Physics of early Solar Nebula

Composition : very likely, same as the Sun's surface

Q Temperature : what is likely?

Q Density?

Pressure : low: enough so that molecular gases like H_2O would go straight from gas to solid as the gas cools (opposite of sublimation)

As gas cools, ions such as Na^+, Al^+, Cl^- form ~~molecules~~ compounds in grains

Metals such as Fe, Ni can just solidify

Table 2.2: Most abundant chemical elements in the solar nebula

Atomic number Z	Name	Chemical symbol	Atomic weight (^{12}C=12)	Melting point at 1 atm (K)	Boiling Point at 1 atm (K)	Abundance (atoms per 10^3 Si atoms) solar atmosphere	CI chondrites
1	Hydrogen	H	1.01	14.0	20.3	28 200 000	5 600
2	Helium	He	4.00	–	4.2	2 400 000	–
8	Oxygen	O	16.00	54.8	90.2	19 000	7 700
6	Carbon	C	12.01	3 820	?	9 330	810
10	Neon	Ne	20.18	24.5	27.1	3 390	–
7	Nitrogen	N	14.01	63.3	77.4	2 340	40
12	Magnesium	Mg	24.31	922	1 363	1 070	1 050
14	Silicon	Si	28.09	1 683	2 628	(1 000)	(1 000)
26	Iron	Fe	55.85	1 808	3 023	890	870
16	Sulphur	S	32.06	390	718	600	435
13	Aluminum	Al	26.98	934	2 740	83	85
18	Argon	Ar	39.95	84.0	87.5	71	–
20	Calcium	Ca	40.08	1 112	1 757	65	62
11	Sodium	Na	22.99	371	1 156	60	58
28	Nickel	Ni	58.69	1 726	3 005	50	49
24	Chromium	Cr	52.00	2 130	2 945	13.2	13.5
17	Chlorine	Cl	35.45	172	239	8.9	5.3
15	Phosphorus	P	30.97	317	553	7.9	10
25	Manganese	Mn	54.94	1 517	2 235	6.9	9.3
19	Potassium	K	39.10	336	1 033	3.7	3.8
22	Titanium	Ti	47.88	1 933	3 560	3.0	2.4
27	Cobalt	Co	58.93	1 768	3 143	2.2	2.2
30	Zinc	Zn	65.38	693	1 180	1.1	1.3
9	Fluorine	F	19.00	53.5	85.0	1.0	0.85
29	Copper	Cu	63.55	1 357	2 840	0.46	0.54
23	Vanadium	V	50.94	2 163	3 653	0.28	0.29

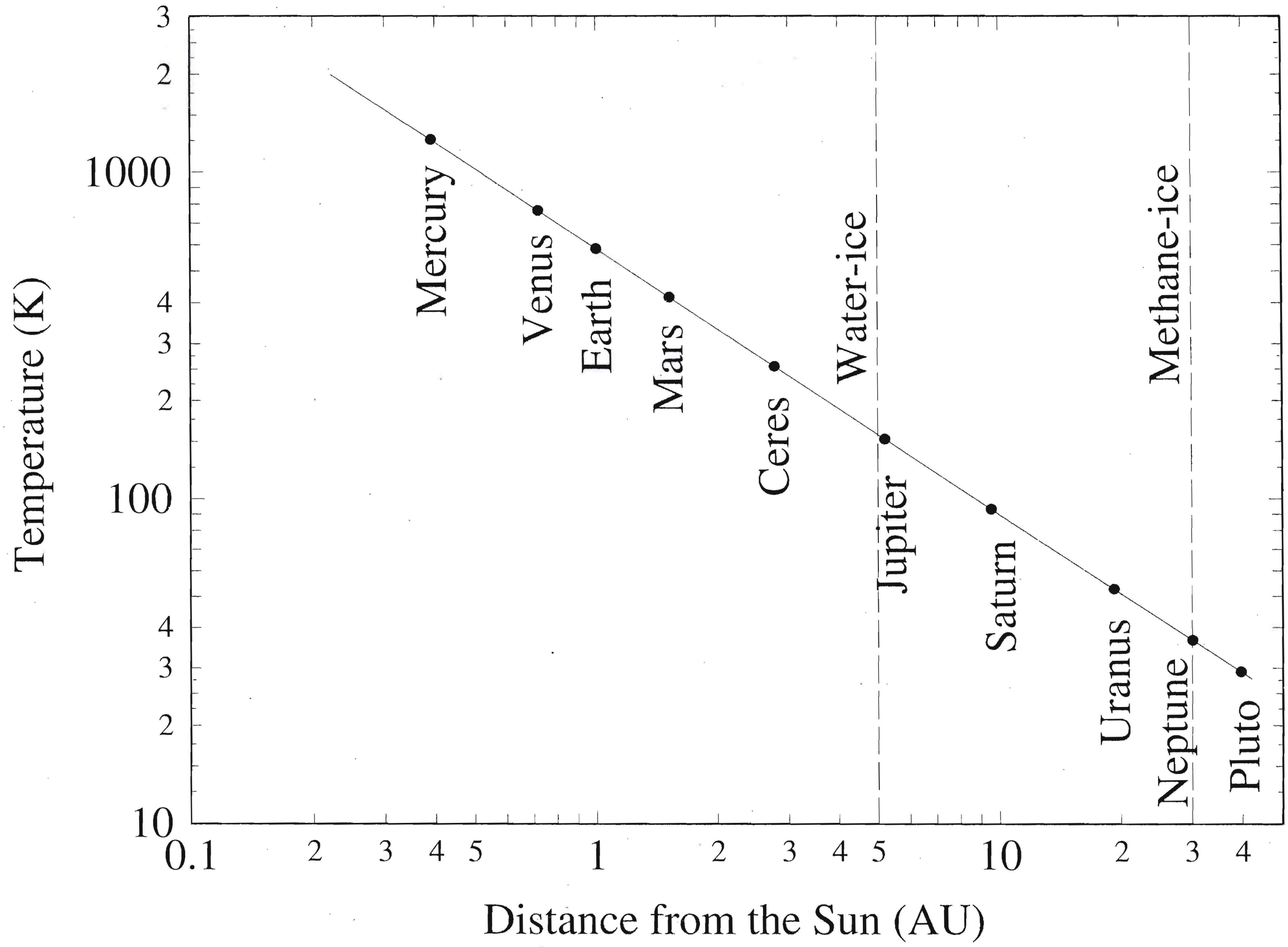
Sources: N. Grevesse & A. J. Sauval 1998, Space Sci. Rev., 85, 161; *CRC Handbook of Chemistry and Physics*, 1986–87 Ed. (Boca Raton, Fla: CRC Press, Inc.), B-5.

integer refers to what is called a **shell**), and more elongated ones (successively *s*, *p*, *d*, etc., where each letter refers to a particular **subshell**). As one goes from light nuclei to heavier ones, the larger nuclear charge pulls the innermost orbits closer and closer to the nucleus, so that the outer orbits have roughly the same size for all atoms. The electron orbits have a much less well-defined character than planetary orbits do— each orbit is a kind of cloud in which the electron is located, but the electrons do not follow a regularly repeated path. Very importantly, each orbit (subshell) also has a maximum number of electrons it can accept: two for an *s* subshell, six for *p*, 10 for *d*, etc. A schematic sketch of a carbon atom ($Z = 6$) is shown in Figure 2.2. Its 1*s* subshell (the smaller circle) and the 2*s* subshells (the two oval orbits) are filled, but the 2*p* subshell (two larger circle) has only two of six possible electrons.

Light and other kinds of electromagnetic radiation

Crucial information about the nature of the orbits followed by the electrons inside the atoms was revealed by experiments concerning the interaction of single atoms (in gases) with light. These experiments are particularly relevant to us because much of the information we have about distant astronomical objects comes to us through light they emit or reflect, and so a knowledge of how atoms interact with light helps us to understand better the objects we observe. To look more closely at the interaction of light and atoms, we need first to recall some basic properties of light itself.

Light is one of many closely related kinds of **electromagnetic radiation**. It is physically almost identical in nature to radio waves (the radiation that carries radio or television signals from a transmitting antenna to a radio or television receiver that obtains its sig-



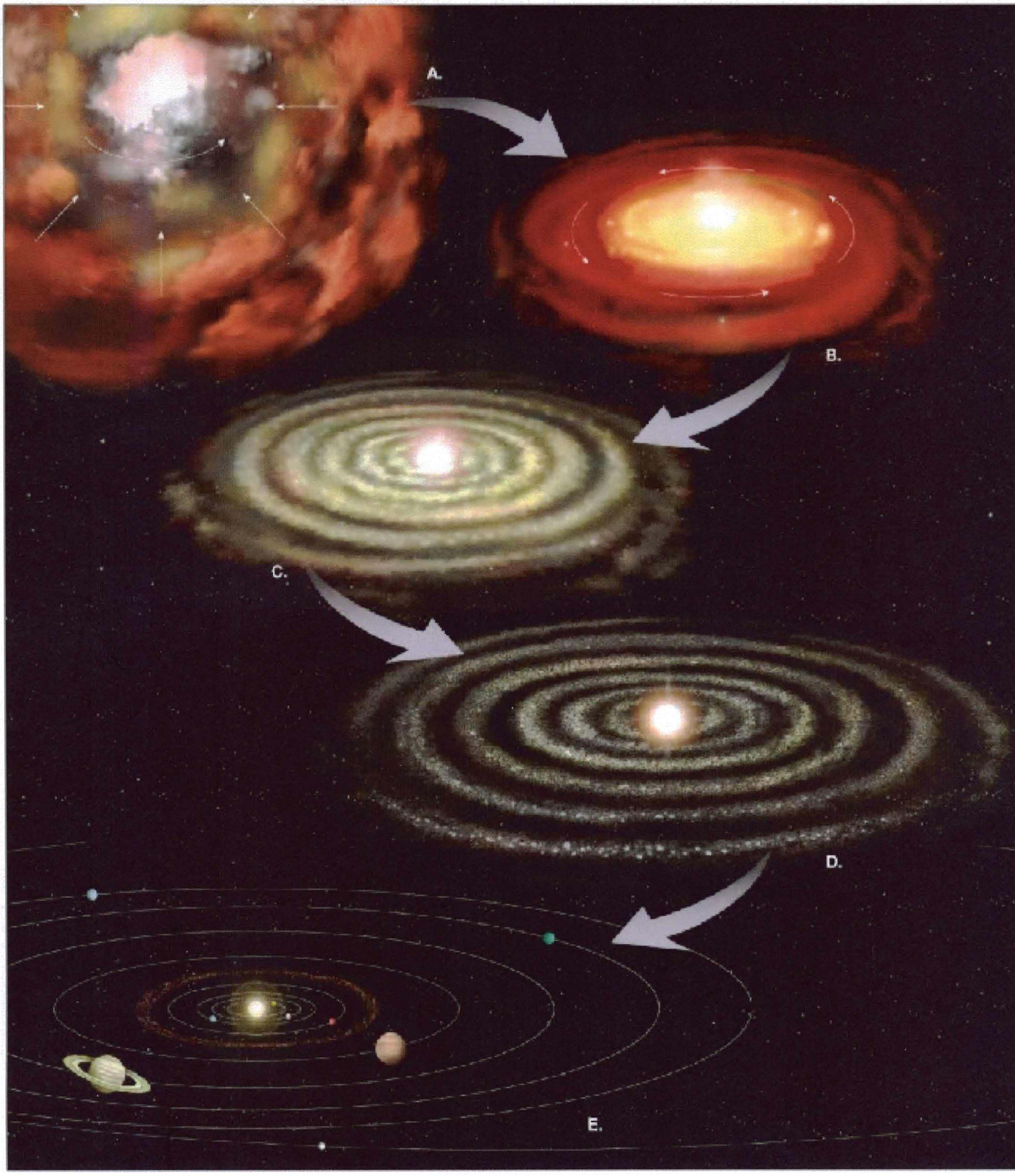
.7 An equilibrium model of the temperature structure of the ebula. Water-ice was able to condense out of the nebula in beyond approximately 5 AU.

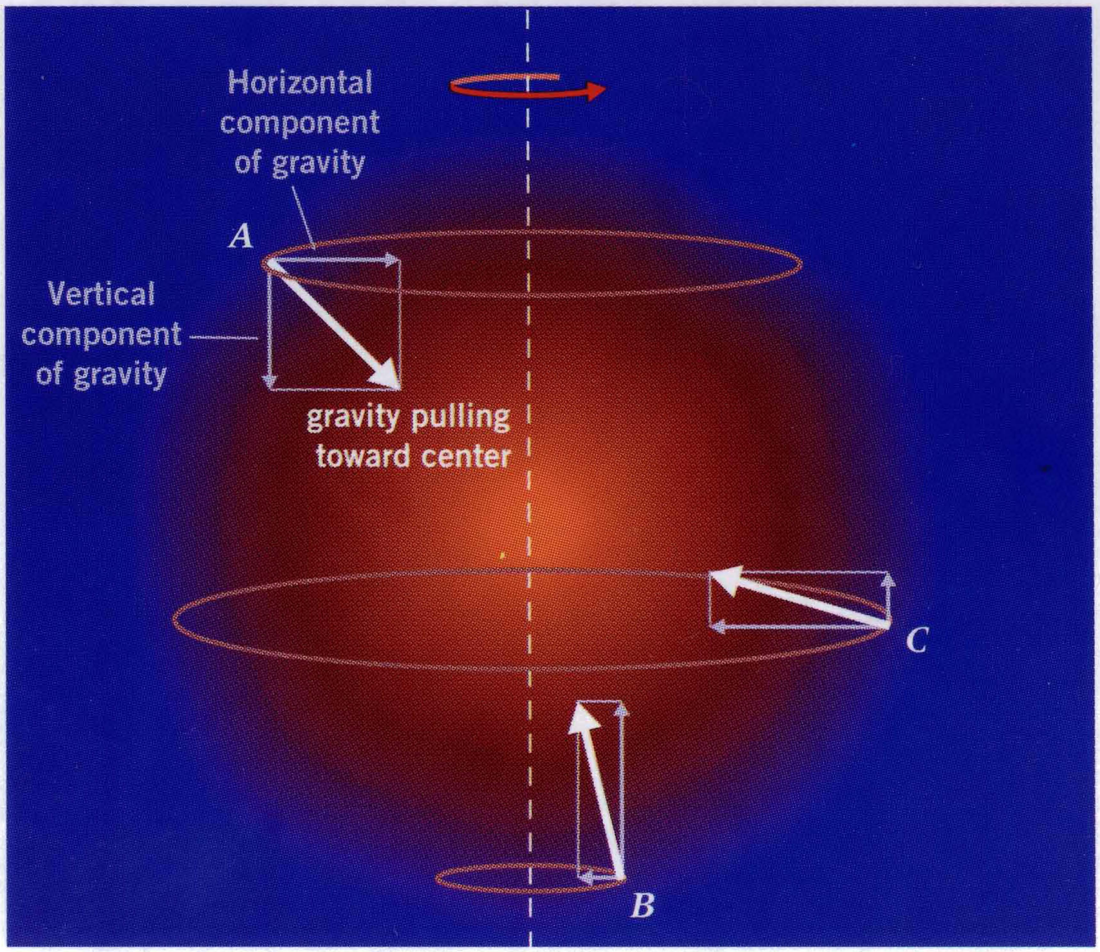
Q

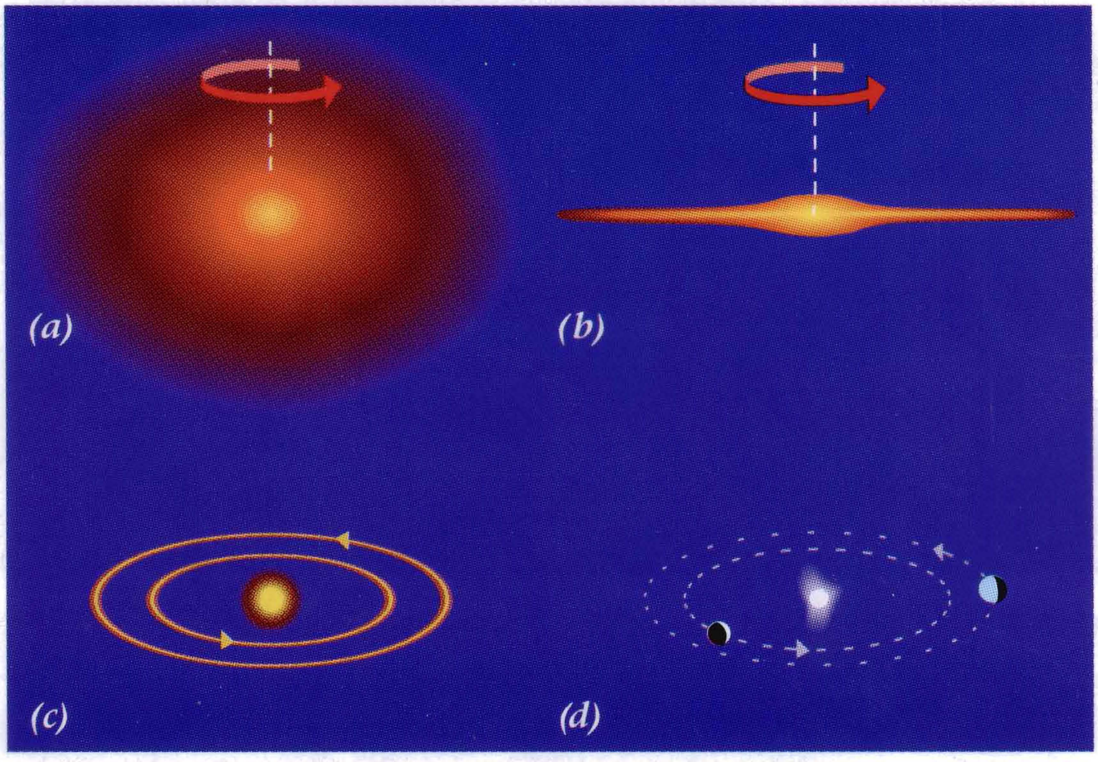
Make an order of magnitude estimate of the density of the early solar system in gm/cm^3

~~→ where is most of its mass?~~

→ why am I making you work in cgs units?


A.
B.
C.
D.
E.


Horizontal component of gravity
A
Vertical component of gravity
gravity pulling toward center
C
B


(a)
(b)
(c)
(d)

SOLAR SYSTEM FORMATION

→ condensation

Q The planets (except Pluto) (which got demoted anyway) divide up into 2 major classes. What are they, & what properties do they share?

Q How might you account for these properties in a formation theory?

A 2 major types of planet:

— inner planets are terrestrial, ie small, rocky.

— outer planets are gas giants, ie larger, contain large amounts of gas as well as small rocky cores.

— icy comets/etc

Q We need to think of something that would ~~[illegible]~~ only allow rocks to form in inner solar system

→ what might it be?

Condensation sequence

as f (density, temp)

- Some elements will never condense out
  (H, He, Ar, ...)
  (permanent gases)

- Some elements will condense out only at low temperatures – "volatile"
  (ices such as H_2O)

- Some elements will condense out almost anywhere in solar system – "refractory" (Fe, FeS, minerals, ...)

Q Where will rocks be solid in the early solar system?

Very close to Sun?

1 AU out?

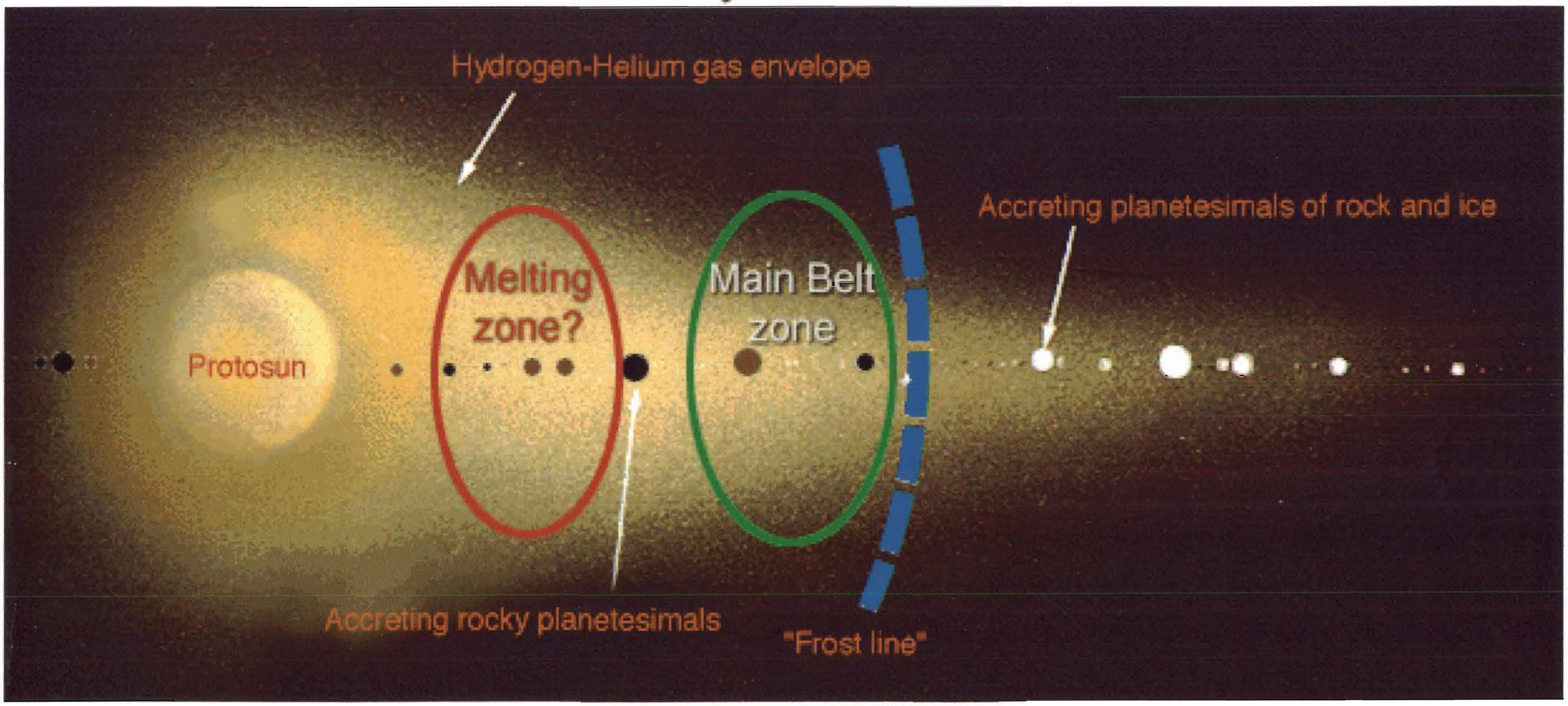
Outer solar system?

Q Where will ice (H_2O) be solid in the early solar system?

Q Why are the gas giants so massive?

Q Make an order-of-magnitude estimate of how much more massive Jupiter's core is than the Earth

Solar System Formation



(Background graphic courtesy of Windows to the Universe, http://www.windows.ucar.edu Ellipses added for emphasis.)

by Bottke & Martel

extremely low cosmic abundance, notably W, Os, Ir, and Re. These are the first condensates to form during cooling of stellar material.

2. Refractory oxides. These include many of the aluminum and calcium compounds that we have already encountered, such as gehlenite, corundum, spinel, and perovskite. Those highly electropositive elements which have valences of 2+ or higher, almost all fall in this category. These include the oxide moieties Al_2O_3, CaO, Ti_2O_3, TiO_2, V_2O_3, VO_2, Sc_2O_3, ZrO_2, SrO, Y_2O_3, and BaO and the family of rare earth element oxides (REEOs), including the major radioactive elements U and Th. Because we will operationally define refractory oxides as those condensing above enstatite and forsterite, we omit them from this list. Uranium and thorium are two of the three (with K) most important heat-producing elements. The mass of refractory oxides is only some 5% of the total mass of silicates, so the concentration of U and Th in early condensates is 20 times that in a planet or meteorite.

3. Iron–nickel metal. Among the minor elements that are present in this round of condensation are Co, Cu, Au, Pt, Ag, and a number of other metals, as well as those nonmetals that have an appreciable solubility in hot iron. These include P, N, and C, with small traces of sulfur, germanium, and perhaps chlorine.

4. Magnesium silicates. In this group we also find small amounts of certain other predominantly lithophilic elements, including Mn, B, F, and some Cr and Li.

5. Alkali metals. Na and K are accompanied at slightly lower temperatures by rubidium and cesium and perhaps by Cl.

6. Moderately volatile chalcophiles. Accompanying and following FeS formation we find Zn, Pb, Ga, Ge, Se, Te, and As and possibly also Br and I.

7. Mineral-bound O and OH. This category includes the chemically labile oxygen in FeO and its compounds, as well as the hydroxyl silicates such as amphiboles, serpentine, and chlorite.

8. Ice minerals. These are water ice itself; the solid hydrates of ammonia, methane, and rare gases; and solid methane.

9. Permanent gases. These are the three gases that are, under natural conditions, virtually uncondensable: H_2, He, and Ne.

For convenient reference, a flow chart for the major elements is presented in Fig. IV.26. The "staircase" formed by the solid line indicates the condensation temperatures for the elements listed across the top of the figure. By following the arrows, the chemical history of each element may be traced

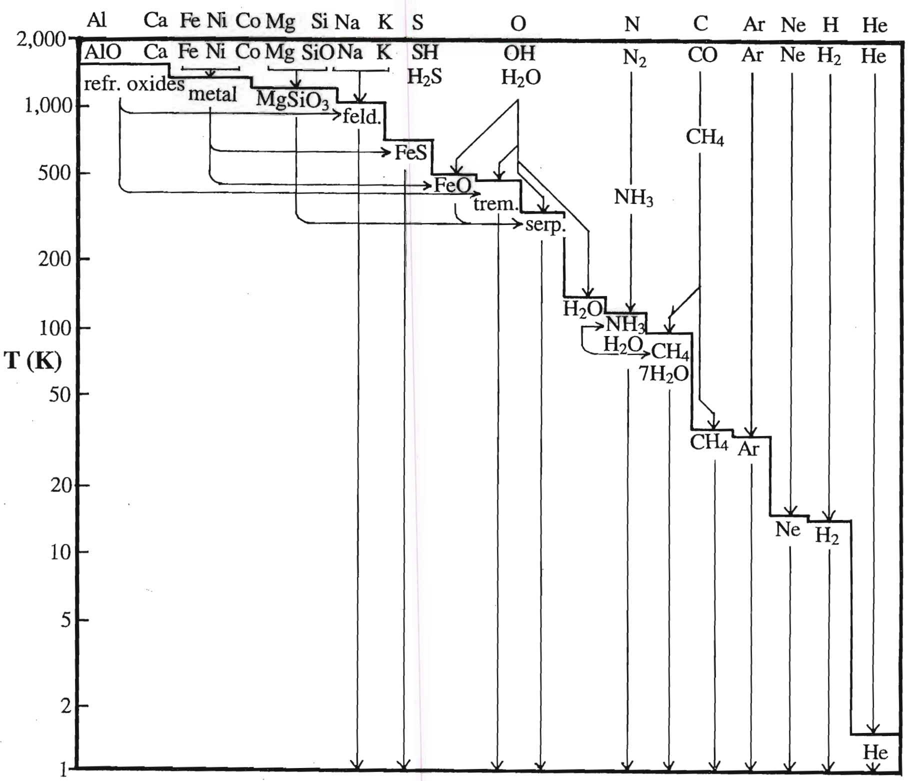


Figure IV.26 Major element flow chart for equilibrium condensation. The sequence of reactions of gases (above the solid line) and condensates (below the solid line) in solar material cooling at equilibrium. A pressure of 10^{-2} bar is assumed.

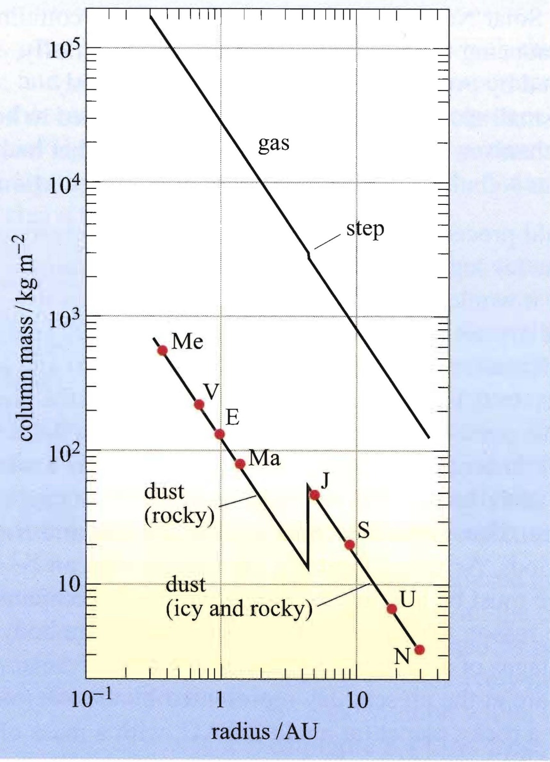


Figure 8.14 The column mass of gas and dust in the Solar Nebula (at a stage represented by Figure 8.13c) plotted against radius from the protoSun. Obvious abbreviations are used to indicate the positions of the planets that ultimately formed. The reason for the increase in column mass of dust near 5 AU is due to the condensation of water (see text). (Smaller steps associated with the condensation of more volatile compounds such as ammonia have been omitted.)