7.2 Formation of the planets

7.2.1 Equilibrium condensation

Given a rough idea of how the solar system formed, the final question is how individual planets accreted and how their layered structures formed.

In a gross sense it seems that the condensation temperature sequence for minerals explains the major feature of the solar system - the difference between terrestrial and outer planets:

The solar nebula was hot enough to vaporize all the material listed (> 1400 ° C) and may have been hotter.

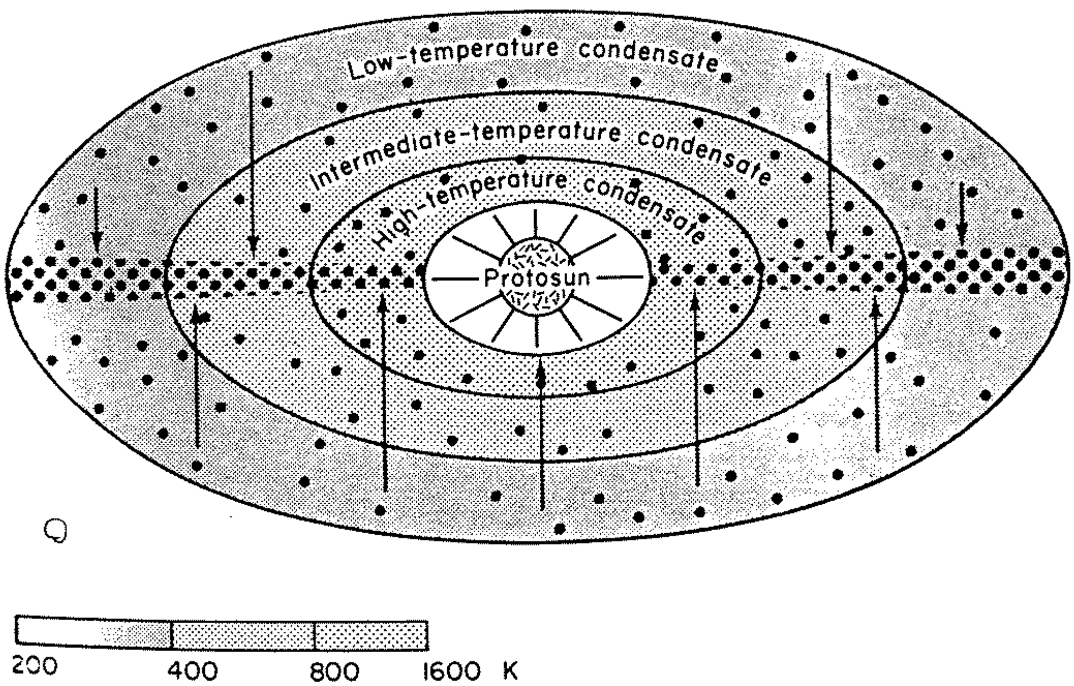


Fig. 10. Sketch showing notional temperature distribution in "cocoon nebula" surrounding sun, and prior to collapse into discoidal configuration. Small first-generation planetesimals form within shell and spiral towards ecliptic plane. Actual paths taken by sinking planetesimals are more complex than indicated and are controlled by a combination of gravity acting perpendicular to ecliptic plane and gas–solid dissipation.

As the nebula cools (as the world turns):

1) The *inner* zone stays warm (>100 ° C) and only *high temperature* condensates form - giving the terrestrial planets - high density planets.

2) Outer zone cools further, so *both* high-T and low-T materials condense into the outer - low density planets - with lots of ice, CH_4, CO_2 etc...

Thus, *ratio* of high-T to low-T condensates is higher in inner planets, which are then denser

the details of the process are complicated - and not well understood.

Even more complicated is the process that produced the *differences* between the terretrial planets.

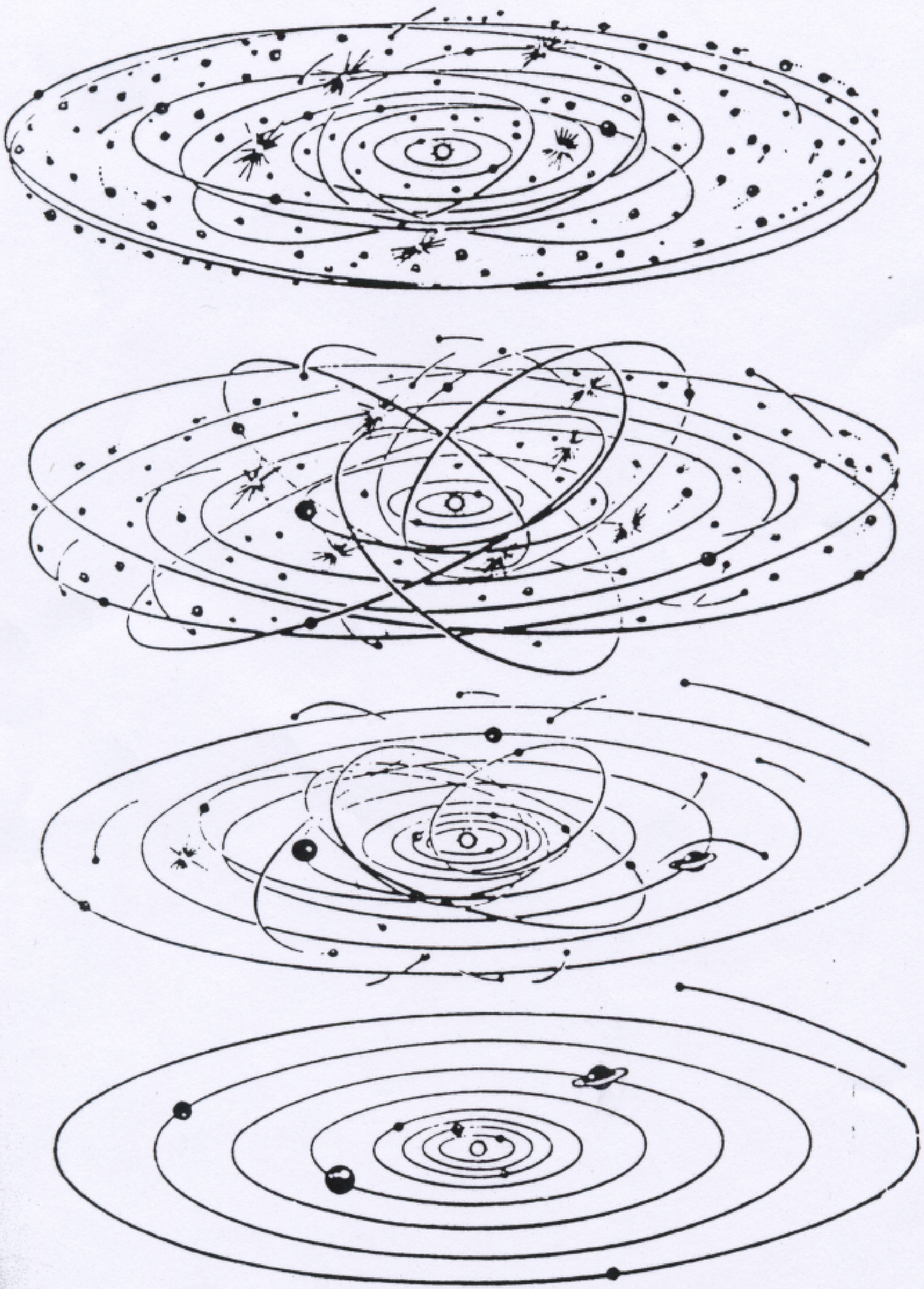
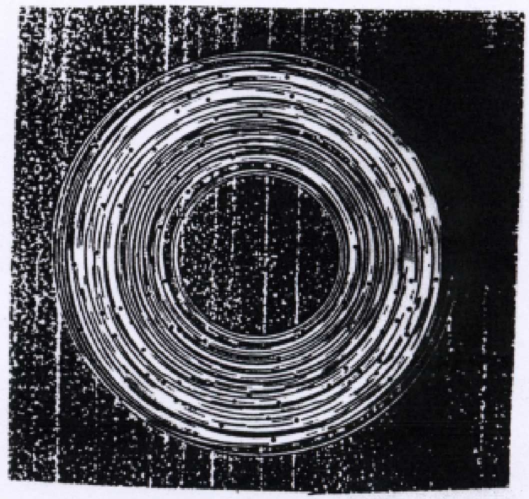
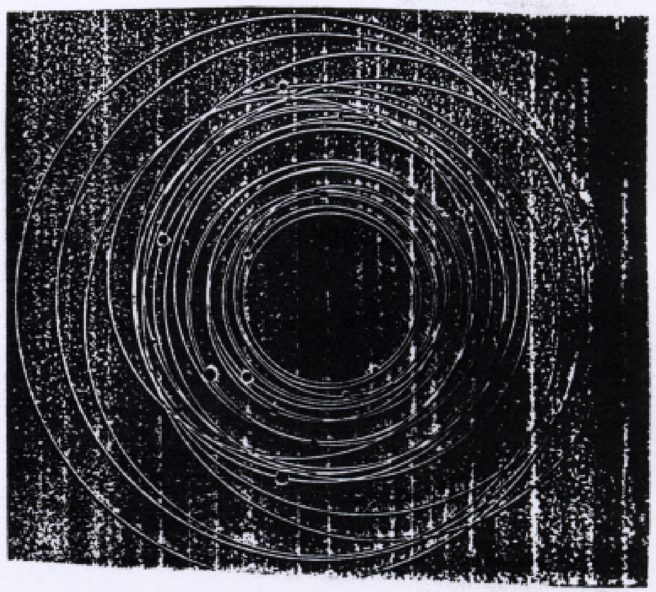


Fig. 11. Stages in the accretion of a planet from a disc of planetesimals in the ecliptic plane as envisaged in the models of Schmidt and Safronov. (From Levin, 1972.)

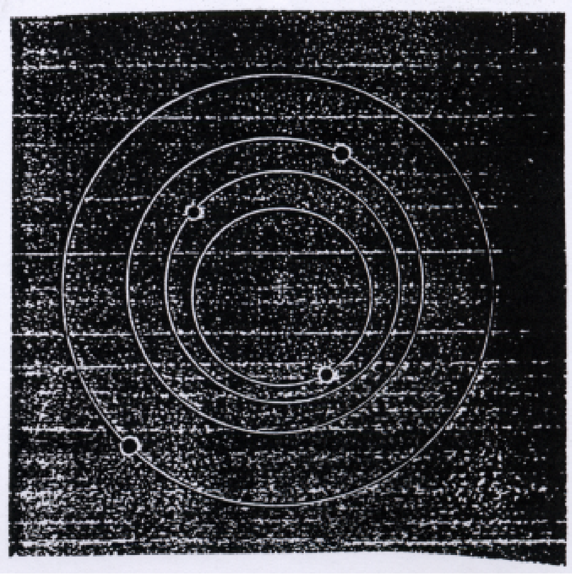
THREE-DIMENSIONAL SIMULATION of the formation of the inner solar system also began with 100 planetesimals. Each one was assigned a mass of 1.2×10^{26} grams, so that the total mass (1.2×10^{28} grams) is that of the rocky planets Mercury through Mars, together with their moons. Again the initial parameters of the orbits were generated at random. The illustration shows the initial ellipses, but it does not suggest the inclination of the ellipses with respect to one another. Because the planetesimals are thought to have formed in a thin layer of dust in the central plane of the cloud from which the solar system condensed, the inclinations are less than five degrees.



INTERMEDIATE STAGE of the simulation shows the developing inner solar system after 30.2 million years have passed and 22 bodies remain. Their orbits have become more markedly elliptical and their velocities with respect to one another are greater. In addition their range of distances from the sun has broadened. The innermost orbits are closer to the sun and the outermost orbits are farther away. The mutual inclinations among the orbits have greatly lessened the incidence of collisions compared with near-misses. Hence tens of millions of years of simulated time must pass before the process reaches an end. In the two-dimensional simulation 61,000 years sufficed.



FINAL STATE of the simulation leaves four fully formed planets in isolated, almost circular orbits around the sun. The planetesimals have all coalesced. The largest planet, the fourth from the sun, is built up from 34 of the original bodies. Although the illustration shows the simulation after 441 million years, the process is almost complete much sooner. There are 11 bodies after 79 million years and six bodies after 151 million years. This suggests that the earth accreted in a time on the order of 100 million years. The simulation was made by the author with a computer at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.



7.2.2 One model: homegeneous accretion

Assume that terrestrial planets consist of a mixture of

-chondritic material

-high-T condensates

Planets condense from material at low temperatures - *no chemical zonation*

Planet heats up due to:

1) *kinetic energy* of impacting bodies

2) *radioactive decay* of both short lived (early in history) Al-26, Pu-244, I-29, and long lived (U,T,K).

As planet heats up, chemical reactions take place, e.g.

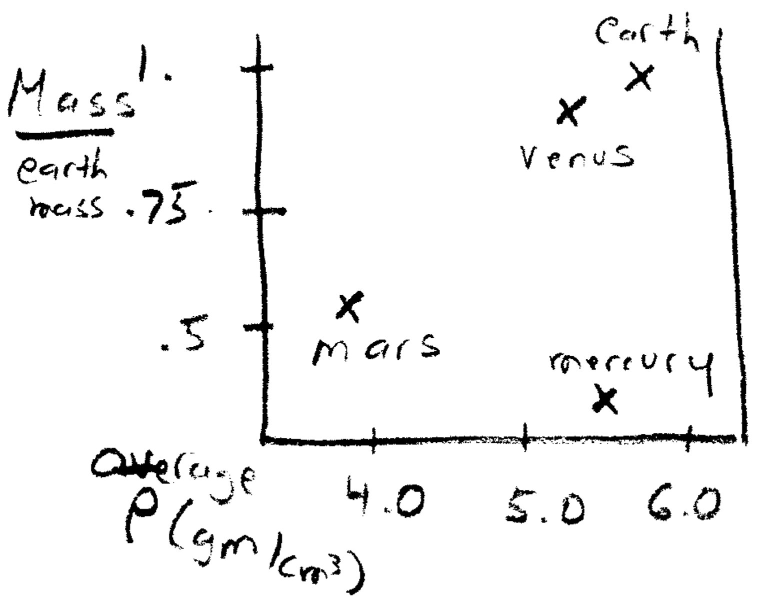
$Mg_2SiO_4 + Fe_2SiO_4 \rightarrow 2MgSiO_3 + 2FeO$

$2FeO + C \rightarrow 2Fe + CO_2$

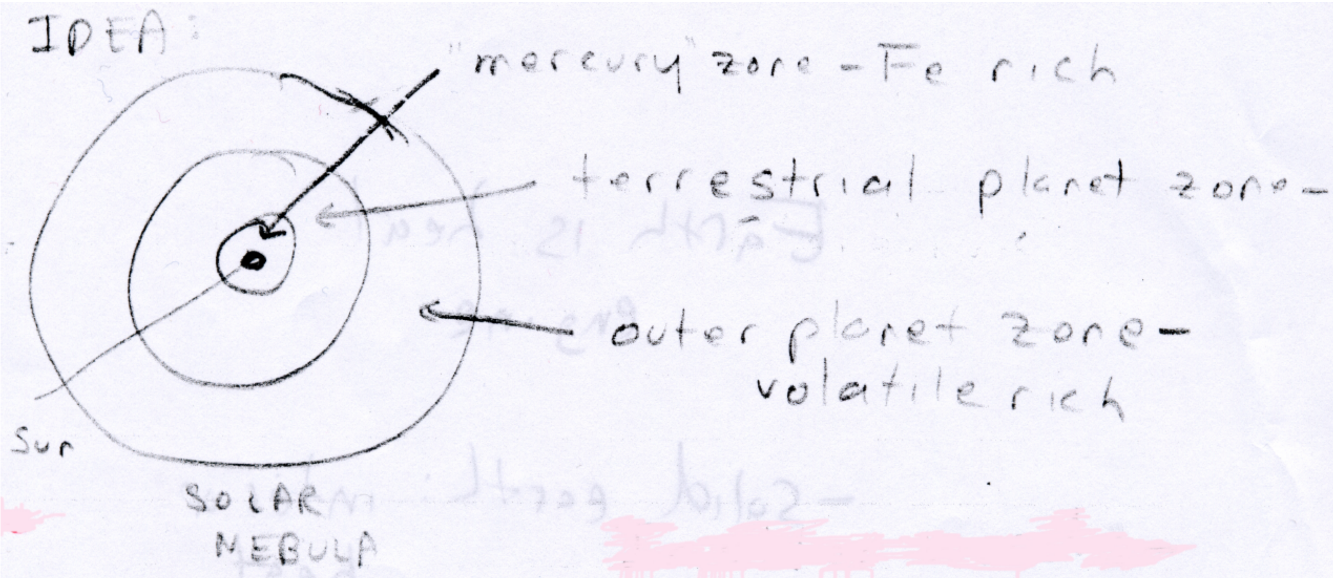
Such reactions allow iron to be released from silicates (reduced) and sink to form the core

core (picking up S on the way), while some of the volatiles (ie. COsub2, H_2O, SO_2) are lost into space

PREDICTION: The differences between planets will be due to the extent that this chemical process operated. This is thought to be related to size since the accretion heating, due to kinetic energy of impacts, will be greatest for more massive planets. Thus the larger planets will - retain less volatile S, including O which is light, be more dense.



This appears to be true for Mars, Venus, and Earth, but not for Mercury: Mercury couldn't be made of the same material as the other three.



In other words - the 3 zones are those predicted by a heterogenous accretion (condensation) model and within the terrestrial planet zone accretion was homogeneous.