 [8] Richardson M. L. A., Scannapieco E. and Thacker R. J. 2013 *The Astrophysical Journal* 771:81-93 [9] Levermore C. D. and Pomraning G. C. 1981 *The Astrophysical Journal* 248:321-334