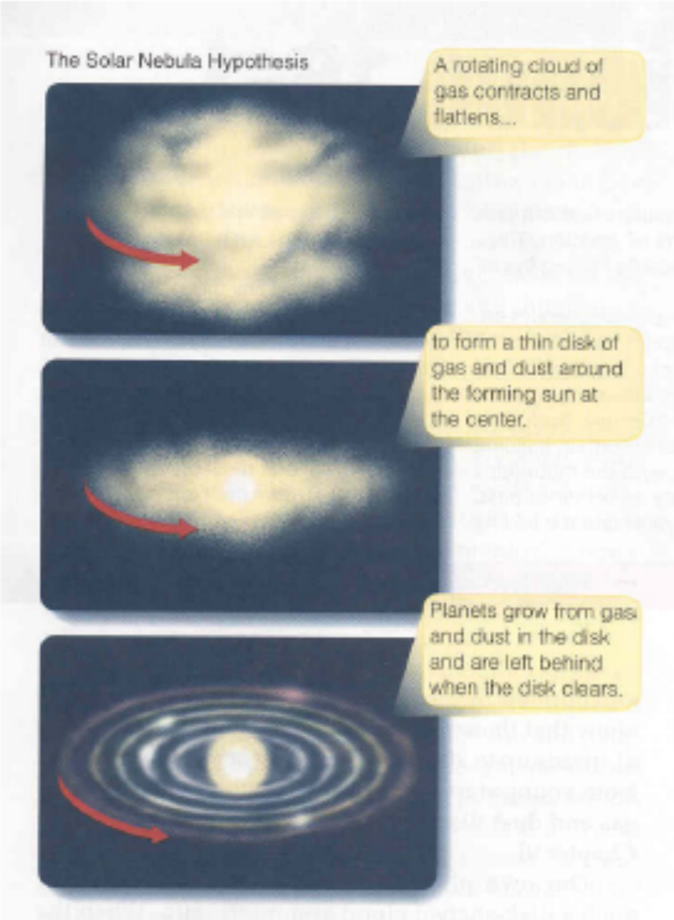
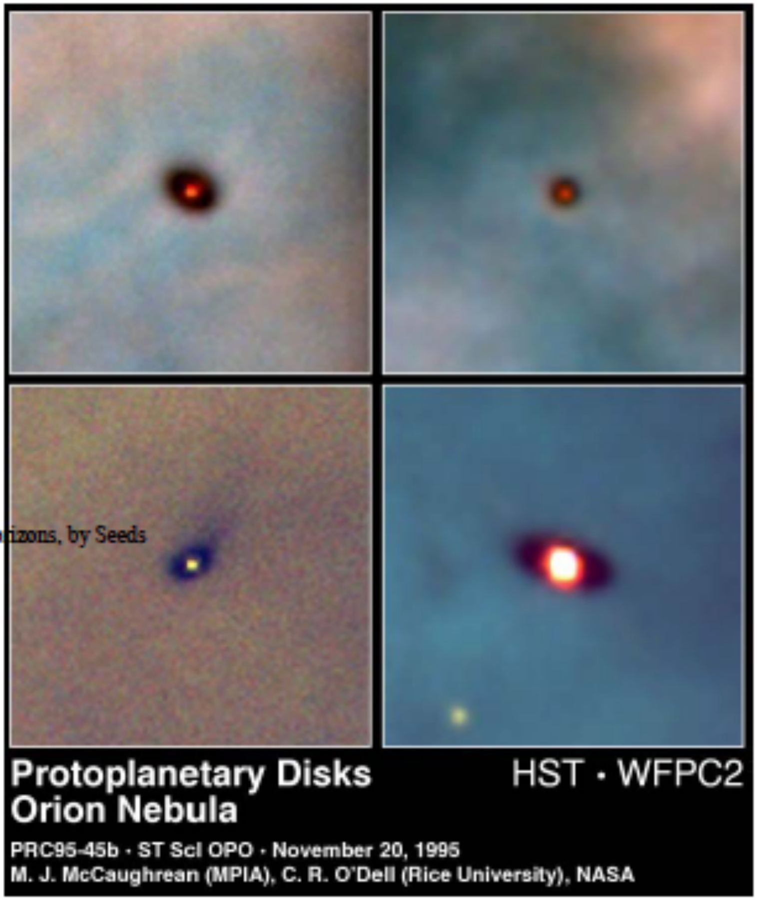
Protoplanetary Disks



our text: Horizons, by Seeds



From Horizons, by Seeds

- Hubble images of "proplyds" in the Orion nebula
- Seen in silhouette against glowing gas clouds
- Central star just visible shining through dust at long (red) wavelengths

Equilibrium Condensation Model

- Start with material of solar composition material
  - (H, He, C, N, O, Ne, Mg, Si, S, Fe ...)
- Material starts out hot enough that everything is a gas
  - May not be exactly true but is simplest starting point

- As gas cools, different chemicals condense
  - First high temperature chemicals, then intermediate ones, then ices
- Solids begin to stick together or accrete
  - snowflakes ⇒ snowballs
- Once large enough gravity pulls solids together into planetesimals
  - planetesimals grow with size

- At some point wind from sun expels all the gas from the system
  - Only the solid planetesimals remain to build planets
  - Composition depends on temperature at that point (in time and space)
  - Gas can only remain if trapped in the gravity of a large enough planet

Material Available

Solar composition ranked by mass

Element	% by #	% by mass
H	91.0	70.9
He	8.9	27.4
O	0.07	0.8
C	0.03	0.3
Ne	0.01	0.2
N	0.008	0.1
Fe	0.003	0.1
Si	0.003	0.07
Mg	0.003	0.06
S	0.002	0.04

- H abundant, but no H compounds condense till relatively low temperature
- He, Ne are noble gasses – don't condense at all
- H_2O, CH_4, NH_3 only condense in outer solar system
- Fe, Si, Mg, +O compounds dominate inner solar system (i.e. Fe core, silicate rocks)

Reason for Jovian Planets

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- Because you cannot condense O by itself (but only in compounds also containing Si, Mg, Fe), you don't have much material available for making terrestrial planets. You are limited by the low abundance of Si, Mg, Fe: Terrestrial planets are relatively small
- Once solid H_2O becomes available you have lots more material
- Starting at Jupiter you can make a big enough core from solid H_2O that you can gravitationally hold onto the H and He gas

<u>Meteorites</u> as samples of asteroids

- Meteorites (which survived) are not associated with comets
- They seem to come from the asteroid belt

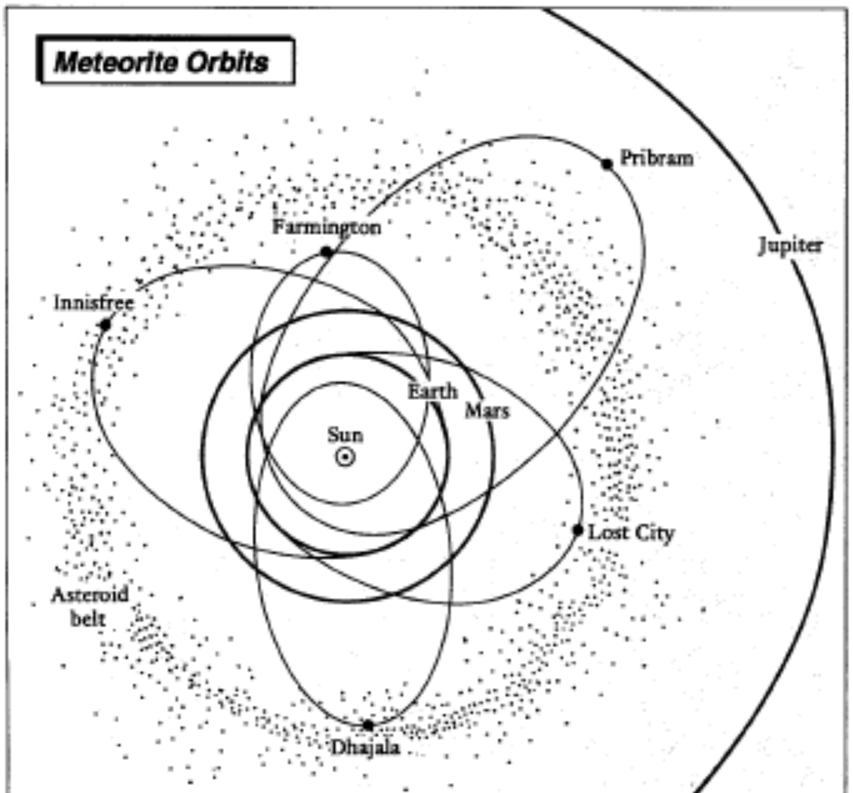
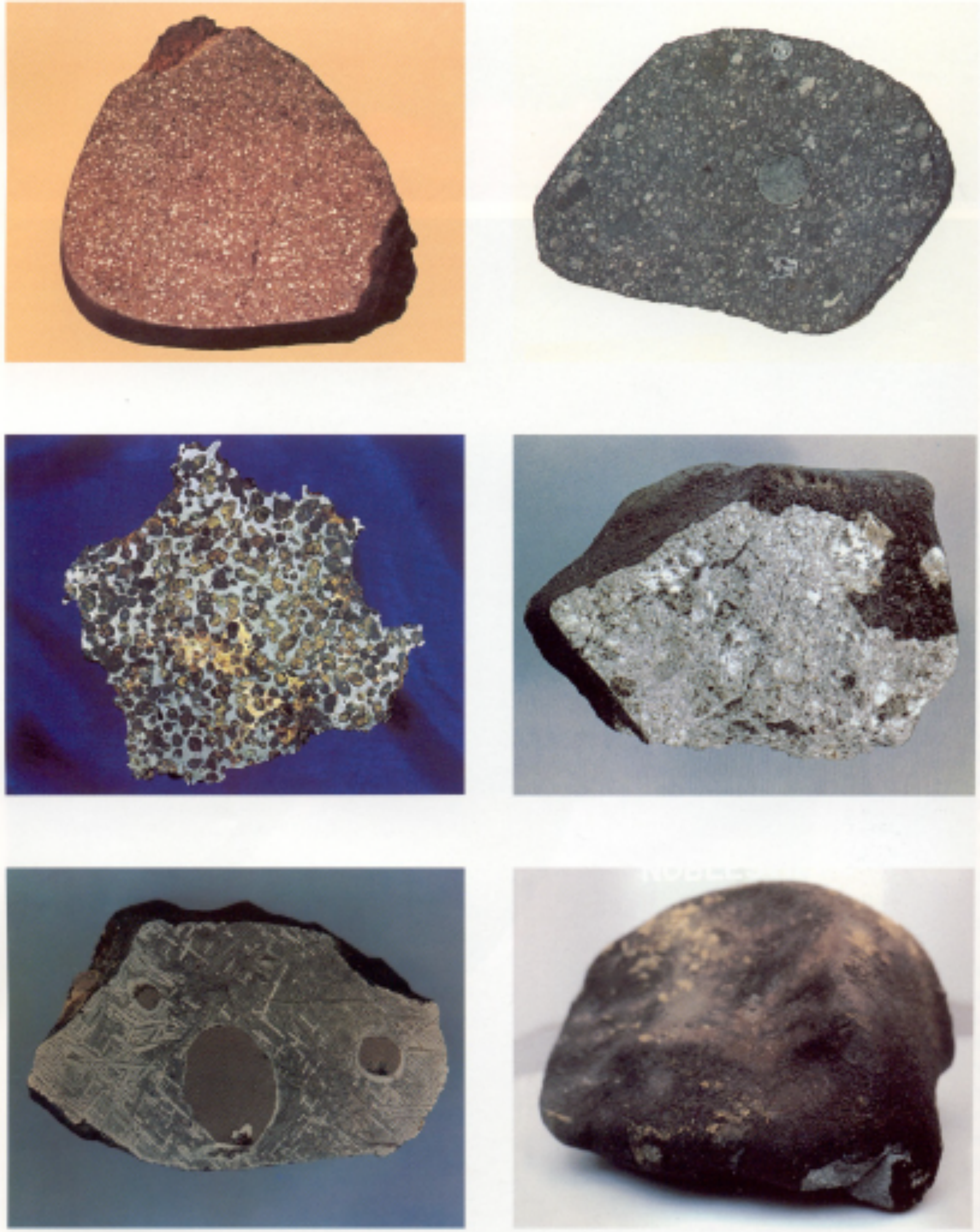


Figure 3.2: The calculated orbits of recovered meteorites provide information on the sources of these objects. Five recovered ordinary chondrites had highly elliptical orbits. All of these had aphelia, the approximate locations of which are illustrated by small dots in this figure, within or near the asteroid belt between Mars and Jupiter. This suggests that chondrites may be fragments of asteroids. The orbits are drawn to scale, but their orientations are chosen for clarity of illustration.

Common Classification of Meteorites

- Simplest classification is
  - Stones Stony-Irons Irons
  - But there are two very different types of stones
    - Stones that look like “ordinary” igneous rocks
    - Stones that are strange assemblages of very primitive components
- Better classification based on how “altered” they are – then with subdivisions based on details of composition

Types of Meteorites



Whole-rock samples of common meteorite types (approximate longest dimension, in cm). Top left: Whitman, H5 (6 cm); top right: Allende C3V (8 cm)—note 1 cm chondrule in center; center left: Springwater pallasite (18 cm); center right: Sioux Co. eucrite (8 cm); bottom left Sanderson IIIB medium octahedrite (13 cm)—note large FeS inclusions. (All Arizona State University) Bottom right: nearly complete fusion crust, the Noblesville H chondrite, which fell on August 31, 1991. (NASA Johnson Space Center)

Undifferentiated

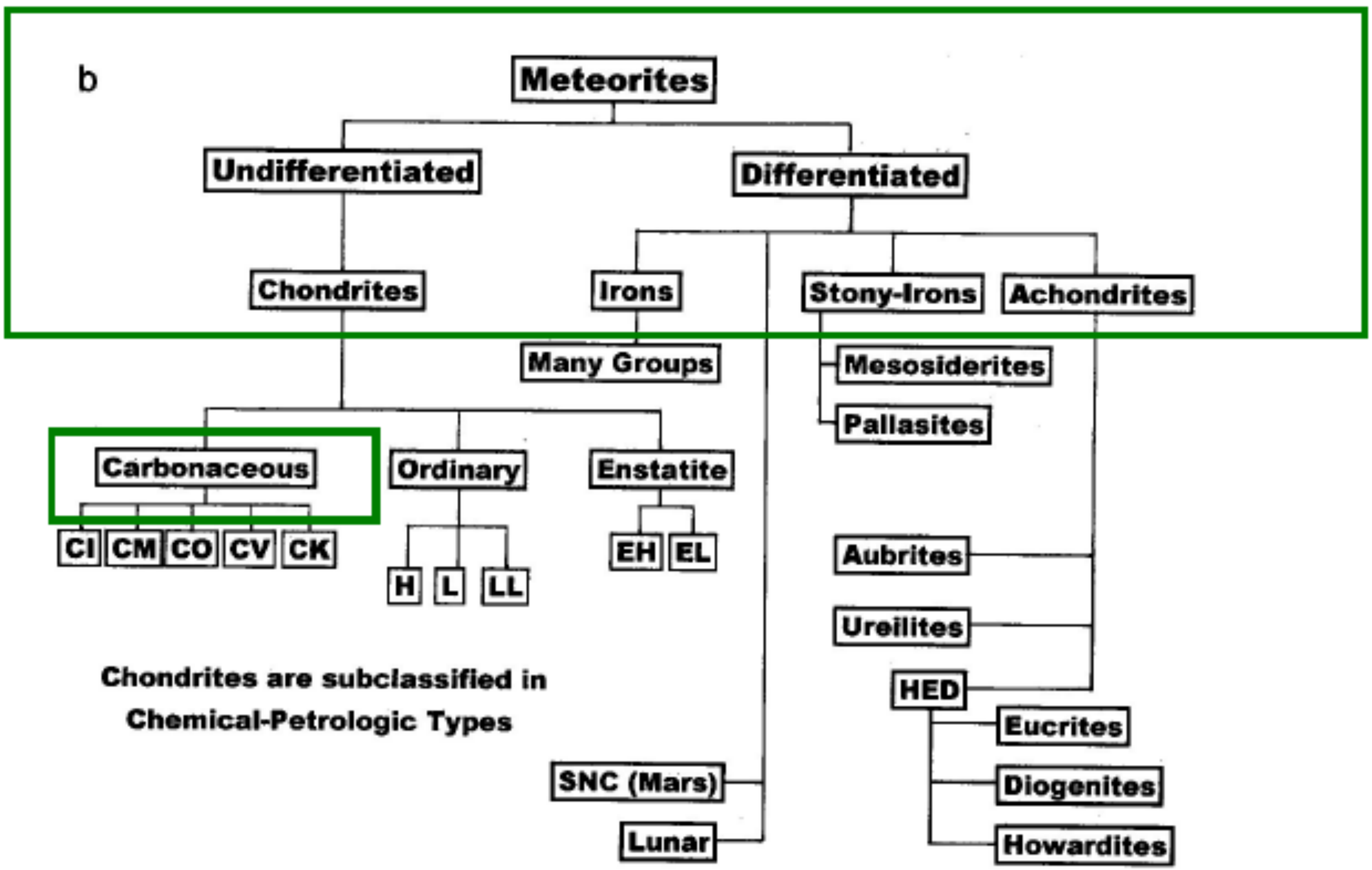
- Ordinary Chondrite
- Carbonaceous Chondrite

Differentiated

- Stony-iron
- achondrite (igneous)
- Iron
- unsliced chondrite

Types of Meteorites

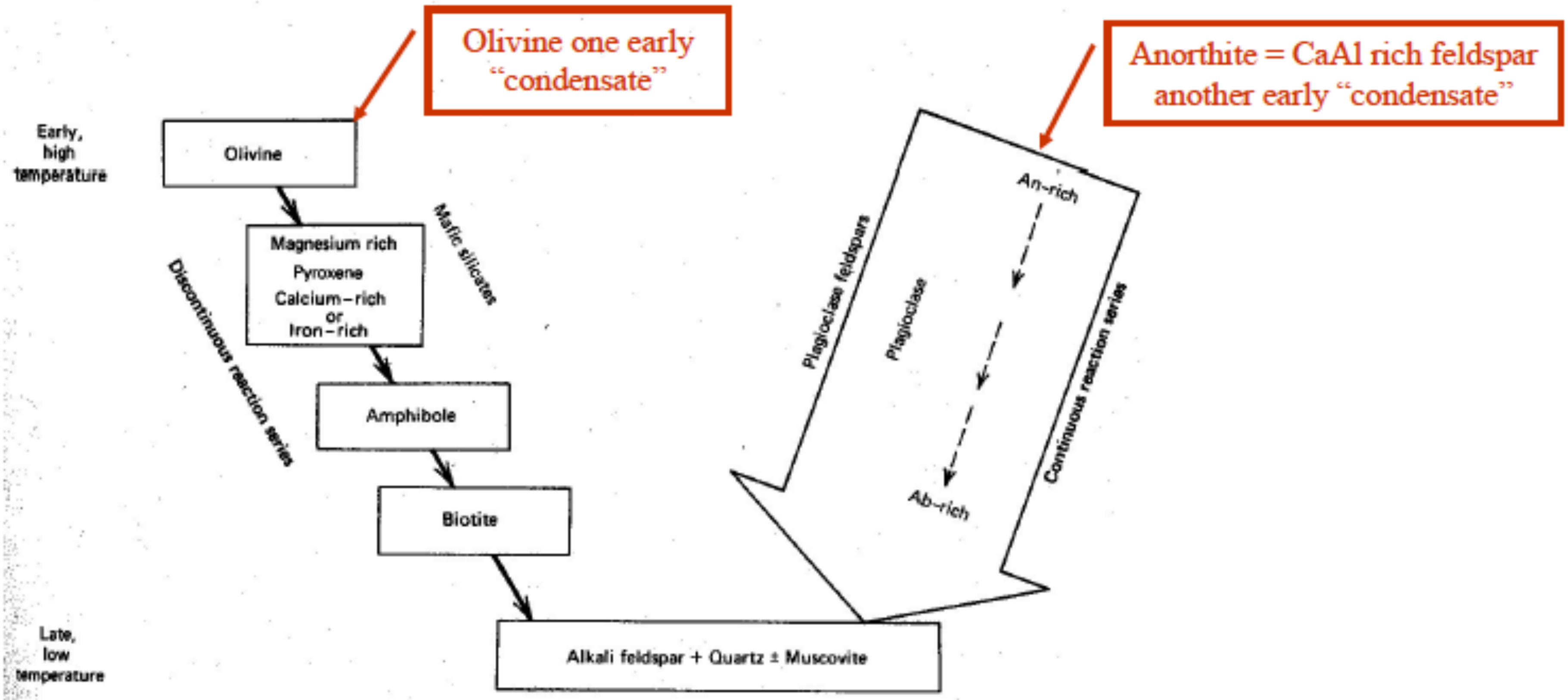
- Many fine divisions, we'll only care about the main ones
- Chondrites are undifferentiated
  - Carbonaceous chondrites are the <u>most</u> primitive of the chondrites



Chondrites: Undifferentiated

- Chondrules: Olivine and Pyroxene
- CAI (Calcium Aluminum rich Inclusions)
- Matrix of phyllosilicates, FeO, Fe, FeS, C compounds

Reminder– Bowen reaction series



- Cool a basaltic magma and ask which minerals crystallize, and in what order
- Liquid ⇔Solid equilibrium for "basaltic" composition

Equilibrium Condensation Model

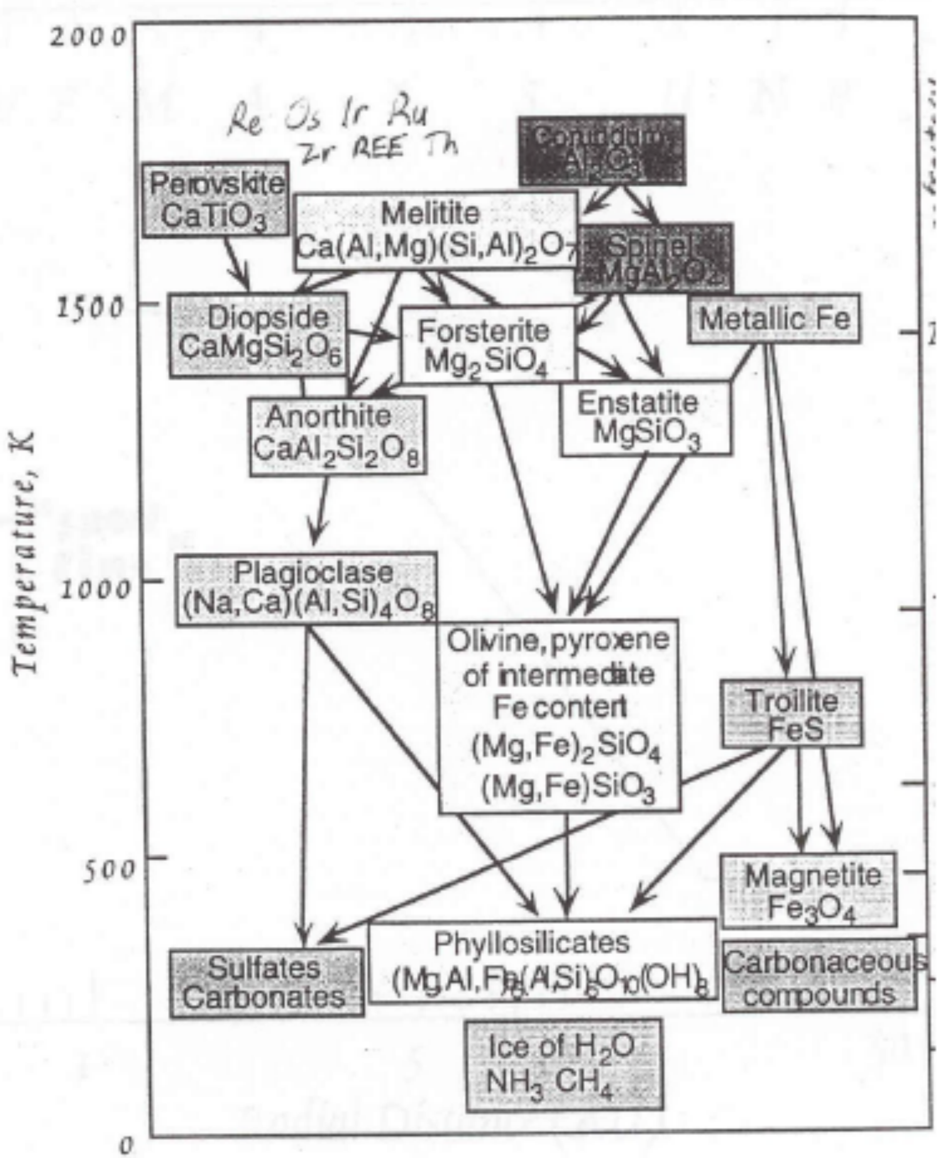


Figure 10.33. Simplified mineralogical condensation sequence.

- Start at top (high T) with everything a gas
- As temperature drops, solids begin to form
- As temperatures continue to drop, more gaseous components condense, reacting with existing solids to create new ones more stable at lower T
- Similar to Bowen Reaction Series but more complex
  - Ca Plag → Na Plag
  - Mg Olivine → Fe Olivine
  - Olivine, Pyroxene → Sheet silicates

Asteroids

Components within primitive meteorites

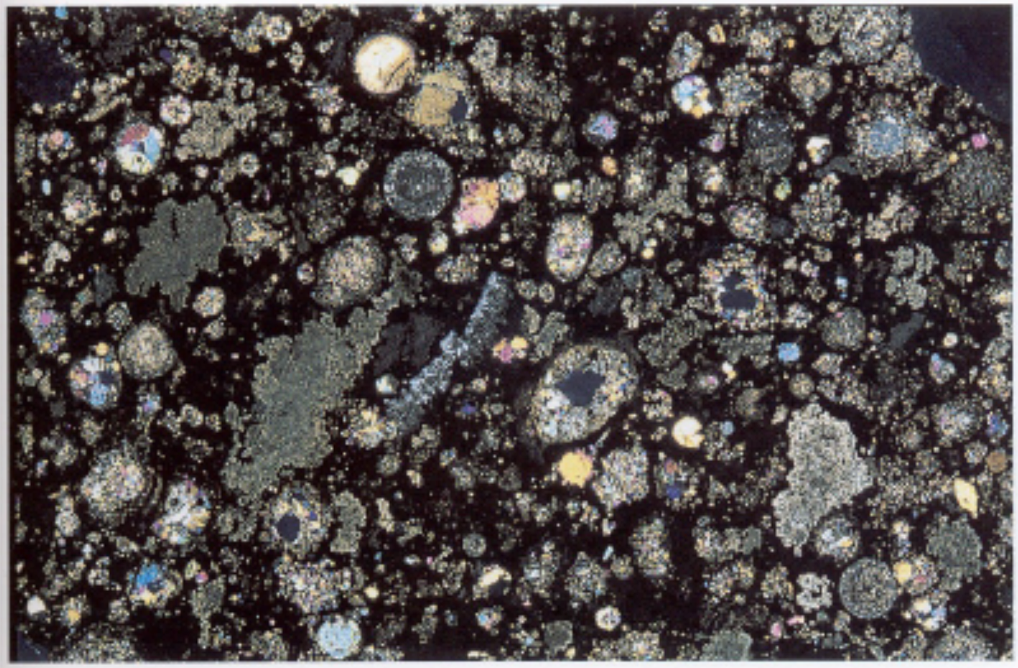


Fig. 7.9. A typical Allende field showing a bewildering array of components. Among them are chondrules of many different structures and mineralogies, olivine aggregates, dark inclusions, individual mineral grains and convoluted calcium-aluminum inclusions, all set in a black matrix of opaque minerals. The field is 22 mm on the long side. The elliptical chondrule below center right is 3 mm in its longest dimension. (Photo by O. Richard Norton.)

From Norton (2002) The Cambridge Encyclopedia of Meteorites

- Chondrules: Olivine and Pyroxene
- CAI (Calcium Aluminum rich Inclusions)
- Matrix of phyllosilicates, FeO, Fe, FeS, C compounds

Crystalline structure in chondrules

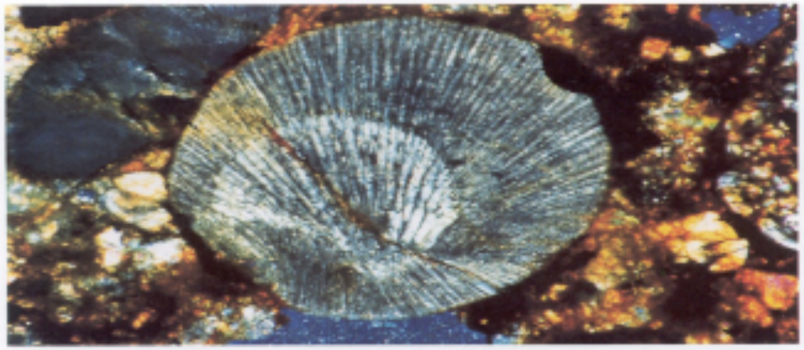


Fig. 6.14. A radial pyroxene (RP) chondrule in crossed polarized light showing thin pyroxene laths radiating from an eccentric nucleation point. A smaller second RP chondrule appears enclosed within the larger chondrule and shares the same nucleation point. The horizontal field of view is 1.9 mm. Thin section from a Faith H5 specimen. (Photo by O. Richard Norton and Tom Toffoli.)

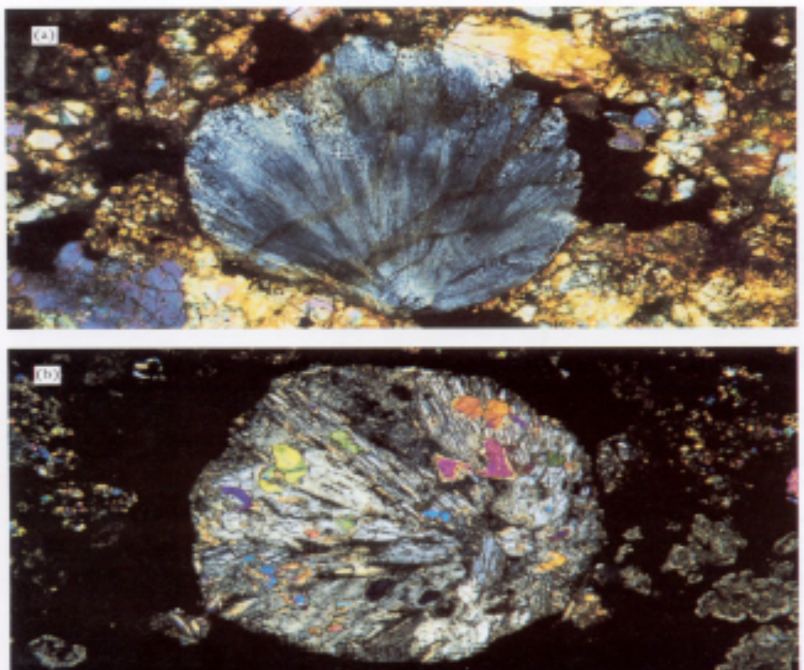


Fig. 6.15.(a) A radial pyroxene chondrule with scalloped borders suggesting chemical erosion of the rim. The pyroxene laths have sub-micrometer thicknesses making them too narrow to be seen individually but different domains in the chondrule go to extinction at different times as the thin section is rotated demonstrating that the chondrule is composed of several sets of laths. Thin section from a Gao-Guenie H5 chondrite. The chondrule diameter is 0.6 mm. (b) This radial pyroxene chondrule under crossed-polarized light shows large blades of clinoenstatite radiating from a nucleation point. Scattered poikilitically within the pyroxene are brightly colored olivine grains with yellow reaction rims. The field of view is 3.4 mm. Thin section from an Allende CV3.2 chondrite. (Photos by O. Richard Norton and Tom Toffoli.)

- Spherical shape shows solidification from liquid droplet
- Radial pyroxene structure shows rapid crystallization from nucleation point

From McSween (1999) Meteorites and their parent planets

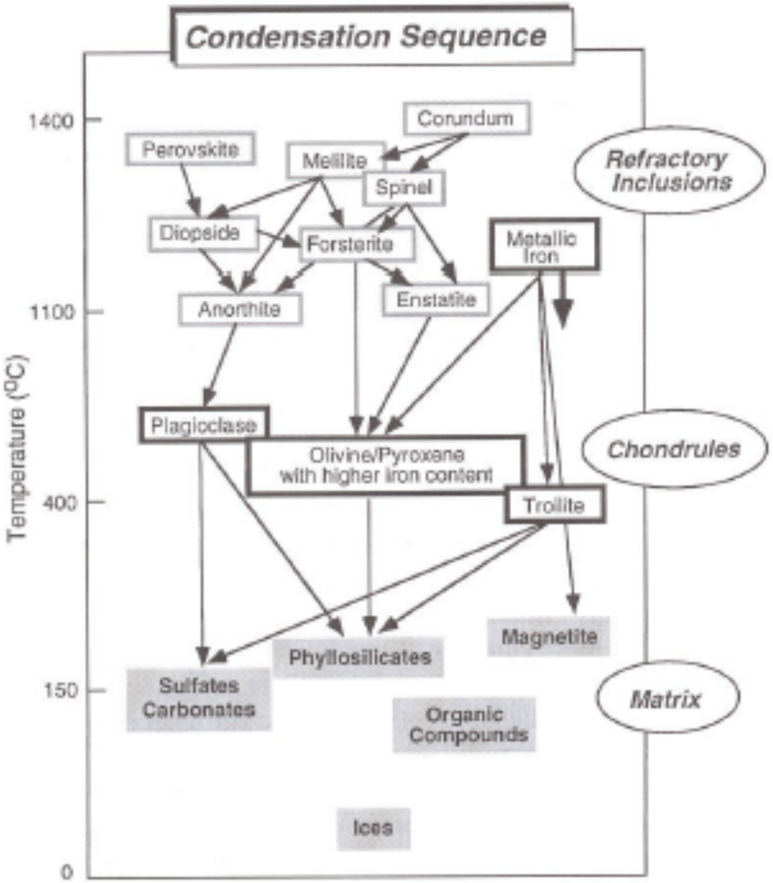


Figure 2.15: The order of appearance of minerals from a cooling nebular gas of cosmic composition has been predicted from theoretical calculations and is schematically summarized in this figure. Minerals like perovskite, melilite, and corundum that form at high temperatures condense directly from the gas, whereas those that form at lower temperatures result from reactions of the gas with previously condensed minerals (reactions are indicated by arrows). The condensation of metallic iron is suppressed, relative to forsterite and enstatite, at lower pressures (indicated by a large arrow). Although this condensation sequence is probably an oversimplified view of the formation of solid matter in the solar system, it does predict the occurrence of minerals that comprise refractory inclusions, chondrules, and matrix. The calculated condensation sequence is based on the work of Larry Grossman (University of Chicago).

From McSween (1999) Meteorites and their parent planets

Primitive Meteorite Components and the Condensation Sequence

- Components seen in primitive meteorites <u>are</u> minerals predicted from various stages of the condensation sequence

- The fact they appear <u>together</u> demonstrates that "equilibrium model" is at best an approximation

Solar System Timeline

- Timeline determined using short-lived isotopes, and very accurate “Pb-Pb” radiometric dates of formation of meteorite components.

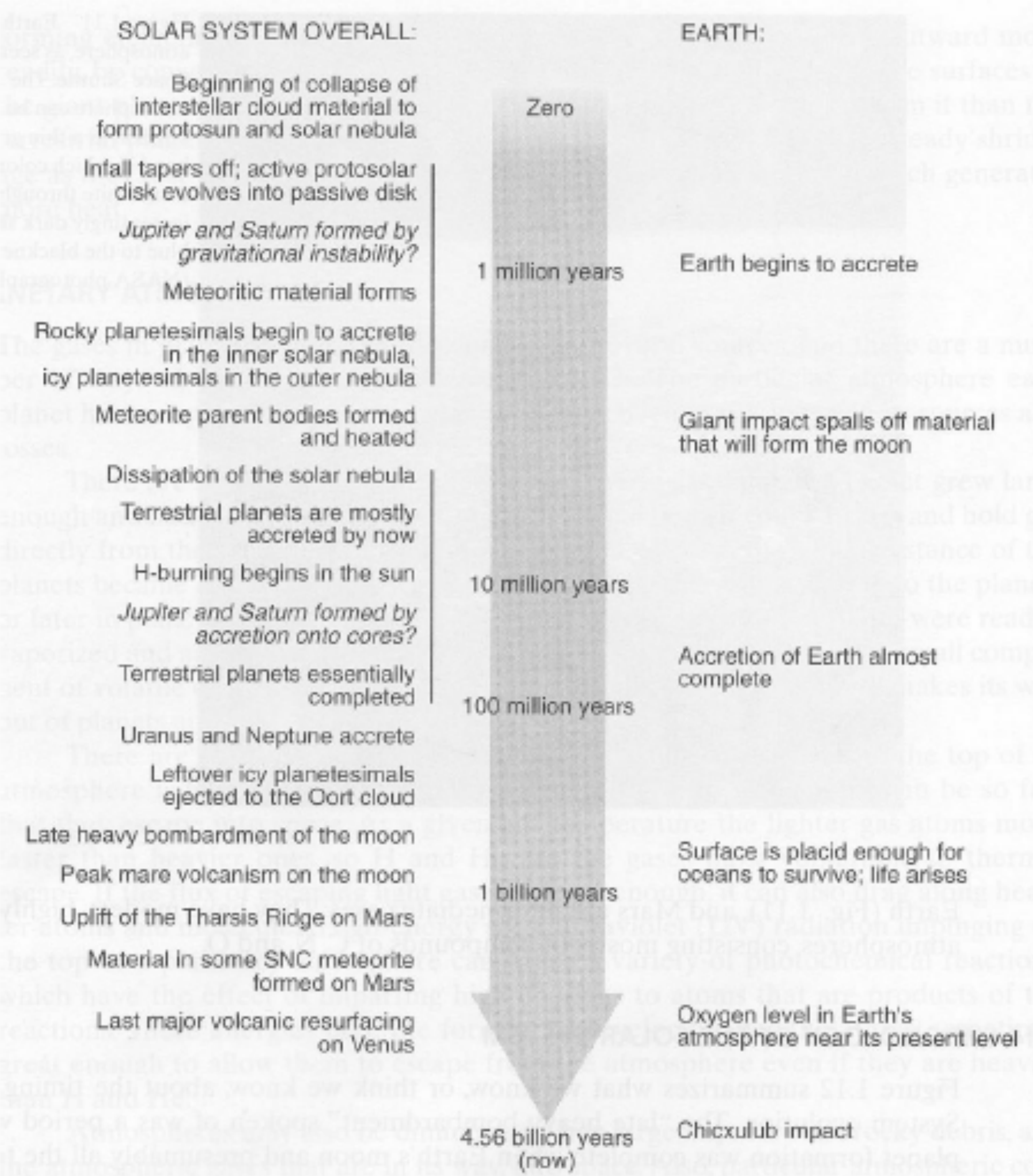


Figure 1.12 An approximate time line for the history of the Solar System. The time scale is not linear; it is greatly compressed at the bottom and expanded at the top. See also Figure 6.16, a time line for meteorites.

Wood Fig. 1.12