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

Melissa Morris and Steve Desch
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Some of the oldest solids in the Solar System

Igneous textures - crystallized from ferromagnesian silicate melts

What process could have melted \( \sim 10^{27} \) g of rock in the solar nebula?
CONSTRAINTS ON THERMAL HISTORIES

1. Presence of volatiles.
   - $T_{pre} < 650$ K.

2. Retention of volatiles, preservation of relict grains, lack of isotopic fractionation of S.
   - Heating time of minutes.

3. Textures, zoning in minerals.
   - Cooling rates 10-1000 K/hr.

4. Retention of volatiles.
   - Cooling rates > 5000 K/hr.

5. Textures, number of nuclei remaining.
   - $T_{peak} \approx 1770 - 2120$ K.
## Non-Thermal Constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>X wind</th>
<th>Lightning</th>
<th>Bow Shocks</th>
<th>Gl Shocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chondrule density (\sim 10 \text{ m}^{-3})</td>
<td>✔️</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Formation region (&gt; 1000 \text{ km})</td>
<td>✔️</td>
<td>✗</td>
<td>?</td>
<td>✔️</td>
</tr>
<tr>
<td>Gas pressure (P &gt; 10^{-3} \text{ atm})</td>
<td>✔️</td>
<td>✗</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>(fO_2) variable, oxidizing</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Chondrules and matrix cogenetic</td>
<td>✗</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Formed 1.6 - 3 Myr after CAIs (multiple events)</td>
<td>✗</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>
# THERMAL CONSTRAINTS

<table>
<thead>
<tr>
<th>Condition</th>
<th>X Wind</th>
<th>Lightning</th>
<th>Bow Shocks</th>
<th>GL Shocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature &lt; 650 K</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Heating in &quot;less than 10 minutes&quot;</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>Peak temperatures &gt; ~ 2000 K</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cooling rate from peak ~ $10^3$ - $10^4$ K/hr</td>
<td>✗</td>
<td>?</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Crystallization cooling rate ~ $10$-$10^3$ K/hr (porphyritic)</td>
<td>✓</td>
<td>✗</td>
<td>?</td>
<td>✓</td>
</tr>
<tr>
<td>Crystallization cooling rate ~ 300-3000 K/hr (barred)</td>
<td>✗</td>
<td>✗</td>
<td>?</td>
<td>✓</td>
</tr>
<tr>
<td>Cooling rate correlated with chondrule density</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
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:

\[ R = \sqrt{Dt}, \quad D = \frac{R^2}{t_r} \quad \Rightarrow \quad \frac{dR}{dt} = \frac{1}{2} \sqrt{\frac{D}{t}} \]

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

so, \( t = \frac{D}{4V_s^2} \) and \( R = V_s t = \frac{1}{4} \frac{D}{V_s} \), where \( D = \frac{64\pi^2 \lambda \sigma T^3}{3\rho_s C_{Vs} C_{Vs}} = \frac{64\pi^2 \sigma T^3}{3\rho_s \rho_g \kappa C_{Vs} C_{Vs}} \)

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

- Higher opacity, by a factor of \( \sim 10 \), would eliminate pre-heating.

- But high opacity in post-shock region drives cooling rates up \( >> 1000 \text{ K/hr} \)

- 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 $a = 300 \, \mu m$
    - 1/3 solids in “microchondrules”, $a = 10 \, \mu m$
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 $2 \sim 9,000 \text{ g m}^{-3}$ proposed
    - Orders of magnitude higher than that thought possible in the solar nebula
      - $3.75 \times 10^{-6} - 3.75 \times 10^{-4} \text{ g m}^{-3}$
• 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.