CHONDRULE FORMATION FROM EJECTA MELTS WITH ADAPTIVE MESH REFINEMENT

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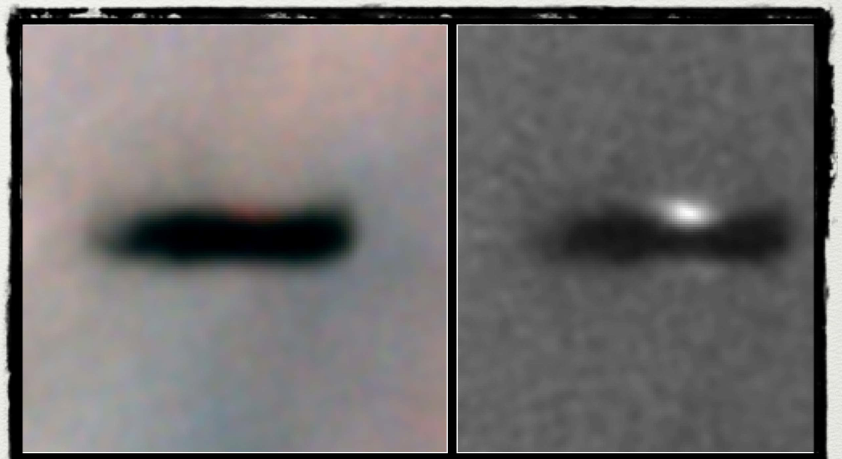
- Motivation -
Understanding the Protoplanetary Disk (PPD)

- Understanding planet formation hinges on knowledge of conditions in protoplanetary disks (PPDs), including gas mass and evolution.

- Solids in PPDs are quickly and substantially sequestered in large (perhaps molten) bodies invisible at observed wavelengths (Williams & Cieza 2011); observations alone cannot determine gas densities in PPDs of any age.



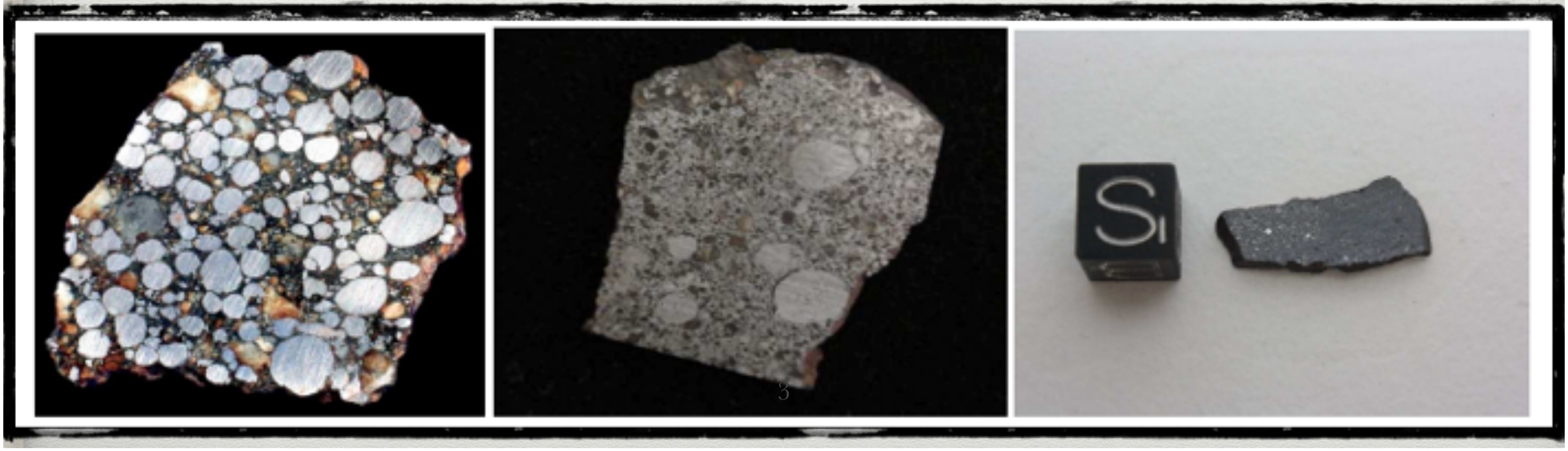
Edge-On Protoplanetary Disk · Orion Nebula

Hubble Space Telescope · Wide Field Planetary Camera 2

PRC95-45c · ST ScI OPO · November 20, 1995 · M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

- The Case for Chondrules -

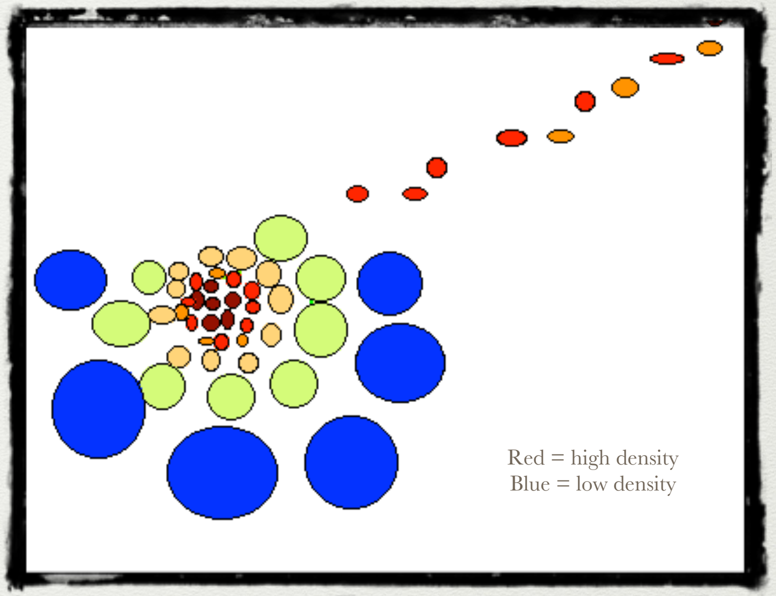
- Meteoritic data constrain conditions in the Sun's PPD, although to date, these data have not been fully explored to probe late stages of the PPD, at an age of ~5 Myr.
- Due to their late formation, likely as a result of a planetesimal impact (e.g., Krot et al. 2005), CH/CB/Isheyevo chondrites (and their components) can constrain conditions at ~5 Myr, in particular the nebular gas density.

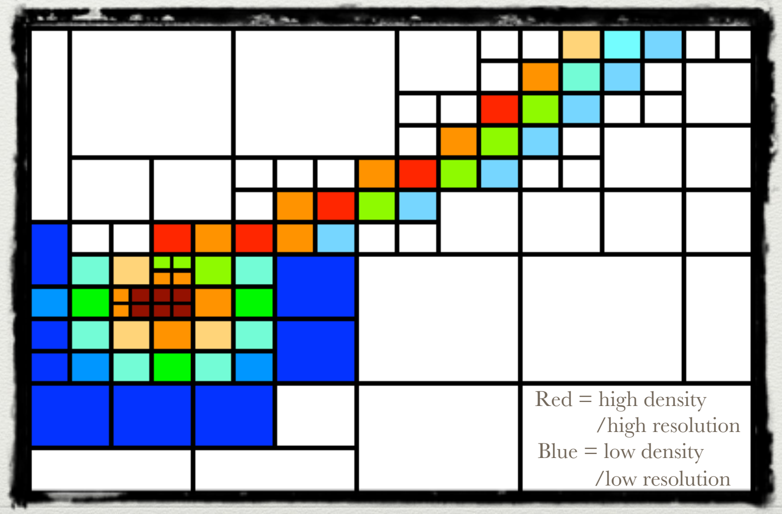


- Collision Simulation Review -

- Studies of planetary collisions and their ejecta typically implement Lagrangian Smoothed Particle Hydrodynamic (SPH) methods (e.g., Asphaug et al 2011), where the fluid is discretized into fluid parcels.

- More recent work has used axi-symmetric Eulerian methods, but these collisions occurred in a vacuum and in 2D (e.g., Johnson et al. 2014; 2015).



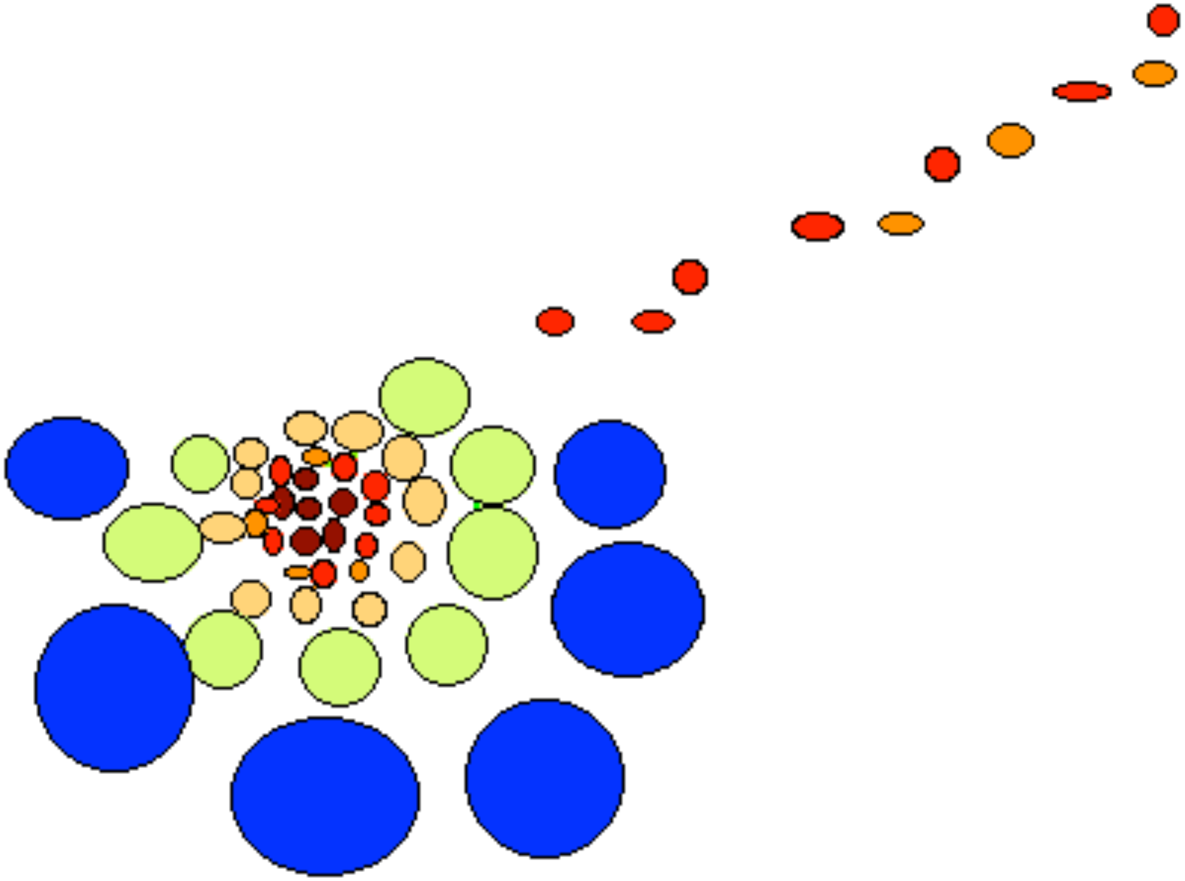


- Methods -

- Compared with AMR, **SPH** generally excels at **conserving angular momentum** (e.g., Thacker et al 2000), **is simple to implement**, **has small advection errors** (Falle et al. 2012), and **runs efficiently**.

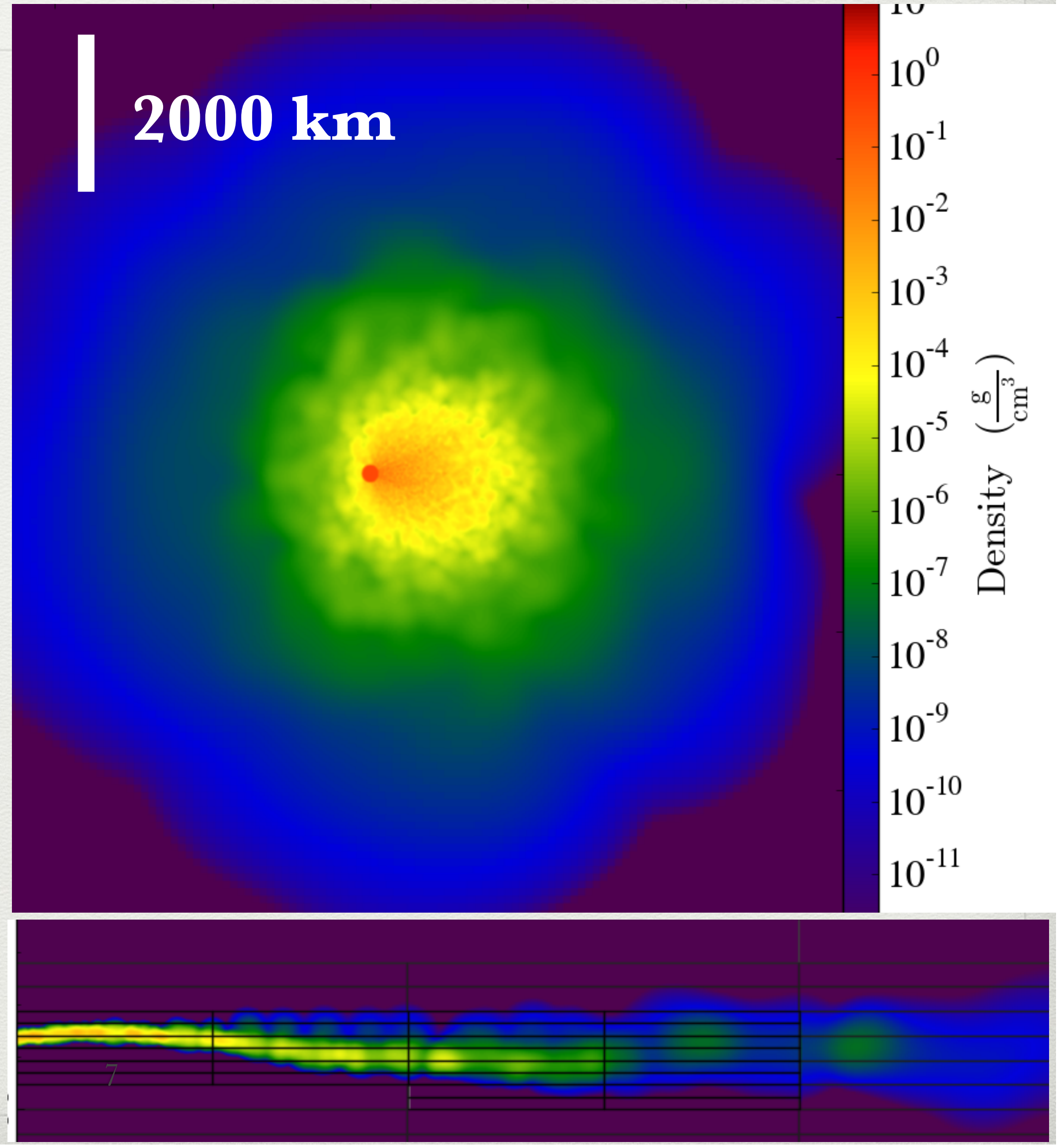
- However, **SPH** has **difficulty** capturing shocks **and interactions between ejecta and the ambient disk**, is **incapable of resolving low densities and small length-scales**, and typically **ignores the presence of the ambient nebular cloud** (Benz et al. 2014).

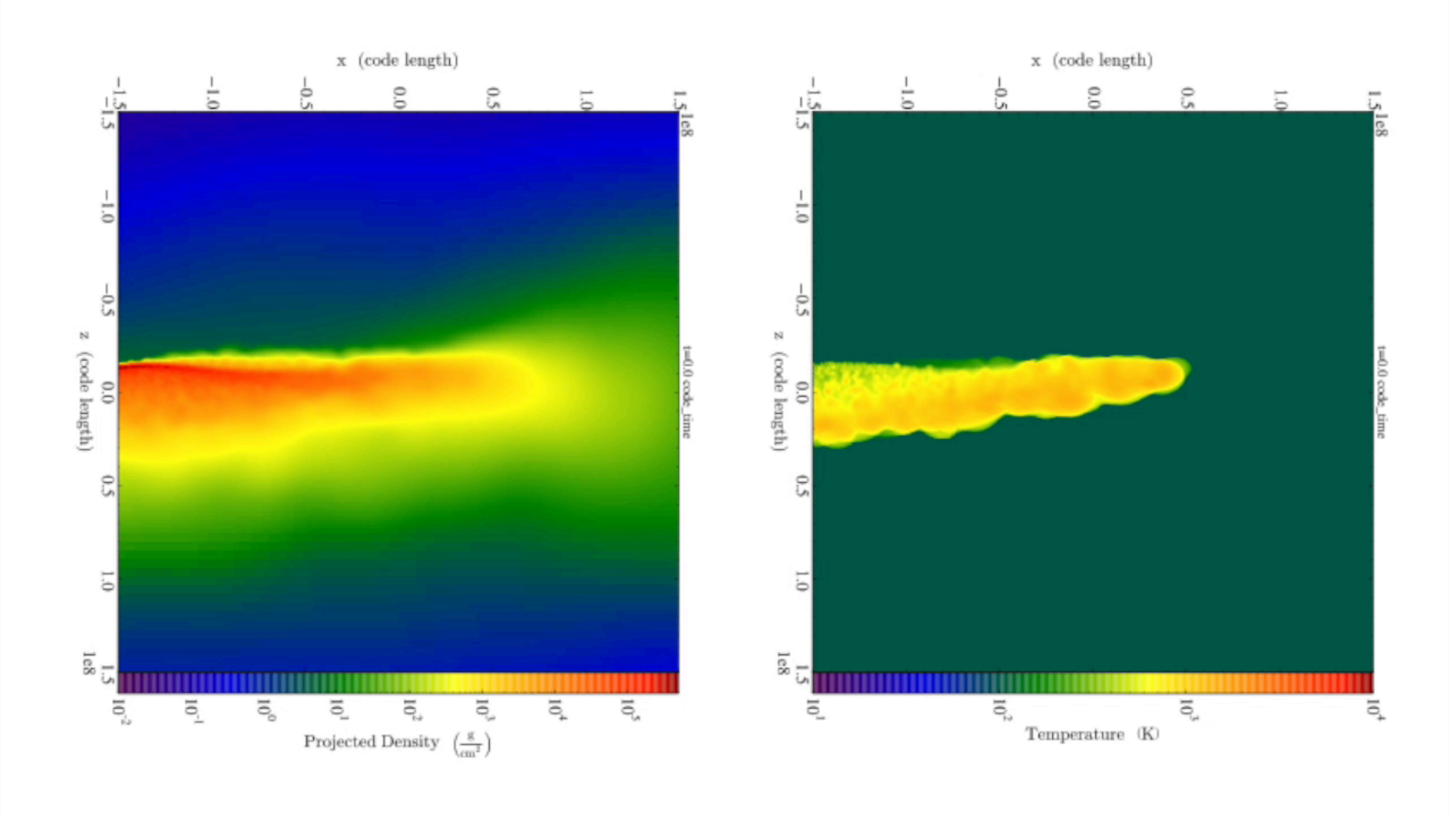
- **For these reasons we use** the **AMR** code FLASH4 (Fryxell et al. 2000) to **follow the evolution of the ejecta**. However, the initial conditions, up to and including the impact, are better generated in SPH (although we are now modeling the impact in AMR for comparison). Thus for our initial conditions we map (see Richardson et al. 2013) an SPH simulation output to the to the AMR grid.



Our first-approach simulation

- Initial conditions are mapped from an SPH output two hours after the impact. The collision has a R=30km object colliding at 30° with a R=100km molten planetesimal at twice the system escape speed Asphaug et al. 2011).
- We have mapped SPH, using the Tillotson equation of state (Tillotson 1962) and evolved the ejecta for several hours, while modelling the target as a sink particle off-grid.



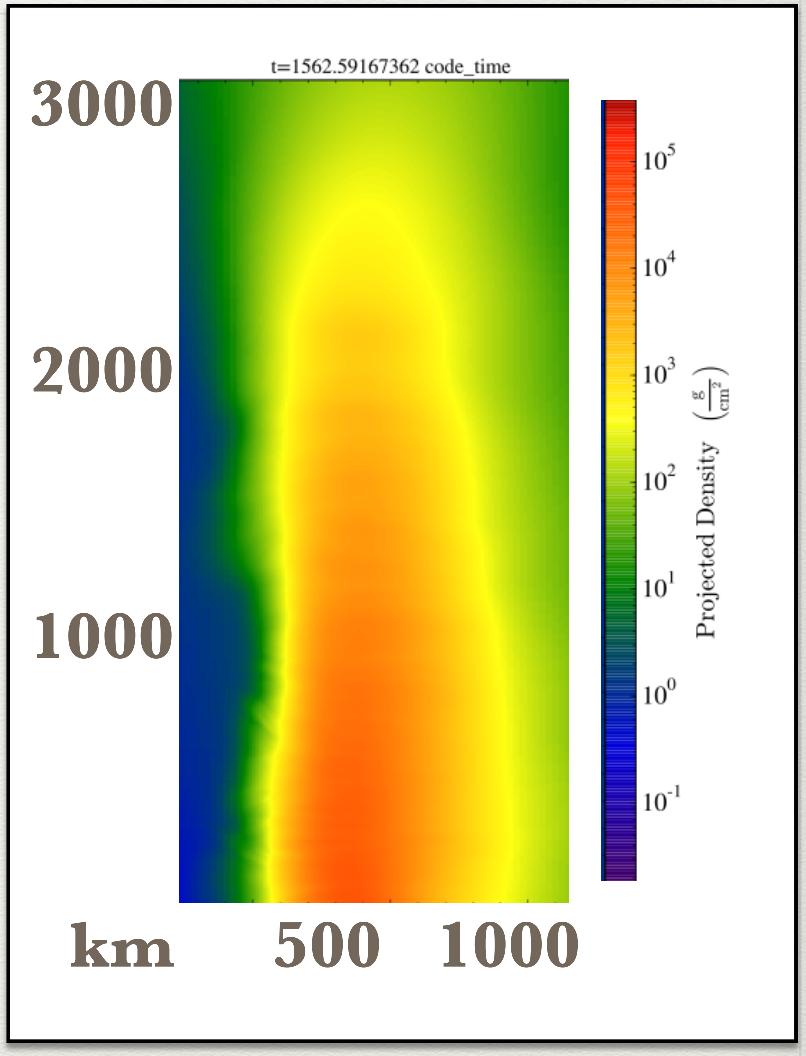


Left: Column density; Right: Projected temperature

- Difficulties & Early Results -

- We have explored ways to limit the numerical errors, both through the mapping (preserving angular momentum to 0.04%), as well as the subsequent AMR evolution (by reorienting the volume to propagate along the *x*-axis).

- We find that the bulk unit cools to 1400K by roughly 25 minutes, expanding out to 3000 km wide, 1000 km thick. This corresponds to a cooling rate of roughly 1-2 x 10^3 K/hr. This is a **lower limit** to cooling.



- Future Work & Challenges -

- We are working towards implementing the ANEOS (Thompson 1990) equation of state, the inclusion of radiative transfer, and ultimately the formation of condensates and chondrules through detailed cosmochemical modeling.
- Although extremely difficult, a 3D, fully simulated evolution of this system is the only way to accurately model the products resulting from planetesimal collision ejecta for comparison to the meteoritic record.

Thank you!

References

- Krot, A. N., Amelin, Y., Cassen, P., & Meibom, A. 2005, Nature, 436, 989; Asphaug, E., et al. 2011, EPSL 308, 369; Morris, M. A., & Desch, S. J. 2010, ApJ, 722, 1474; Benz, W. 2000, SSRv, 92, 279; Thacker, R. J. et al. 2000, MNRAS, 319, 619; Falle, S., et al. 2012, ASPC, 459, 298; Johnson, B. C., et al. 2014, Icarus, 238, 13; Johnson, B. C., et al. 2015, Natur, 14105; Fryxell, B., et al. 2000, ApJS, 131, 273; Richardson, M. L. A., et al. 2013, ApJ, 771, 81; Tillotson, J. H. 1962, General Atomic Report GA-3216; Thompson, S. L., 1990, SAND, 89, 2951

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