Lecture 30

High Temperature Geochemistry

Solar System Formation and Early Evolution

Reading this week:

White Ch 8.1 – 8.4.1(dig. 313-326) and
Ch 10.1 to 10.5.3 (dig. 421-464)

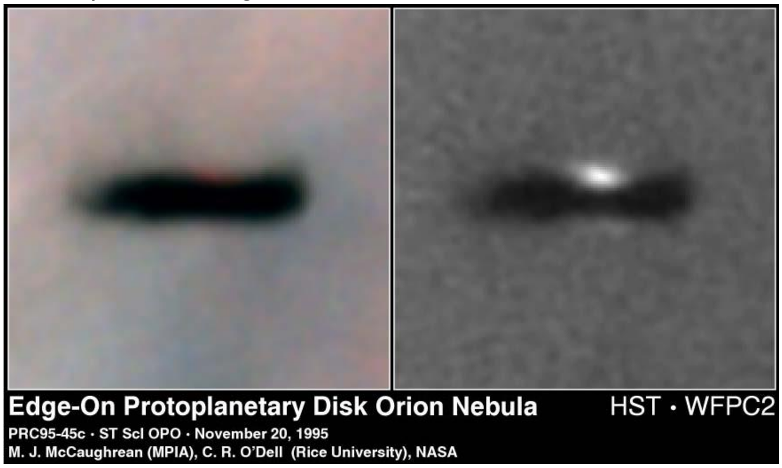
Today

1. Planetesimal Accretion
2. Early Solar System Evolution

The transition from glowing nebulae to a solar system

Our solar system evolved from something like this, in which the condensation sequence operated, to today's system composed of

- a Star
- planetary bodies
- their satellites
- fine particles
- gasses



Hubble Telescope Image: a disk of dust seen edge-on around a newborn star in the Orion nebula (1,500 light-years away). The view of the disk is edge-on so the star is largely hidden inside. Our solar system probably formed out of just such a disk 4.6 billion years ago. At 17 times the diameter of our own solar system, this disk is the largest of several recently discovered in the Orion nebula.

http://hubblesite.org/newscenter/archive/releases/1995/45/image/c

Accretion of solid objects in the proto-solar system

How did these objects accrete from the condensates?

To answer this question, we must look past subsequent processes such as planetary-scale differentiation (e.g., as has occurred on the Earth).

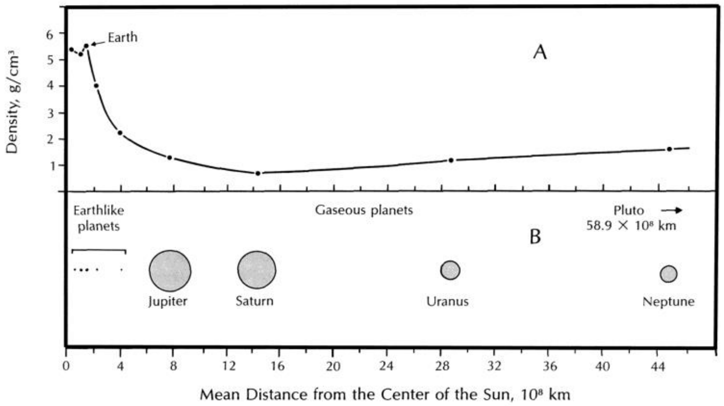
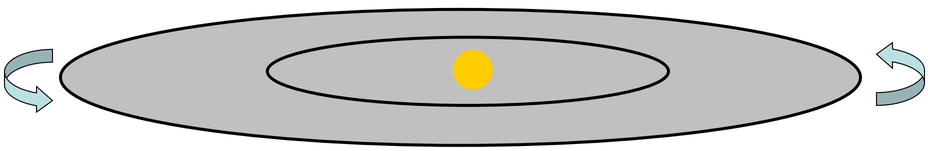


Figure 3.1 **A:** Variation of density of the planets with mean distance from the Sun. Note that the Earth has the highest density among the earthlike planets, which, as a group, are more dense than the outer gaseous planets. **B:** The planets of the solar system magnified 2000 times relative to the distance scale. The earthlike planets are very small in relation to the Sun and the gaseous planets of the solar system.

Nevertheless, the distribution of material in the solar system today provides some clues.

The spacing of the planets, shapes and velocities of their orbits, and rates of rotation on their axes all tells us that the nebula was likely spinning.



Collisions between dust-size particles led to aggregation of larger objects, called **planetesimals**, in a series of more or less regularly spaced bands (jet streams) around the sun.

As planetesimals grew in size, the gravitation of the larger planetesimals attracted smaller objects to them, building up larger and larger (and fewer and fewer) bodies, eventually leading to the planets we see today.

The most widely accepted scenario for this process, the Safronov-Schmidt model, is depicted in the next slide.

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Aspects of Planet Formation in the Primordial Solar Nebula

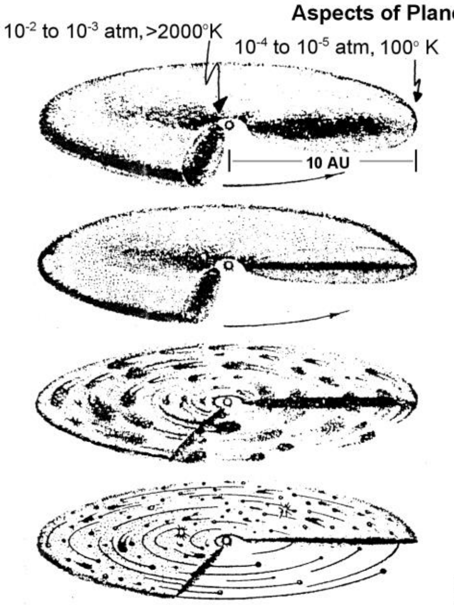


Figure 6.2 Stages in the development of the solar nebula according to the model of Schmidt and Safronov. Sedimentation of dust and small planetesimals to the ecliptic plane is followed by gravitational instability of the dust disk and formation of a population of asteroidal-sized planetesimals. (From Levin, 1972a, with permission.)

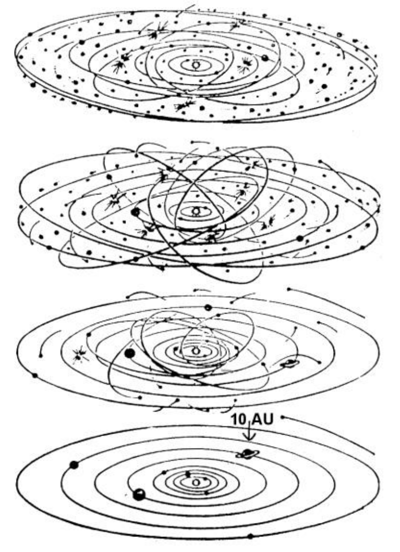


Figure 6.3 Stages in the accretion of terrestrial planets from an initial disk-like configuration of asteroidal-sized planetesimals, according to the Schmidt-Safronov model. The initially flat system of intermediate bodies first thickens due to their mutual gravitational perturbations, but returns to the flat configuration at the termination of planet formation owing to the averaging effects of large numbers of random planetesimal orbits (From Levin, 1972a, with permission.)

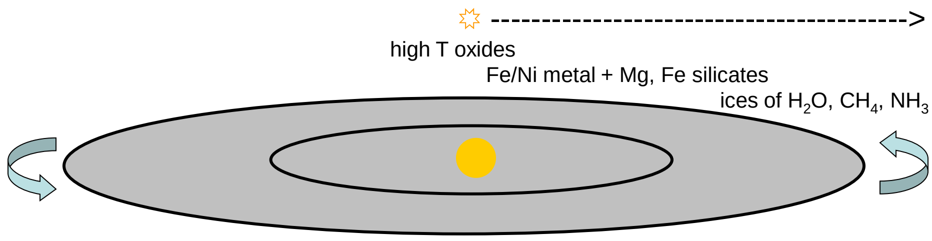
From: Ringwood, "Origin of the Earth and Moon"

Overall, planetary density decreases with increasing distance from the sun -- qualitatively like we would expect in a just-condensed nebula with a temperature gradient.

Conditions probably varied rather smoothly from the center to the edge of the accretionary disk, reflecting the T (and P) gradient going outward from the proto-sun:

- ❖ mostly dense, volatile-poor, high-T condensates survived closer to the proto-sun
- ❖ something closer to the full range of condensates farther out from the sun, making the material farther out closer to the sun's composition.

The lowest-T phases remaining at various radii would be:



To a first order, this explanation works fairly well. In summary, we can assume that …

the condensates formed from a gas cloud of initially rather uniform composition.

The composition and density of solid materials at any radius from the sun will reflect the P-T path the material took as the solar nebula cooled.

Those compositions should be broadly true in what's left today, the planets, which accumulated from dust sized particles that form, collide, and accrete..

However, although equilibrium condensation explains a lot of what we see, the expected temperature gradient from the sun to Pluto **does not** result in

- observed variations in gas contents of the outer planets (i.e., Saturn and Jupiter have too much H and He; Uranus and Neptune don't have enough).

- the observed variations in density of the stony planets (i.e., lower than expected densities of Mars and the asteroid belt - which is a "failed" or "broken up" planetary mass between Mars and Jupiter)

Both observations have usually been explained by appealing to more-or-less chance occurrences that led Saturn, and especially Jupiter, to grow more massive faster (i.e., *early* in the accretion process) than expected.

The gravitational fields of these planets then attracted material from neighboring zones in the accretion disk, and they grew large enough fast enough to capture large amounts of H_2 and He (which don't condense).

However, it has also recently been suggested that these two planets may have accreted farther out from the sun, then slowly migrated inward to their present positions.

Varies as $R^{-3/2}$
(where R is the sun to annular zone radius)

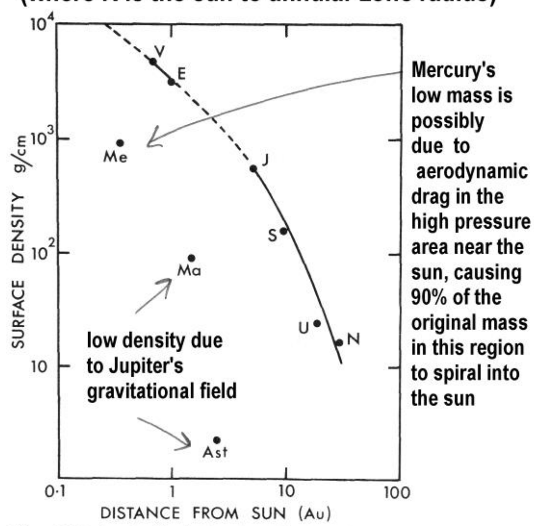
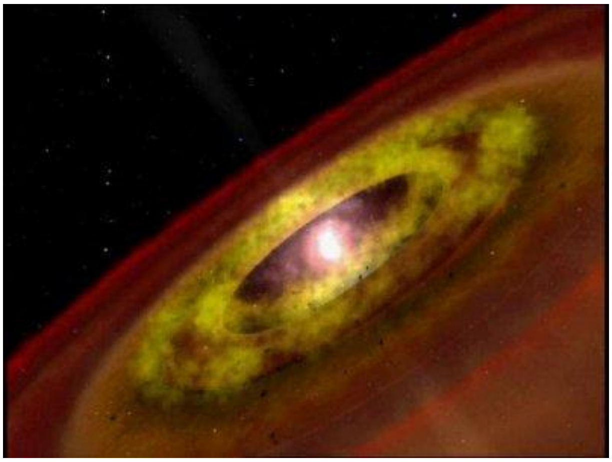


Figure 6.1 Surface densities in the primordial solar nebula obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. Anomalies at the orbits of Mercury, Mars, and the asteroids are believed due to specialized processes of mass loss. (After Weidenschilling, 1977.)

The contrast in density between the rocky and gaseous planets is thought to partly reflect the influence of a **"T-Tauri"** superluminous phase of our sun during its first 10^7 yr, which expelled up to 25% of its original mass toward the outer reaches of the solar system.

Artist's rendition of a T-Tauri star and proto-planetary disk



Source: Nasa

This powerful solar "wind" and accompanying radiation pressure also removed nearly all the remaining gaseous components from the inner solar system.

Important accretion questions that bear on planetary compositions

1. Was the solar nebula originally compositionally homogeneous?
2. Did metals and silicates accrete together?
3. Did planetesimals accrete homogeneously and continuously, or in stages interspersed by differentiation events?
4. How long did accretion take, particularly the planetesimal stages? Time affects the *retention of heat* produced from early radioactive decay and collisions, and also affects the *redox state* of early planetesimals by determining how much H_2 is present.
5. How did planetary satellites (moons) form, and why is ours so large compared to other moons (i.e., $r_{moon}/r_{earth} >> r_{other\ moons}/r_{other\ planets}$)?
6. What causes the inner, rocky planet vs. outer, gassy planet distribution?
7. Why are Earth's two close neighbors Venus and Mars so different, especially in surface temperature?

For answers to such questions, one of the most important sources of clues is the meteorites and their compositions.

Meteorites - a primer

The 3 basic types are:

- Stony (silicate)
- Fe (metal)
- Stony/Fe (mixed metal & silicate).

Stony meteorites include *Chondrite* and *Achondrite* types.

A slice of the Allende Carbonaceous Chondrite

Chondrites *are the most primitive rocks in the solar system.*

Subclasses are based on mineralogy and thermal history.

All are clastic sediments of early condensation sequence material.

They have been variably metamorphosed by later collisions and radio-decay heating.

Meteorites - a primer

There are significant compositional and mineralogical differences among chondrites, but all Chondrites contain:

- ✓ *chondrules:* high T blobs with quenched igneous textures.
- ✓ *Refractory Inclusions:* aka CAI's for Ca-Al Inclusions, also containing other very high T condensing elements like 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.

An important class is the **carbonaceous chondrites**, containing plenty of carbon and high abundances of low T phases.

They are subclassed as C1 to C4 (least to most metamorphosed).

C1 chondrites figured into our age of the universe discussion last lecture.

C3 chondrites are least metamorphosed, C1 to C3 chondrites are:

- volatile rich, contain high abundances of C-rich phases, including $CaCO_3$.
- up to 20% H_2O by weight, in phyllosilicates
- more oxidized than other chondrites
- Have ***very similar element ratios to those of the sun*** (in the non-
- gaseous elements).

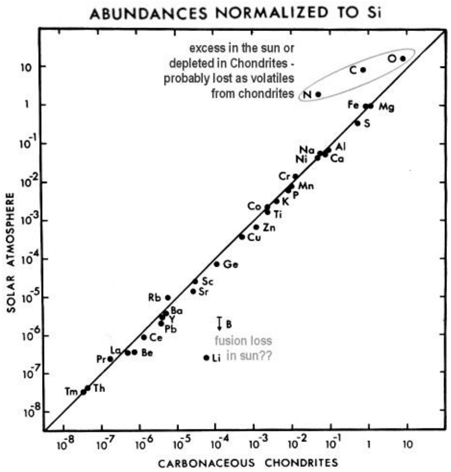


Figure 2.2 Comparison of elemental abundances in Type 1 carbonaceous chondrites with those in the solar photosphere. All abundances are normalized on the basis of Si = 10^6. (From J. E. Ross and Aller, 1976.)

The many varieties of non-carbonaceous chondrites are called ordinary chondrites.

ordinary chondrites are :

- ♦ more metamorphosed
- ♦ contain coarser textures, remelted chondrules, and sometimes segregated Fe/Ni blobs
- ♦ chemically depleted (according to volatility) relative to C3 chondrites.

Chondritic Meteorites

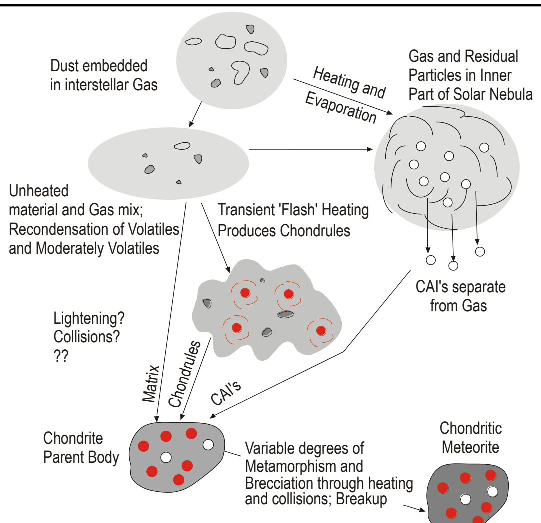
are a mix of materials formed under different conditions and places in the solar nebula.

Most compositional variations between chondrites are from:

♦ variations in the relative proportion of

- refractory material (e.g., Al/Si ratios)
- volatiles (e.g., water)
- siderophiles

♦ variations in oxygen fugacity (~P_{O2})



○ CAI = Ca-Al rich inclusions. These seem to be refractory residual solids heated to ~1700K in the inner part of the solar nebula.

● Chondrules were melted due to rapid heating and subsequent quick cooling.

The matrix is nebular dust, mostly not subsequently heated..

Figure 10.36. Cartoon illustrating the processes involved in the formation of chondrites and their components. Modified from McSween (1987).
modified from White, Geochemistry

A Chondritic Earth

Geochemists commonly assume a model in which the Earth accreted from material with chondritic ratios of the non-volatile elements. However, there are important differences in the compositions of the Earth relative to an assumed "original" C1 chondrite composition.

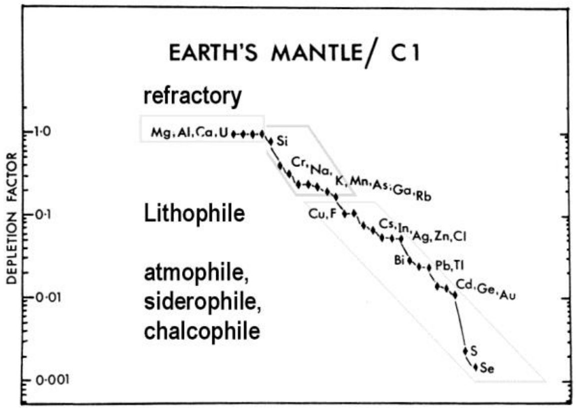


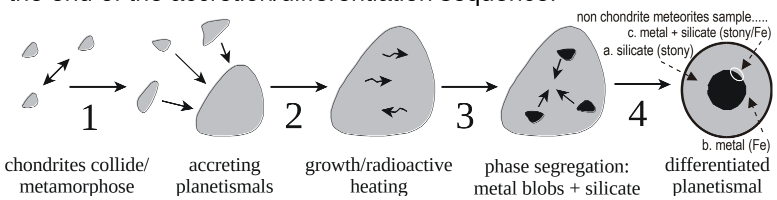
Figure 2.3 Abundances of elements in the Earth's mantle compared to primordial abundances as given by C1 chondrites. (From Ringwood and Kesson, 1977, with permission.)

Some recent research challenges the idea of chondritic composition for the initial bulk solid Earth, the differences are not large and the arguments are still evolving, so we will stick with the canonical Bulk Chondritic Earth assumption here.

Non Chondritic Meteorites

There are many classes, including ones believed to be chunks of the lunar and martian crust that have been transported here following large impacts.

The most important classes for the present discussion are those with very similar ages to Chondrites (some indistinguishable) and which appear to be samples from the end of the accretion/differentiation sequence:



a. Achondrites:
These Stony meteorites are differentiated and broadly basaltic in composition, with igneous textures.

b. Irons:
alloys of Fe/Ni, broadly similar to our core

c. Stony/Fe:
mixtures of metallic and silicate materials, believed to have formed at the margins of segregated liquid metal and crystal-rich silicate melt.

This achondrite meteorite is thought to be a sample of the crust of the asteroid Vesta, making it only the third known solar system object (excluding Earth) of which we have a hand sample. The meteorite is made almost entirely of pyroxene, as is Vesta (based on its reflected light spectrum).

http://www.solarviews.com/eng/meteor.htm

How long did early accretion take?

There are many radiometric lines of evidence; Here are 4 examples:

1. <u>in stony meteorites</u>: ^{238}U-^{206}Pb dating, $t_{½}$ = 4.468 Ga

The oldest chondrite age comes from *CAI inclusions* of two carbonaceous chondrites: 4.5672 ± 0.0006 Ga. *Chondrules* in these meteorites are nearly the same age: 4.5647 ± 0.0006 Ga. (Amelin et al., Science, 2002).

This is ~5 Ma older than the best ages for ordinary chondrites.

Ages of *achondrites* are as old as 4.5578 ± 0.0004 Ga (Angra dos Reis), and extend to about 30 Myr younger than that.

2. <u>in chondrites</u>: $^{26}Mg/^{24}Mg_{CAI's}$ > $^{26}Mg/^{24}Mg_{Chondrules}$
(a record of live $^{26}Al \rightarrow {}^{26}Mg$, $t_{½}$ = 700 ka)

Therefore, CAIs formed very soon after the last r-process event that contributed material to our solar nebula. Chondrules do not show this anomaly. Was our nebula heterogeneous or, more likely, did chondrules form some 2-3 Myr after the CAIs?

How long did early accretion take?

3. <u>in achondrites</u>: High $^{60}Ni/^{58}Ni$ relative to terrestrial and lunar rock values (a record of $^{60}Fe \rightarrow {}^{60}Co \rightarrow {}^{60}Ni$, $t_{½}$ = 1.5 Ma)

High $^{60}Ni/^{58}Ni$ in old, Ca-poor achondrites ("eucrites") implies differentiation of a parent body in the first 1-2 Ma of solar system history, very soon after the last nearby r-process event. (Shukolyukov & Lugmair, *Science*, 1993).

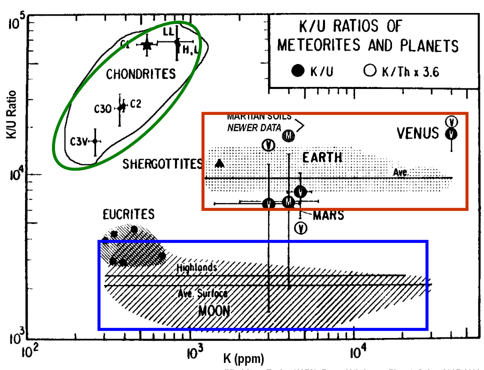
4. <u>On Earth</u>: $^{129}Xe/^{132}Xe_{mantle} > {}^{129}Xe/^{132}Xe_{atmosphere}$ (a record of $^{129}I \rightarrow {}^{129}Xe$, $t_{½}$ = 15.7 Ma)

Implies rapid accretion of the Earth while ^{129}I was still "alive" and radioactive production of some ^{129}Xe inside the mantle after the Earth had degassed/differentiated to form an atmosphere.

What were planetesimal temperatures like during accretion?

One line of evidence comes from ratios of volatile to non-volatile elements with otherwise similar geochemistry. The best-documented example is K/U.

- K and U are important heat-producing elements because of their radioactive isotopes (^{238}U, ^{235}U and ^{40}K). U is a refractory element; K is moderately volatile.
- K/U ratio is not fractionated much during *igneous* processes.
- K/U data for the inner planets and asteroids indicate that different amounts of volatilization of K (T ≥ 1200°K) occurred during accretion and early differentiation.
- present decay rates can be measured remotely by gamma radiation.



modified from Taylor (1979), Proc. 10th Lunar Planet. Sci , p2017-2030

- 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.

Summary of Accretionary Conditions in the Solar Nebula

The compositions of chondrites and other meteorites place important bounds on the formation of the solar system, although some are not mutually consistent. This indicates our incomplete understanding of the process.

Temporal constraints

- An absolute *upper limit* on the time of collapse of the solar nebula is $<10^8$ years after the last pre-solar nucleosynthesis (e.g., evidence of live ^{129}I on early Earth), and it was probably much less.

- Newly synthesized nuclear material was injected into our solar nebula < 3-5 Myr before the CAIs formed. Most CAIs show ^{26}Mg anomalies, indicating ^{26}Al still existed when they formed. This infusion of material also produced anomalies from other short-lived isotopes: ^{107}Pd, ^{53}Mn, and ^{41}Ca ($t_{½} = 10^5$ yr).

More Temporal constraints

- Chondrules formed, at most, a few million years after CAIs (with rare exceptions, they do not show ^{26}Mg anomalies, indicating ^{26}Al "died" before they formed, but their ages are very similar to CAI ages).

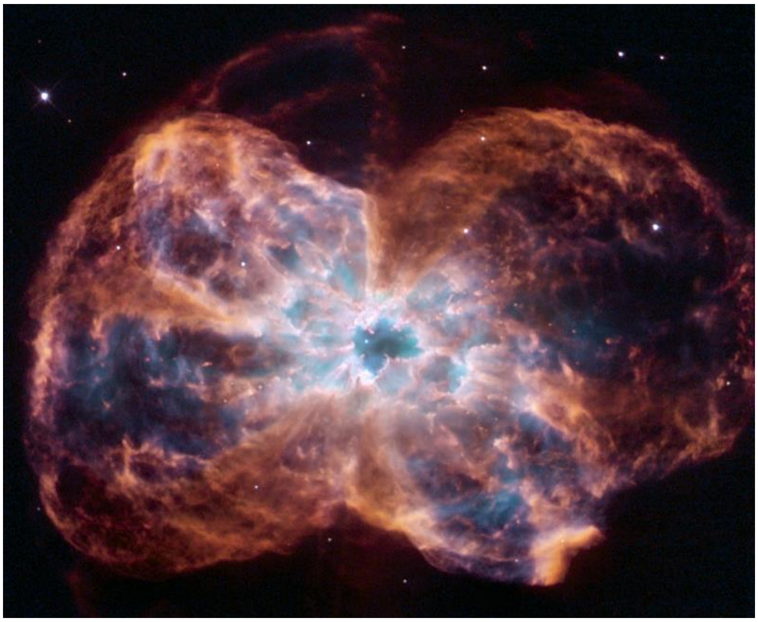
- The CAI and chondrule data probably bracket the time span of condensation and chondrite formation.

Compositional constraints

- Variations in the chemical composition of chondrites clearly indicates chemical inhomogeneities within the solar nebula and some fractionation during condensation.

Hubble image of stellar supernova Star

http://hubblesite.org/newscenter/archive/releases/nebula/2007/09/



More Compositional constraints

- Oxygen fugacity also varied within the solar nebula, given that a significant fraction of condensed matter was as oxides even though the coexisting gas was dominated by H_2. This may reflect gas:dust ratio variations caused by gas turbulence or differential settling of grains to the nebular mid-plane.

- Siderophile element variations in meteorites imply preferential transport of metal grains by density or magnetic property differences during early planetismal accretion.

- Oxygen isotope ratios vary between many meteorites and planetary bodies.

- Isotopes of some stable elements with radioactive precursors also vary in interstellar grains.

The last two points imply that the nebula was not entirely homogenized or entirely gaseous for a significant length of time. Oddly enough other isotope systems are not likewise affected, instead implying a homogeneous nebular composition.

⌿ *Thermal constraints* ⌿

⛱ The interstellar dust in the matrix of Carbonaceous chondrites predates the solar system and contains microdiamonds implanted with supernova-produced Xe. To retain this noble gas signature, they were never heated above ~700 K.

⛱ But chondrules require nebular temperatures ≥1700 K (locally). Chondrules cooled rapidly (over hours or less), so that the high temperatures were transient. Much of the nebular dust would have been melted in the locale where chondrules formed (i.e., because some meteorite are up to 80% by weight chondrules).

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⌿ *More Thermal constraints* ⌿

⛱ CAI's were formed in areas where up to 95% of the nebular dust was either still gaseous (during initial condensation) or where nebular dust was subsequently heated and evaporated (so CAI's would be refractory residues). In either case they also require very high temperatures, probably in the inner-most solar system. Some CAI's cooled rapidly (0.5-50 K/hr), whereas others remained longer at high temperatures.

⛱ The parent bodies (Planetismals) of non-chondritic (stony, stony-irons, irons) meteorites were heated enough to melt and differentiate. The oldest achondrites are not significantly younger than many chondrites, implying planetismals accreted, melted, and differentiated ≤2 Ma after chondrites formed.

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