OUTLINE

Reading this week:
White Ch 10 until p468

Today
1. Condensation
2. Accretion
Planetary Systems I: Solar Nebula

- solar system formed from interstellar material already processed by short-lived early stars + supernova(e)
  **WHY IS THIS NECESSARY AGAIN?**

  …otherwise periodic table would have only H+He

  **Timing:** Effect of several short-lived isotopes suggests supernova few Ma prior to solar system

Age of the solar system: ~4.568 Ga
**HOW DO WE KNOW THIS?**

Ages of meteorites = leftovers of solar system formation

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Meteorites - a primer

The 3 basic types are:
- **Stony** (silicate): *Chondrite* and *Achondrite* types
- **Fe** (metal)
- **Stony/Fe** (mixed metal & silicate).

**Chondrites:**
- *most primitive rocks in the solar system.*
- Clastic sediments of early formed materials
- Affected by collision, decay, metamorphosis
- Subclasses based on mineralogy, thermal history
Chondrites

Chondrites contain:

- **Chondrules**: high T blobs with quenched igneous textures.
- **Refractory Inclusions = CAI’s**: (Ca-Al Inclusions): Ti, Re, U, Th and the Rare Earth Elements.
- **Matrix**: very fine-grained, dark mix of FeO, olivine, pyroxene carbonaceous minerals, & low T phases like hydrated silicates.

Important class = carbonaceous chondrites: plenty of carbon and lots of low T phases.

They are subclassed as C1 to C4 (least to most metamorphosed).
What does this plot say about the composition of carbonaceous chondrites vs the Sun?

Almost the same!
- **very similar element ratios to the sun** (non-gaseous elements).
- And:
  - volatile rich, lots of C (CaCO$_3$).
  - up to 20% H$_2$O (micas)
  - oxidized > other chondrites
  - Most other chondrites = ordinary chondrites: more processed

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Age from Meteorites

Using several phases from 1 Chondrites meteorite, get best age estimate for solar system

Oldest fragments in them are CAIs

Different fractions from CAI in sample: **U-Pb age = 4568.2 Ma**

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Bouvier and Wadhwa, 2010
Planetary Systems I: Solar Nebula Continued

- So we now know when, but how & what?
- Solar nebula begins hot; solids **condensed** from vapor of solar composition, as temperature decreased…

Rightarrow key to element distribution is **volatility**… preference of element for gaseous species over solid, quantified by the 50% condensation temperature

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Condensation Temperatures

**T** for which 50% of element = transferred to solid phase:

Variation of values exist: fractionate if dust separates from gas

![Condensation Temperatures Chart](image-url)

*Source: Lodders (2003)*
Subcategories seen in periodic table:

- early condensate (refractory elements – CAI)
- silicates
- metals
- volatiles

Volatiles are mainly on the sides

Condensation Temperatures

Focusing on 4 elemental groups within crust/mantle (lithophile) silicates, or core (sidero/chalcophile) sulfides and metals

Major elements condense as minerals while minor and trace elements condense in solid solution with the major phases.
P and T control what material is made at what distance from the Sun, in the solar system.

Result: elements end up distributed unevenly across the solar system.

### Condensation of our Solar Nebula

<table>
<thead>
<tr>
<th>Group</th>
<th>Compounds</th>
<th>wt.-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I</td>
<td>H, He</td>
<td>98.0</td>
</tr>
<tr>
<td>Group II</td>
<td>C, N, O, Ne, S, Ar, Cl</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>(as hydrides, except Ne, Ar)</td>
<td></td>
</tr>
<tr>
<td>Group III</td>
<td>Na, Mg, Al, Si, Ca, Fe, Ni</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>(as oxides)</td>
<td></td>
</tr>
</tbody>
</table>

* The data are based on solar photosphere abundances given by J. E. Ross and Aller (1976).

* The oxygen abundances in Group II is adjusted for oxygen combined with Group III elements.

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**Condensation sequence**

Condensing the ices is what gave the giant planets the mass to gravitationally capture H and He from nebula.

Bulk oxidation state of a planet is set by how much O is condensed as FeO and how much H is retained as H₂O.
Condensation of our Solar Nebula

In more detail, condensation occurs to certain mineral phases, dependent on T.

So what are the (high) T phases?

Following slides: examples of gas-solid phase diagrams for Si, Ca, and Al as a function of T at $10^{-4}$ atm, ~ early pre-solar nebula.

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**Where does an element go?**

Plots show with increasing cooling:

- Increasing amount of elements in certain phase(s), until all = solid.
Putting them all in sequence
Condensation sequence shows expected order at low pressure, over large cooling range

Figure 6.6 Condensation of the elements from a gas of solar composition at $10^{-4}$ atm.
(From Grossman and Larimer, 1974, with permission.)

Condensation sequence minerals
Key minerals, formulas and T
Note some minerals disappear & turn into different phase

<table>
<thead>
<tr>
<th>Phase</th>
<th>Condensation temperature (°K)</th>
<th>Temperature of disappearance (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corundum</td>
<td>$\text{Al}_2\text{O}_3$</td>
<td>1258</td>
</tr>
<tr>
<td>Perovskite</td>
<td>$\text{CaTiO}_3$</td>
<td>1567</td>
</tr>
<tr>
<td>Nephelane</td>
<td>$\text{Ca}_2\text{Al}_2\text{Si}_4\text{O}_9$</td>
<td>1555</td>
</tr>
<tr>
<td>Spinel</td>
<td>$\text{MgAl}_2\text{O}_4$</td>
<td>1513</td>
</tr>
<tr>
<td>Metallic Iron</td>
<td>$\text{Fe}<em>n\text{Ni}</em>{1-n}$</td>
<td>1473</td>
</tr>
<tr>
<td>Enstatite</td>
<td>$\text{Ca}_2\text{MgSi}_2\text{O}_6$</td>
<td>1450</td>
</tr>
<tr>
<td>Forsterite</td>
<td>$\text{Mg}_2\text{Si}_3\text{O}_6$</td>
<td>1444</td>
</tr>
<tr>
<td>Anorthite</td>
<td>$\text{Ca}_2\text{Al}_2\text{Si}_4\text{O}_10$</td>
<td>1393</td>
</tr>
<tr>
<td>Enstatite</td>
<td>$\text{Mg}_2\text{Si}_3\text{O}_6$</td>
<td>1349</td>
</tr>
<tr>
<td>Eskolaite</td>
<td>$\text{Ca}_2\text{O}_3$</td>
<td>1294</td>
</tr>
<tr>
<td>Metallic Cobalt</td>
<td>$\text{Co}$</td>
<td>1274</td>
</tr>
<tr>
<td>Alabandite</td>
<td>$\text{MnS}$</td>
<td>1130</td>
</tr>
<tr>
<td>Rutile</td>
<td>$\text{TiO}_2$</td>
<td>1125*</td>
</tr>
<tr>
<td>Alkaline Feldspar</td>
<td>$(\text{Na}, \text{K})\text{AlSi}_3\text{O}_8$</td>
<td>$\sim$1000</td>
</tr>
<tr>
<td>Troilite</td>
<td>$\text{FeS}$</td>
<td>700</td>
</tr>
<tr>
<td>Magnesite</td>
<td>$\text{Fe}_2\text{O}_4$</td>
<td>405</td>
</tr>
<tr>
<td>Ice</td>
<td>$\text{H}_2\text{O}$</td>
<td>$\leq$200</td>
</tr>
</tbody>
</table>

* Below this temperature, calculations were performed manually using extrapolated high temperature vapor composition data. In some cases, gaseous species which had been very rare assumed major importance at low temperature (CH$_4$), Grossman, Geochem. Cosmochim. Acta, 1972.
Mineralogical condensation sequence:
expected sequence in a closed system at chemical equilibrium.

Expected order, roughly:

1. Corundum, Al₂O₃, and perovskite CaTiO₃ (refractories: Ti, Al, Ca, Os, Zr, Th, U, REE, platinum group metals)
2. Fe + Ni as a metal alloy and the first silicates (Mg, Ca-Mg)
3. Alkalis/alkaline earths as feldspars
4. Sulfide minerals, oxides like magnetite, oxidized Fe into olivine, pyroxene.
5. Hydrated silicates below about 550°K; sulfates, carbonates below this
6. Ices below about 200°K

Planetary Systems I: Solar Nebula Continued

- Object composition and size = function of:
  - Position/T in the solar nebula
  - size of the body from gravitational (impact) gathering (= accretion), related to decreasing density in nebula away from the sun
Formation of the solar system

The Nebular hypothesis:

a) a diffuse ~spherical, slowly rotating nebula begins to contract

b) Contraction = faster rotation, flattening; at the center – protosun

c) Gas and dust form grains, which collide and form planetesimals

d) Terrestrial planets: multiple collisions + accretion due to gravity; gas giants start as ice, attract H, He

Temperature variations

Why rocky inner, gas outer planets?

Gravitational energy turns into heat: Condensation forms rocky materials closer to sun (hot), icy materials away (cold)
Making the planets

Planets (with moons) build from miniature rotating disks
Solar wind pushes leftover gas to outer planets, where it gets collected

Density and Size of Planets

<table>
<thead>
<tr>
<th>Object</th>
<th>Total Matter</th>
<th>Metals</th>
<th>Oxides</th>
<th>Ices</th>
<th>Gases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass 10^24g</td>
<td>Fe, Ni</td>
<td>SiO2,Mg(O,Fe)2</td>
<td>H2O,CH4,NH3</td>
<td>H2,He</td>
</tr>
<tr>
<td>Mars</td>
<td>3.30</td>
<td>0.1</td>
<td>0.17</td>
<td>1.2</td>
<td>96.5</td>
</tr>
<tr>
<td>Earth</td>
<td>5.97</td>
<td>0.06</td>
<td>3.36</td>
<td>14</td>
<td>82</td>
</tr>
<tr>
<td>Venus</td>
<td>4.87</td>
<td>0.16</td>
<td>1.73</td>
<td>14</td>
<td>80</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.33</td>
<td>0.18</td>
<td>50</td>
<td>1.2</td>
<td>80</td>
</tr>
<tr>
<td>Mars</td>
<td>0.64</td>
<td>0.06</td>
<td>90</td>
<td>14</td>
<td>80</td>
</tr>
</tbody>
</table>
Chemistry for timing: how long did early accretion take?

Many radiometric lines of evidence, some examples:

1. **Meteorite age range**: achondrites about 10 Ma younger, stony meteorites up to 100 Ma younger than oldest CAIs (4.568Ga)

2. **Very short lived isotope systems**: $^{26}$Al $\rightarrow$ $^{26}$Mg produced differences between CAIs & chondrules; $^{60}$Fe $\rightarrow$ $^{60}$Ni produced differences between achondrites & Earth; both systems “dead” in few Ma; formation processes have to occur prior

3. **Short lived isotope systems**: $^{129}$I $\rightarrow$ $^{129}$Xe produced differences between Earth’s mantle vs atmosphere; only possible within 100 Ma; Core formation within ~20 Ma (Hf-W)

Summary of accretion timing

🧳 Absolute *upper limit* on solar nebula collapse is $<10^8$ years after the last pre-solar nucleosynthesis (e.g. short-lived isotopes – $10^8$ probably overestimate)

🧳 Newly synthesized nuclear material was injected into our solar nebula $<$ 3-5 Myr before the CAIs formed. (multiple very short-lived isotope systems).

🧳 Chondrules formed, at most, a few million years after CAIs (They do not record all the anomalies in very short-lived isotope radioactivity)

🧳 CAI and chondrule formation probably bracket the time span of condensation and chondrite formation
Using chemistry for conditions

Planetesimal T from K/U:
- U is a refractory element; K is moderately volatile; both radioactive
- K/U ratio is not fractionated much during igneous processes.
- K/U data for the inner planets: different amounts of volatilization of K (T > 1200°K) occurred during accretion and early differentiation.
- we can correct for heat production and decay.

- Chondrites have high K/U ≈ 20,000-70,000, and low temperatures of formation.

- K/U ≈ 12,000 in silicates on Earth. Values on Mars and Venus are similar.

- The moon and differentiated meteorites (eucrites) appear to have formed at higher temperatures, as K/U ≈ 1000-4000.