Protoplanetary Disks

Formation of planets requires different processes to operate in stages:

1. Condensation - molecule by molecule growth, e.g., as in the formation of dust grains.

2. Accretion - solid particles stick to each other by weak electrical forces, becoming planetesimals up to 1 km in diameter

3. Coalescence - planetesimals are attracted by gravity, which holds them together

The main difficulty with this scenario is in phase 2. "Pebbles", which are rocks 1 mm - 1 m in size collide with high energy, which must be absorbed to allow them to merge. Their relative velocity comes from aerodynamic drag with the gas, which is rotating slower. Drag also causes pebbles to spiral in to the star.

"Pebble accretion" can be rapid if "planetary embryos" have already formed and can attract pebbles by gravity. Also, they can capture more pebbles because gas drag slows the pebbles.

Pebble accretion also allows for the formation of giant planets beyond the "frost line", because it is fast enough to allow the mass of the planet to accrete H and He before there light elements are dissipated by the star.

Frost line (Ice line, snow line) was at 2.7→3 AU, corresponding to sublimation temperatures of 150 - 200 K. (Presently it is at ~ 5 AU).

A core mass of ~15 $M_\oplus$ is needed to retain H and He.

Radioactive Dating

Radioactive decay is a random process such that the number of parent nuclei left as a function of time, $N(t)$, is

$$N(t) = N_0 \, e^{-t/\tau}$$

where τ is the mean lifetime. The decay can also be written in terms of the half-life $T_{1/2}$

$$N(t) = N_0 \left(\frac{1}{2}\right)^{t/T_{1/2}}$$

You should show that $T_{1/2} = \ln(2)\,\tau$ (0.693)

There are four alpha-decay sequences, beginning with uranium, neptunium, or thorium, and ending with lead or bismuth. Let the atomic mass be A, and n is an integer that describes

	n(start)	A	start	end	n(end)
$T_{1/2} = 4.6 \times 10^9$ yr	59	4n+2	^{238}U	^{206}Pb	51
	59	4n+1	^{237}Np	^{209}Bi	52
	58	4n+3	^{235}U	^{207}Pb	51
	58	4n	^{232}Th	^{208}Pb	52

Stable isotopes of lead are 204, 206, 207, 208
^{204}Pb is not a radioactive decay product, and its abundance can be used to determine the initial amounts of the other isotopes.

Potassium → Argon is also very useful

$$e^- + {}^{40}_{19}K \rightarrow {}^{40}_{18}Ar \quad (11\%), \quad T_{1/2} = 1.25 \times 10^9 \text{ yr}$$

$$^{40}_{19}K \rightarrow {}^{40}_{20}Ca + \beta^- \quad (89\%)$$

^{40}K is only 0.01% of terrestrial potassium.
The stable isotopes are ^{39}K (93%) and ^{41}K (7%)

Terrestrial Argon is ^{40}A, which is 1.3% of the atmosphere by mass. (N_2 is 76%, O_2 is 23%)

Solar argon is ^{36}Ar, ^{38}Ar.

^{40}K decay is the main source of natural radioactivity in animals and humans.

Radioactive heating in the Earth's mantle is due to ^{232}Th, ^{238}U, ^{40}K, and accounts for much of the geothermal heat flux of 0.05 W/m^2. Compare this with 340 W/m^2 solar flux averaged over the surface.

The age of meteorites is

$$4.53 - 4.58 \text{ Gyr}$$

determined by radioactive dating.

The spread of 50 myr is due to the time it took to accrete the planets.