Meteorites and the Timing of Planet Formation

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HL Tauri is no more than a million years old: large proto-planets forming within a million years.
Condensation

- The early solar nebula was hot, particularly near the Sun.
- The first particles to condense from the gaseous nebula were mostly smoke-sized.
- These tiny particles bumped into each other, probably clinging to each other due to static electricity.
Condensation

- The first formed particles contain elements that condense from gas at the highest temperatures (>1300 K)
- Ca, Al, Mg, Ti silicate and oxide minerals
- Anorthite, melilite, perovskite, aluminous spinel, hibonite, calcic pyroxene, forsterite
- These clumped together to form “calcium aluminium inclusions” or CAIs
- Pb-Pb dating of the CAIs gives us the age of initial condensation of the solar system: \( T_0 = 4567.30 \pm 0.16 \) Ma.

*Allende meteorite*
## Refractory or Volatile?

<table>
<thead>
<tr>
<th>Classification</th>
<th>Lithophile</th>
<th>Siderophile &amp; Chalcophile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractory (T_c 1,850-1,400 K)</td>
<td>Al, Ca, Ti, Be, Ba, Sc, V, Sr, Y, Zr, Nb, Ba, REE, Hf, Ta, Th, U, Pu,</td>
<td>Mo, Ru, W, Re, Os, Ir, Pt</td>
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<tr>
<td>Main component (T_c 1,350-1,250 K)</td>
<td>Mg, Si, Cr, Li</td>
<td>Fe, Ni, Co, Pd</td>
</tr>
<tr>
<td>Moderately volatile (T_c 1,230-640 K)</td>
<td>Mn, P, Na, B, Rb, K, F, Zn</td>
<td>Au, As, Cu, Ag, Ga, Sb, Ge, Sn, Se, Te, S</td>
</tr>
<tr>
<td>Highly volatile (T_c &lt; 640 K)</td>
<td>Cl, Br, I, Cs, TI, H, C, N, O, He, Ne, Ar, Kr, Xe</td>
<td>In, Bi, Pb, Hg</td>
</tr>
</tbody>
</table>
Condensation

- The next particles to form after the CAIs were the chondrules...
- Round spheres of silicate minerals + FeNi metal + FeS
- Sparse dating suggests that these formed ~2 m.y. after the CAIs
Accretion

- Many chondrules accumulated through gravitational attraction. Cemented in sub-micron silicate dust, with dispersed metal and troilite (FeS)
- Stochastic growth; bigger start to dominate through greater gravity:

\[ F = G \frac{m_1 m_2}{r^2} \]
Metal versus FeO in silicates

Very Reduced

Oxidised
Solar system chemical zonation

S Class: Silicate-rich asteroids
C Class: Carbonaceous asteroids
D Class: Organic-rich, hydrated silicates
Short-lived radioisotopes in the early solar system

Drivers of Heating:
$^{26}\text{Al} \rightarrow ^{26}\text{Mg}$: half life = 717 k.y.
$^{60}\text{Fe} \rightarrow ^{60}\text{Ni}$: half life = 2.6 m.y.

Early solar system was seeded with short-lived isotopes from a nearby supernova or giant stars

Thought to be evenly distributed
- Short-lived isotopes generate a lot of energy when they decay = heat

- Silicates conduct heat slowly, good insulators

- Radiogenic heating caused metamorphism in larger bodies

- This led to melting and segregation of dense metal to the cores of asteroids
Radiogenic Heating

Temperature vs. Time since CAI formation (Myr)

- H4 Ste-Marguerite
- H4 Forest Vale
- H5 Nadiabondi
- H5 Richardton
- H5 Allegan
- H6 Kernouve
- H6 Guareña
- H6 Estacado
Impact Heating

- Shock heating can instantaneously melt silicate material
- Rapid cooling quenches the melt
- “Impact melt breccia” in cold settings
Impact Heating

- In already warm settings relatively mild shock heating is sufficient to cause melting
- In already warm and insulated settings, heat takes a long time to dissipate
- Impacts were common during the period of radiogenic metamorphism

Monnerreau et al., 2013
Heat Contributions

- Rubin & Co (several publications) found many meteorites were impacted and then annealed:
  - Type 4-6 ordinary chondrites,
  - Type 4-6 CK chondrites,
  - R chondrites,
  - acapulcoites-lodranites
  - enstatite chondrites

- A strong indication that impact and radiogenic heating were concurrent

Impact heating alone: assumes no radiogenic heating
• The most volatile-rich meteorite groups contain no metamorphosed examples

• Implies that their parent asteroids formed after $^{26}$Al had decayed away

• Implies that volatile-rich asteroids, and thus planets (e.g., Jupiter), formed late relative to the refractory inner solar system bodies

• Or perhaps their parent bodies were simply too small to retain much heat
An old idea.

There are several highly metamorphosed oxidised meteorites and meteorite groups, which imply that some volatile-rich bodies formed while $^{26}\text{Al}$ was active.
## Meteorite Classification Table

### Crust/Mantle

#### Chondrites (85.8%)

**Ordinary Chondrites (73.5%)**
- **H3-7 Chondrites (31.4%)**
  - Mainly Opx & Olivine (16-20 mol% Fa), minor Plag, Fe-Ni = 15-19%, FeS.
- **L3-7 Chondrites (34.8%)**
  - Mainly Opx & Olivine (21-25 mol% Fa), minor Plag, Fe-Ni = 4-10%, FeS.
- **LL3-7 Chondrites (7.2%)**
  - Mainly Opx & Olivine (26-32 mol% Fa), minor Plag, Fe-Ni = 0.3-3%, FeS. Larger Chondrules.

#### Achondrites (8%)

**Evolved (6.3%)**
- **Martian**
  - 2 Types: Lherzolitic (Coarse Opx cumulates) & basaltic (Cpx-Plag. cumulus & flow textures).
- **Shergottites**
  - Augite-rich clinopyroxenes with minor Ol. Cumulates.
- **Nakhites**
  - 3 samples. Olivine-chromite cumulate dunite 99% Ol, 5% Plag, 2% Chrm.
- **Chassignites**
  - 1 sample. Cumulate orthopyroxenite. 96% Opx, 2% chrome, 1% Plag.
- **Basaltic breccias**
  - Heterogeneous regolith breccias
- **Augite Basalt**
  - Fine grained augite-rich basalt

#### Carbonaceous Chondrites (3.6%)

- **CI1 Chondrites**
  - No chondrules or metal. Phyllosilicates, olivine & magnetite in black matrix. Up to 20% H2O. Solar abundance of elements.
- **CM1-2 Chondrites**
  - ~30% small (~0.3mm) chondrules, part repl. by phyllosilicates. No metal. Common CAIs and OAAs. 70% matrix.
- **CV3 Chondrites**
  - Matrix/chondrule = 0.5-1.2. mm sized porphyritic chondrules. Abund CAIs & OAAs. Unique salite-hedonbegite nodules.
- **CK3-7 Chondrites**
  - Abund matrix. 0.7-1mm porphyritic chondrules. No metal. Abund. magnetite, Ni-rich sulfide. Rare CAIs & OAAs.
- **CO3-3.7 Chondrites**
  - ~35-45% small (~300um) chondrules. ~10% CAIs & OAAs. Abund metal-rich Mg chondrules. Anhydrous Alt chondrules.
- **CR1-2 Chondrites**
  - Abund large metal-rich Mg chondrules. Minor CAIs & OAAs. Heavily hydrated matrix & matrix-like lithic clasts.
- **CB Chondrites**
  - 80-95% metal (as large chondrules). Non-porphyritic Mg-rich (Fa<4, Fs<4) metal-free chondrules. Rare CAIs. No matrix. Hydrated clasts.
- **CH Chondrites**

#### Enstatite Chondrites (1.5%)

- **EH3-7 Chondrites**
  - More metal & sulfide. Niningerite: (Mg,Fe,Mn)S diagnostic. 56-63 vol% enstatite. Si in karnacite.
- **EL3-7 Chondrites**
  - Less metal & sulfide. Alabandite: (Mn,Fe)S diagnostic. 64-66 vol% enstatite.

#### Kakangi-type Chondrites

- 2 samples only. 70-77% matrix. 6-9% metal. Fs = 4, Fa = 2.

### Stones (93.8% of Falls)

#### Irons (5% of Falls)

**Magmatic**
- **IC**
- **IIAB**
- **IC**
- **ID**
- **IF**
- **IIIAB**
- **IIIE**
- **IIIF**
- **IVA**
- **IVB**

**Non-magmatic**
- **IAB**
- **IIICD**

### Stoney-Irons (1.2% of Falls)

**Pallasites**
- Approx. equal olivine (Fo = 82-88 mol%) & metal (minor troilite).

**Eagle Station**
- More Fe & Ca-rich olivine than Mg pallasites. Metal has higher Ni & In than Mg pallasites.

**Pyroxene**
- 14-63 vol% olivine, 30-43 vol% metal, 0.7-3 vol% pyroxene, 0-1 vol% troilite.

**Mesosiderites**
- Approx. equal silicates & metal + troilite. Basalt, gabbro, pyroxenite, dunite, anorthosite clasts, & Ol, Opx, Plag clasts in fine-grained igneous matrix.
Short-lived radioisotopes in the early solar system, Part II

**Used in Geochronology:**

\[^{182}\text{Hf} \rightarrow ^{182}\text{W}: \text{half life} = 9 \text{ m.y.} \]

(there are others)

Hf prefers to be in silicate melts

W prefers to be in metallic melts

So Hf-W system can be used to date core formation
Iron Meteorites

- Most iron meteorites are very old
- This means that the cores of planetesimals had to form very quickly
- Indistinguishable from CAI age, so within 1 m.y.
- Interp: “Rapid core formation occurred because there was lots more $^{26}$Al around right at the start”

Carlson et al., 2009
Implications

• > 20 km sized bodies formed within first 1 m.y.

• Question: Were asteroids (planets) actually forming at the same time as the Sun – or even before?

• If yes, would require rethinking the use of CAIs as a tool for dating the beginning of the solar system.
Dating Core Formation

- Assumes perfect equilibration of Hf and W between silicate and metallic liquids.
  - Not valid where metal segregation to core is very rapid (> 1 m/yr)

- The initial $^{182}\text{Hf}/^{180}\text{Hf}$ and $^{182}\text{W}/^{184}\text{W}$ ratios are derived from the age of the CAIs - i.e., assumed that CAIs were the first solids in the Solar System

- Using the iron meteorites to define the initial ratios gives essentially the same result as using the CAIs

- There are no basaltic meteorites as old as the iron meteorites

*Kruijer et al., 2012*
Conclusions

• The oldest dated particles in meteorites, the CAIs, formed from a high temperature gas

• These define the age of the solar system as 4.567 billion years old

• The cores of the earliest asteroids formed within 1 million years of the CAIs

• Most asteroids formed within the first 5 million years