PRELIMINARY ASSESSMENT OF CHONDRULE COOLING RATES USING A SIMPLE SIZE DISTRIBUTION OF PRECURSOR PARTICLES

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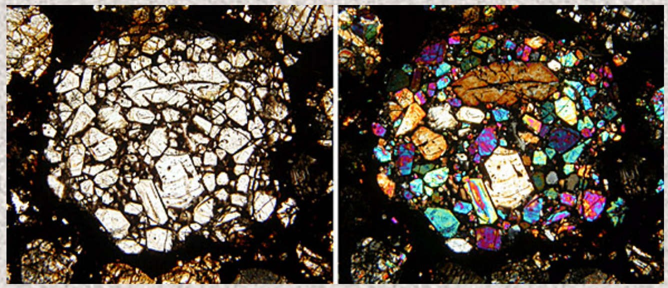
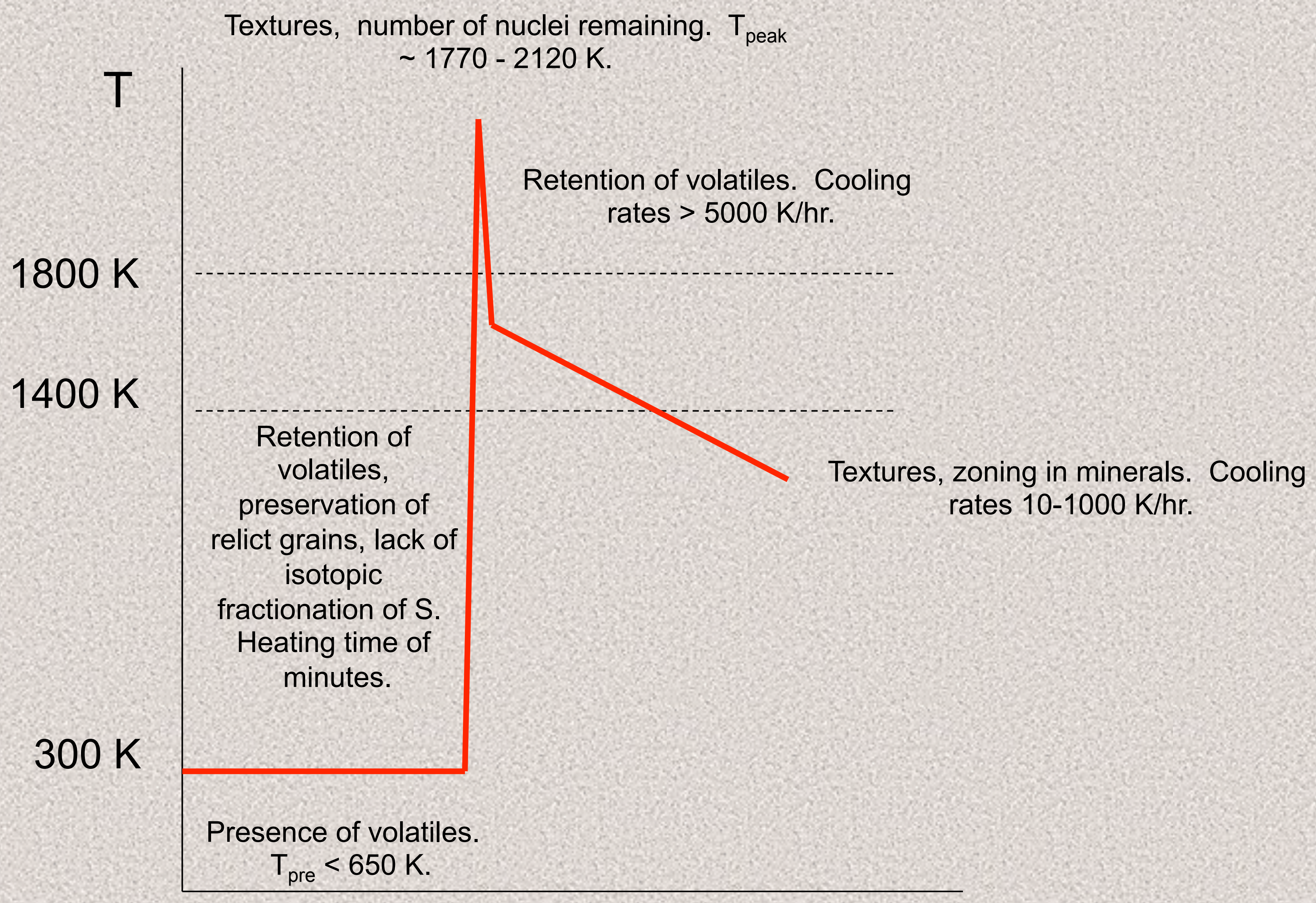
CHONDRULES



- Some of the oldest solids in the Solar System
- Igneous textures - crystallized from ferromagnesian silicate melts
- What process could have melted ~ 10^{27} g of rock in the solar nebula?

CONSTRAINTS ON THERMAL HISTORIES



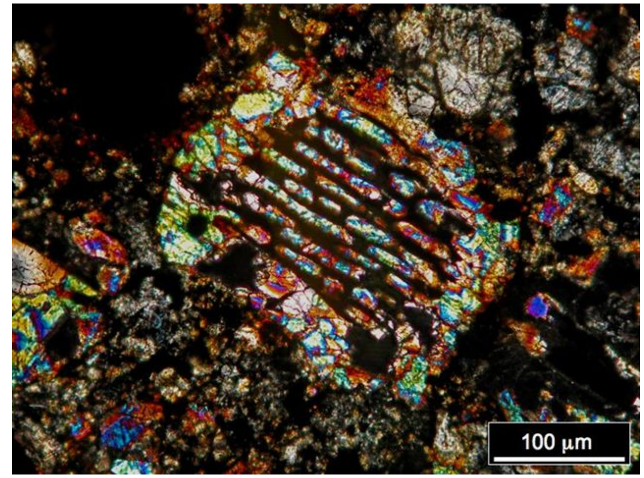
NON-THERMAL CONSTRAINTS

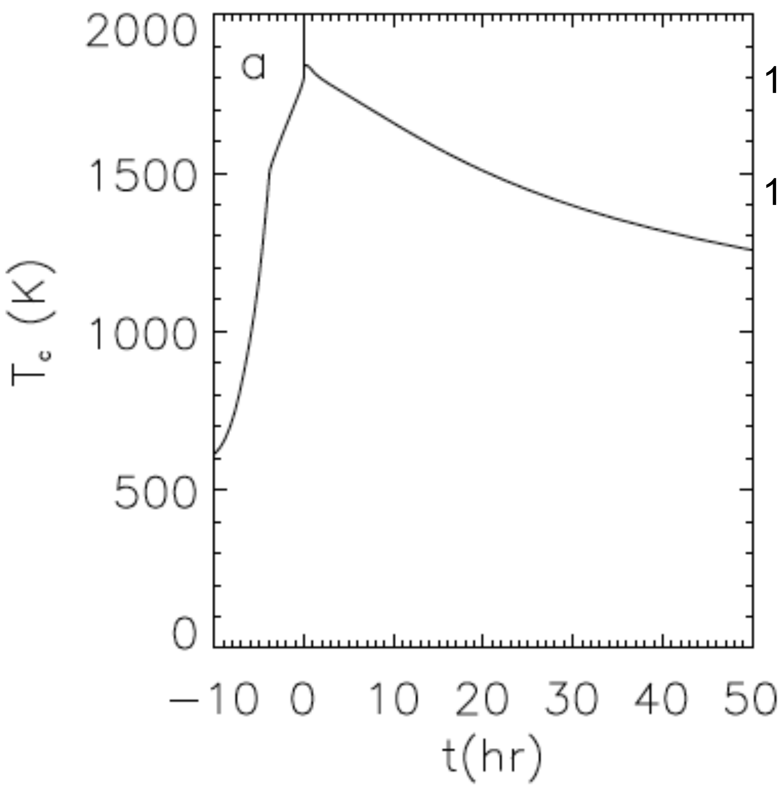
	X wind	lightning	bow shocks	GI shocks
Chondrule density ~ 10 m-3	✓	?	?	?
Formation region > 1000 km	✓	✗	?	✓
Gas pressure P > 10^{-3} atm	✓	✗	✓	✓
fO_2 variable, oxidizing	?	?	?	?
Chondrules and matrix cogenetic	✗	✓	✓	✓
Formed 1.6 - 3 Myr after CAIs (multiple events)	✗	✓	✓	✓

THERMAL CONSTRAINTS

	X wind	lightning	bow shocks	GI shocks
Ambient temperature < 650 K	✗	✓	✓	✓
Heating in "less than 10 minutes”	✗	✓	✓	?
Peak temperatures > ~ 2000 K	✗	✓	✓	✓
Cooling rate from peak ~ 10^3 - 10^4 K/hr	✗	?	✓	✓
Crystallization cooling rate ~ 10-10^3 K/hr (porphyritic)	✓	✗	?	✓
Crystallization cooling rate ~ 300-3000 K/hr (barred)	✗	✗	?	✓
Cooling rate correlated with chondrule density	✗	✗	✓	✓

Modeling of chondrule formation (Desch & Connolly 2002; Morris & Desch 2010) supports transient heating of chondrules in place by nebular shocks.





REMAINING PROBLEMS

- Heating too long in pre-shock region
  - No way to avoid – Marshak wave
- Primary Na in olivine phenocrysts (Alexander et al. 2008)
  - Requires high partial pressure of Na vapor

REMAINING PROBLEMS – "PRE-HEATING"

- A Marshak wave is a radiation front that diffuses into the pre-shock region from the hot post-shock region at the same rate that new material moves into it:

$$R = \sqrt{Dt}, D = R^2 / t_{rd} \Rightarrow \frac{dR}{dt} = \frac{1}{2}\sqrt{\frac{D}{t}}$$

$$\text{Now the Marshak wave stops when } \frac{dR}{dt} = V_s \Rightarrow \sqrt{\frac{D}{t}} = 2V_s$$

$$\text{so, } t = \frac{D}{4v_s^2} \text{ and } R = V_s t = \frac{1}{4}\frac{D}{V_s}, \text{ where } D = \frac{64\pi^2\lambda\sigma T^3}{3\rho_s C_{V_s} C_{V_g}} = \frac{64\pi^2\sigma T^3}{3\rho_s\rho_g\kappa C_{V_s} C_{V_g}}$$

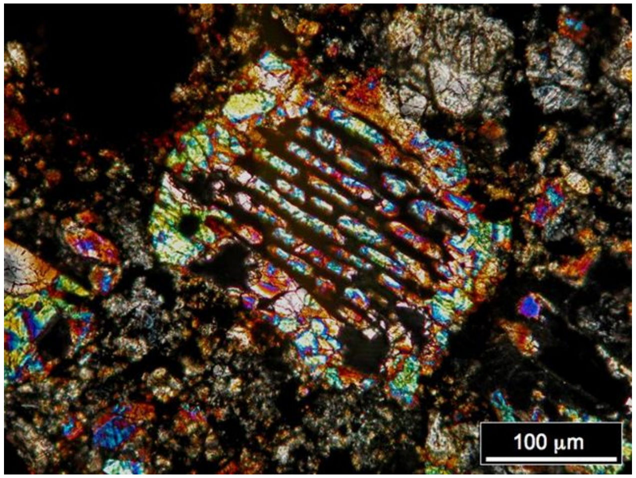
For $\kappa = 0.3$ cm^2 g^{-1}, R ~ 375,000 km and t ~ 13 hr; For $\kappa = 1.0$ cm^2 g^{-1}, R ~ 113,000 km and t ~ 4 hr

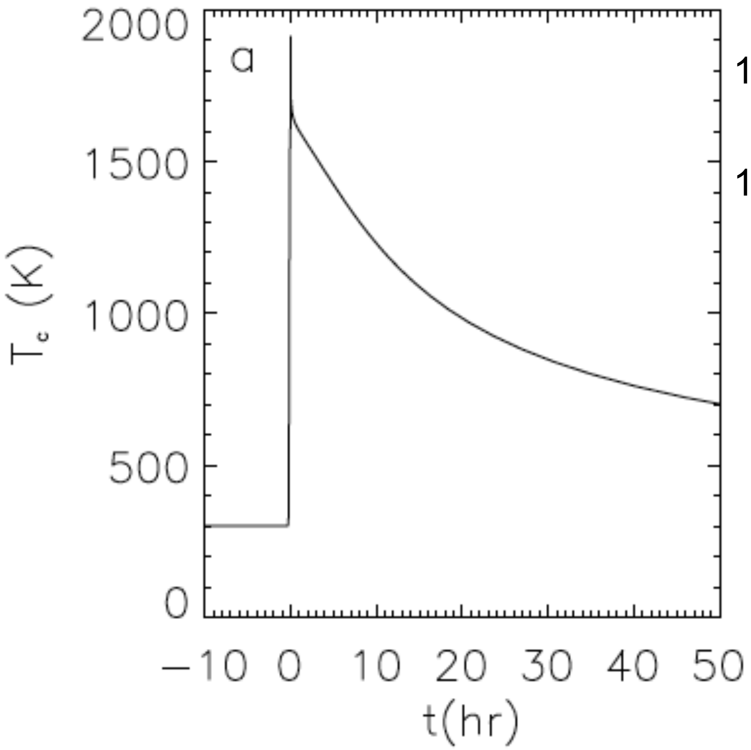
- Higher opacity, by a factor of ~ 10, would eliminate pre-heating.
- But high opacity in post-shock region drives cooling rates up >> 1000 K/hr
  - UNLESS opacity comes from particles that survive in the pre-shock region (the Marshak wave), but vaporize at shock front.

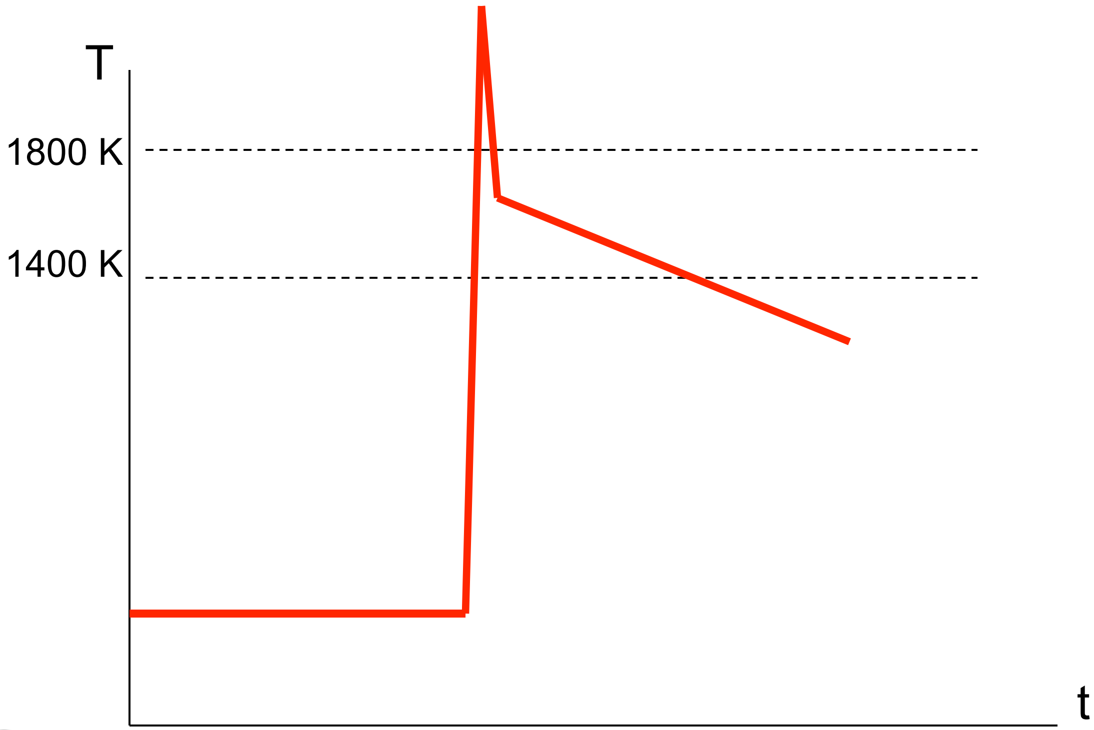
SIZE DISTRIBUTION OF PARTICLES

- Previous shock models typically included chondrule precursors of only one size (MD10 used 300 μm)
  - Not physical
  - Smaller particles contribute more to opacity
  - Can have significant effect on thermal histories
- Simple size distribution
  - Micron-sized dust
  - Chondrule precursors
    - 2/3 solids in particles with a = 300 μm
    - 1/3 solids in "microchondrules", a = 10 μm

Inclusion of a simple size distribution eliminates excess pre-heating of chondrules! Cooling rates increase slightly from 10-20 K/hr to 20-40 K/hr.

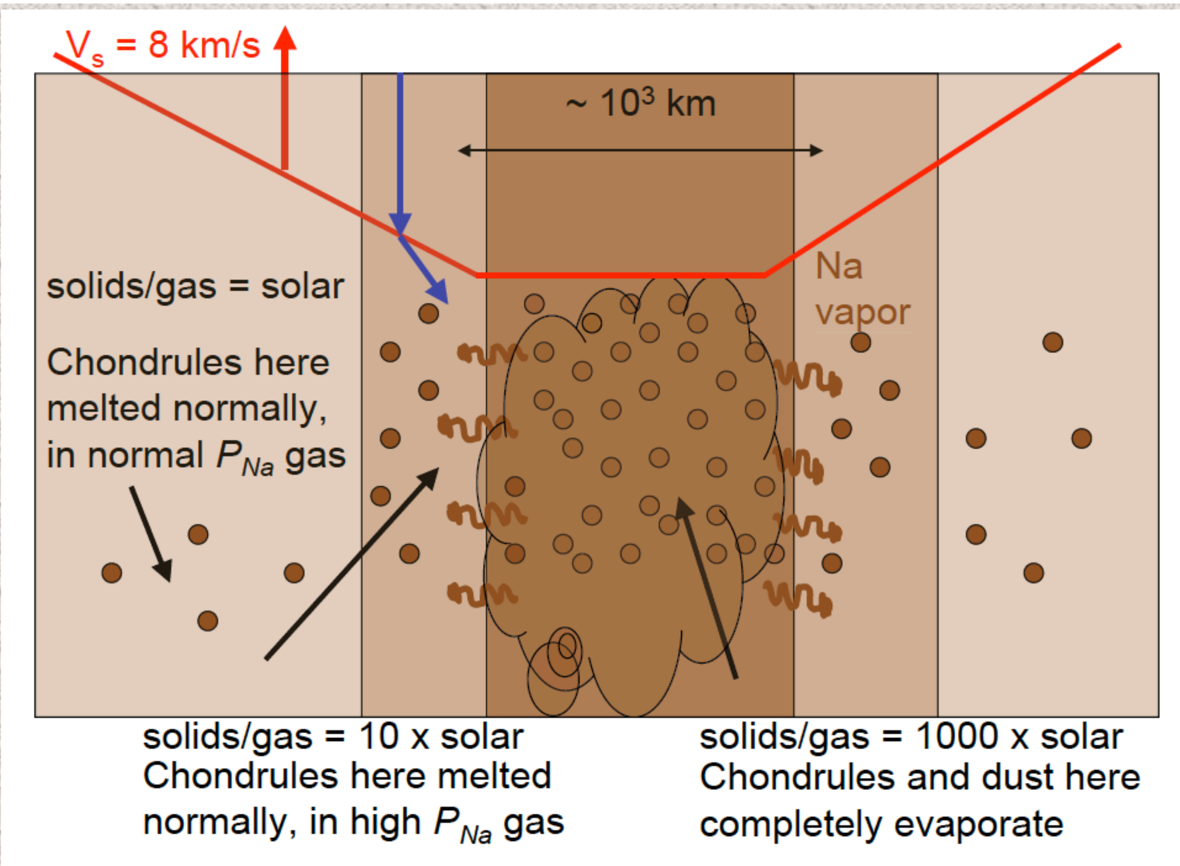






REMAINING PROBLEMS - Na

- Primary Na in olivine phenocrysts (Alexander et al. 2008)
  - Requires high partial pressure of Na vapor
  - "Supracanonical" chondrule densities?
    - Densities 2 ~ 9,000 g m^{-3} proposed
    - Orders of magnitude higher than that thought possible in the solar nebula
      - 3.75×10^{-6} - 3.75×10^{-4} g m^{-3}



- Shock propagates more slowly through the clump than the surrounding gas .
- The trajectories of chondrules entering the shock refracted.
- Chondrules focused into the clump (after clump has experienced peak heating).
- Some fraction of chondrules should experience otherwise normal thermal histories indicative of moderate chondrule concentrations, but in the presence of very high pressures of chondrule vapor that can only arise from regions of higher chondrule concentration.

Requires 2-D Modeling
with radiative transfer

CONCLUSIONS

- Inclusion of a simple size distribution eliminates excess pre-shock heating of chondrules in shock model applicable to gravitational instabilities.
- Cooling rates remain consistent with meteoritic constraints on thermal histories.
- Predict similar results with our new 2-D model including radiative transfer.
- "Focusing" of chondrules may solve primary Na mystery and may also ameliorate pre-heating problem.
- Shock model remains leading candidate for formation of chondrules.