Solar System Formation

The processes by which stars and planets form are active areas of research in modern astrophysics

The formation of our own solar system is central to the first half of our course, and important to the second half as well when we study the formation of stars

Astronomy/Astrophysics

- Question:

How do you think astronomy might differ from other sciences? Why?

Hypotheses for Solar System Formation

Fall into two major categories:

(i) The formation of the planets was tied to the formation of the Sun

(ii) The Sun was already there and something else formed the planets

Nebular Hypothesis (Kant, Laplace ~1700s)

The Sun and planets started as a blob of gas which cooled, collapsed and formed the Sun and planets (type (i) above)

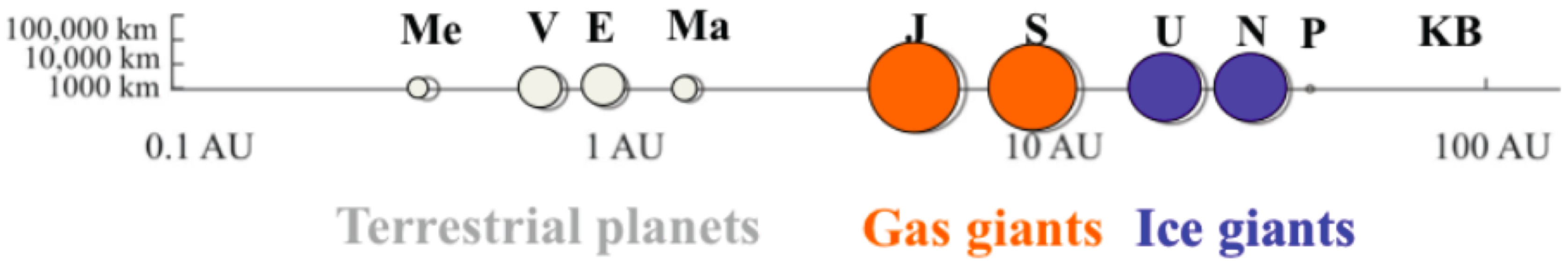
Relevant data for formation theories

Question: What are some important and relevant trends in the Solar system that will help us test theories? Why?

Question: What parts of physics (chemistry?) will be useful? Which parts are less likely to be needed?

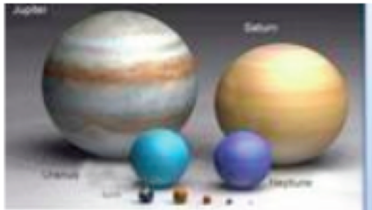
Planets: trends

Note logarithmic scales!

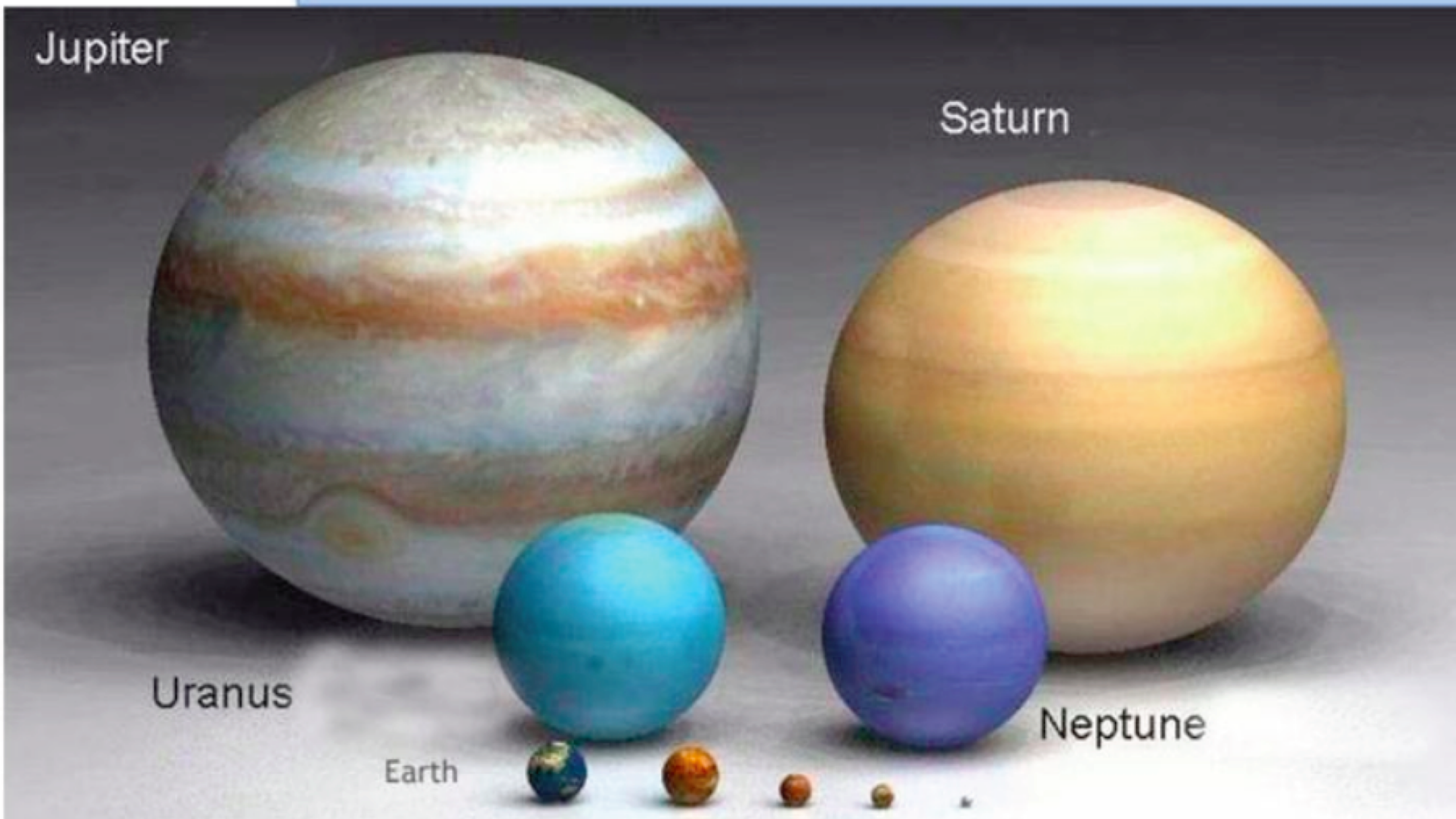


Cartoon from Francis Nimmo, UCSC

- Terrestrial planets in inner solar system, gas and ice giants in outer solar system



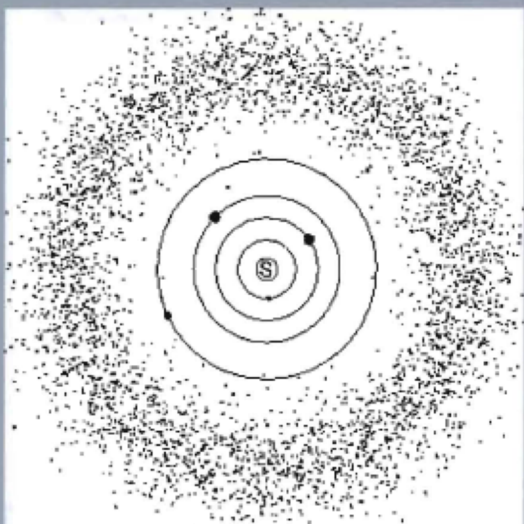
Giant and Terrestrial Planets



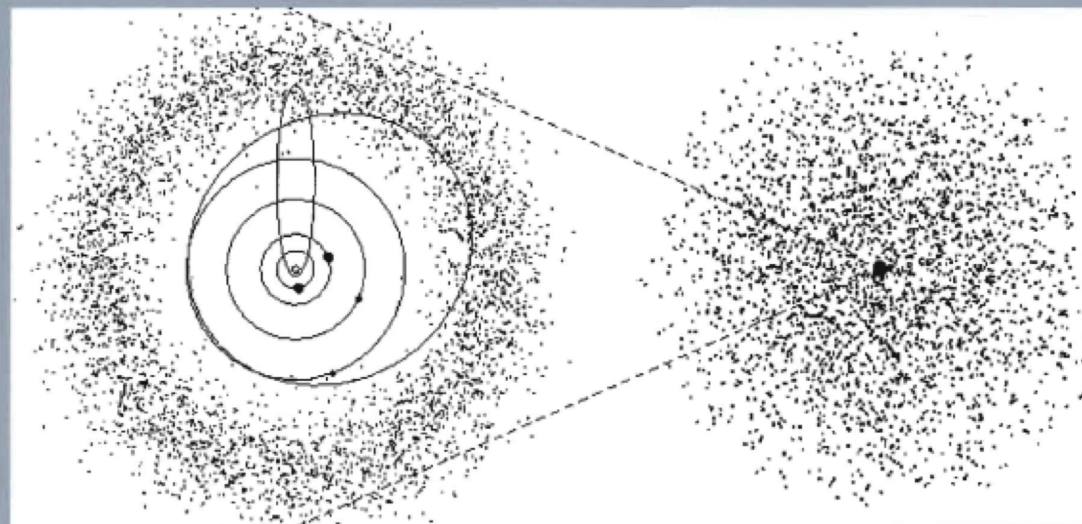
Jack Lissauer NASA Ames

Overview of the Solar System

In addition to the terrestrial and giant planets, the solar system contains two belts and an extended cloud of small objects.

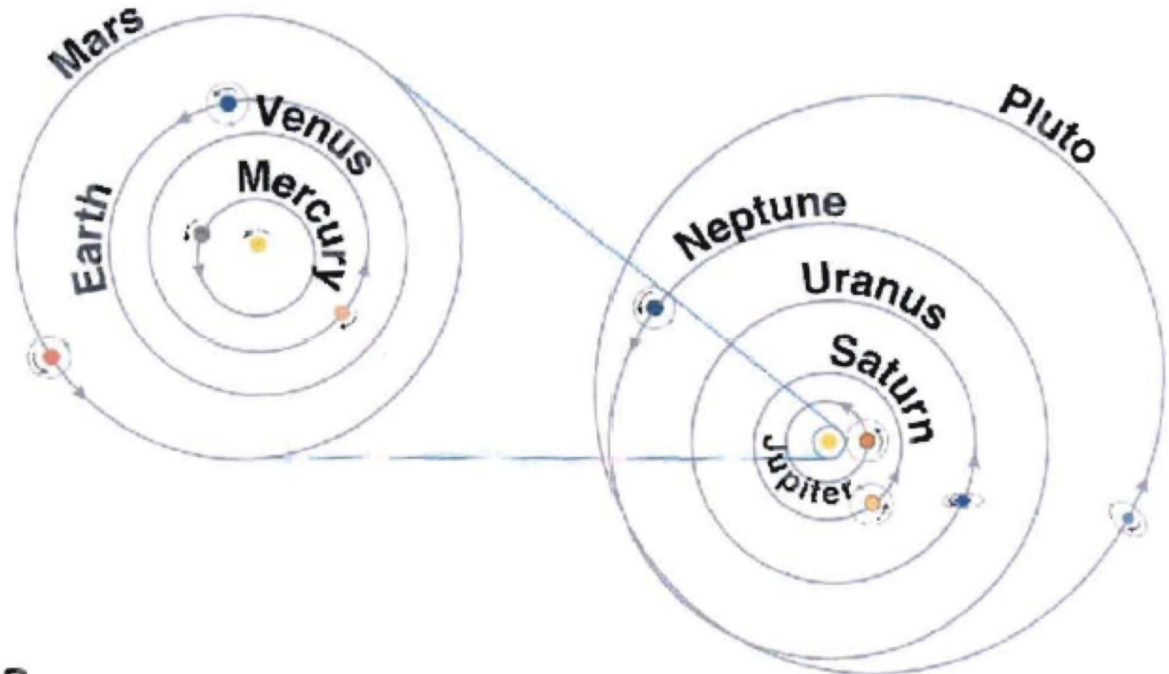


Inner Solar System: Mercury, Venus, Earth, Mars and asteroids.

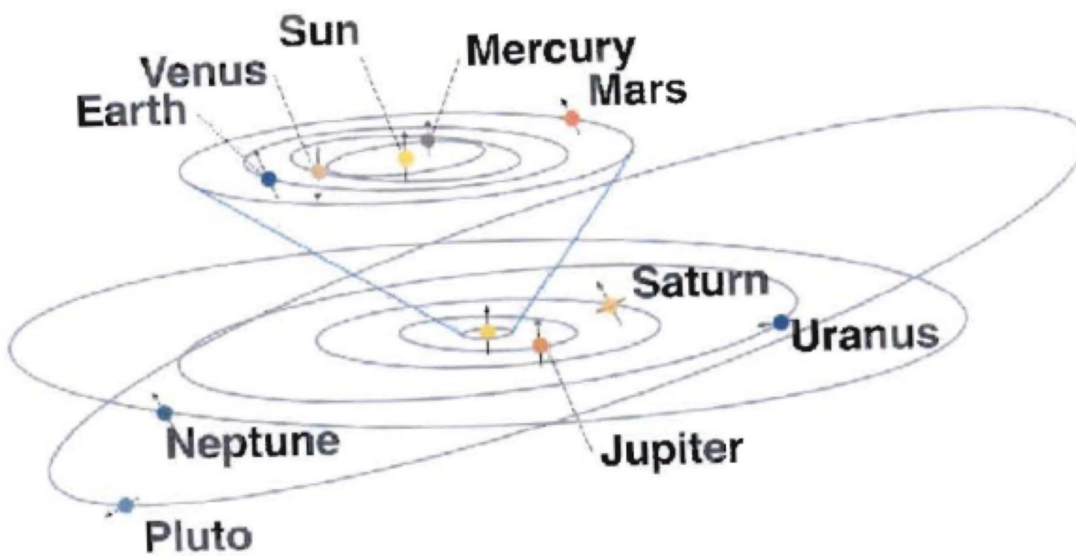


Outer Solar System. Left: Jupiter, Saturn, Uranus, Neptune, Pluto, a comet, and the Kuiper belt. Right: The Oort cloud.

Josh Barnes, U of Hawaii


Mars
Venus
Mercury
Earth
Pluto
Neptune
Uranus
Saturn
Jupiter

a


Sun
Mercury
Venus
Earth
Mars
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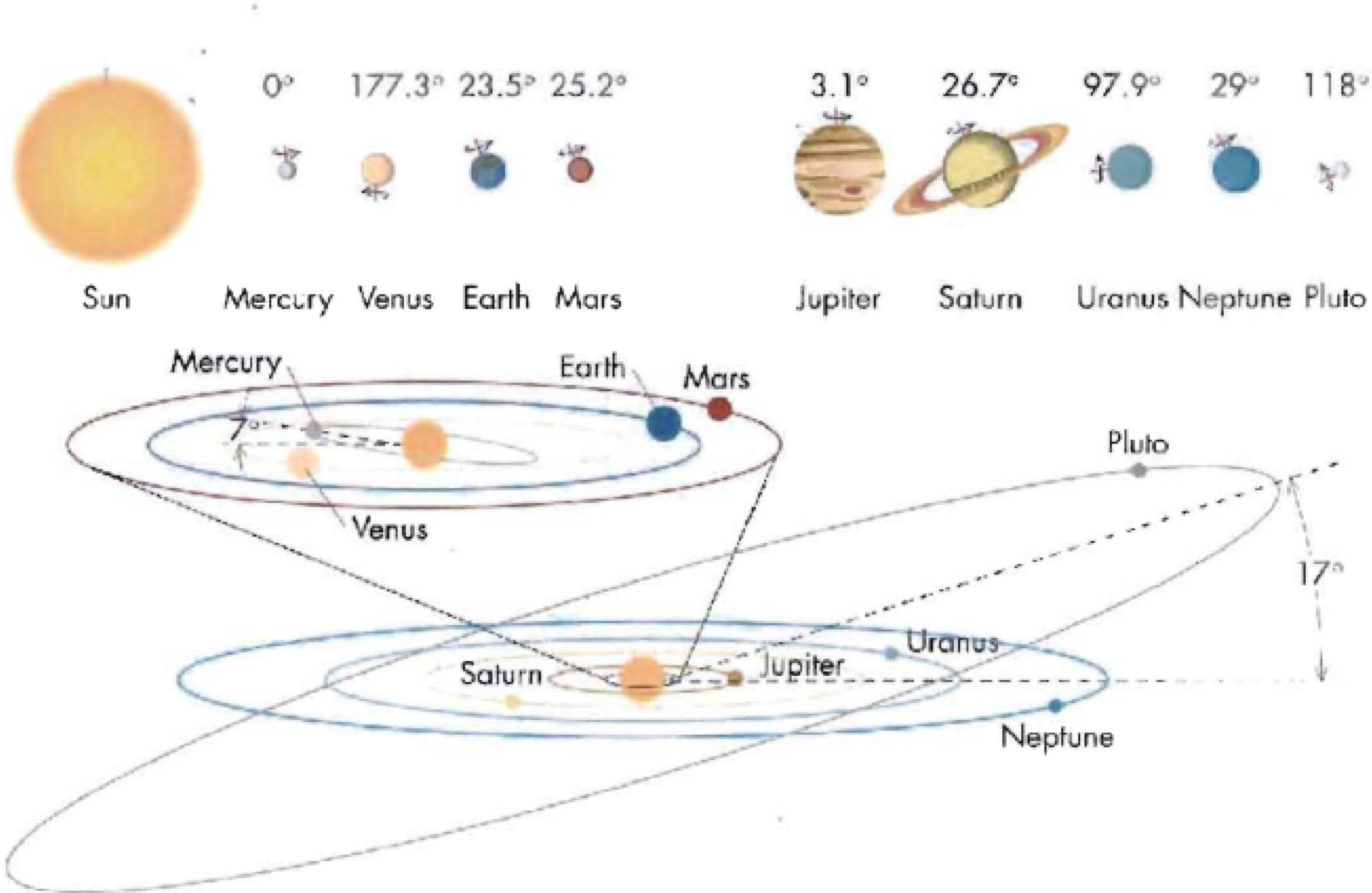
Uranus
Neptune
Jupiter
Pluto



0°
177.3°
23.5°
25.2°
3.1°
26.7°
97.9°
29°
118°
Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
Mercury
Earth
Mars
7°
Venus
Pluto
17°
Uranus
Saturn
Jupiter
Neptune

Important orbital trends

All planets orbit in close to the same plane (remember that Pluto is no longer considered a planet)

All planets orbit in the same direction, which is the same direction that the Sun rotates

These both suggest that the Solar system formed from the collapse of a single cloud, rather than from capturing passing material

(but see homework…..)

History of formation hypotheses

Despite these known trends, the Nebular hypothesis went out of fashion in the 1930s because

(a) A simple collapse which conserved angular momentum would cause the Sun to spin so fast it would break up, and

(b) If you distributed the current mass of the Solar System evenly through its volume, its density would be too small for it to collapse

Question:

What would cause a blob of gas to collapse gravitationally?

What would cause it to stay at its original size or expand?

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What would cause it to stay at its original size or expand?

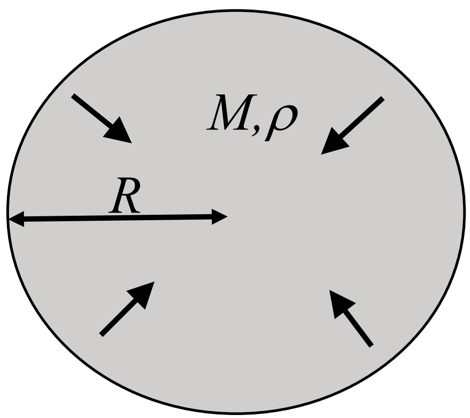
If the gas is too hot, then its pressure will overcome gravitational inward force

If it can cool (by radiating) and is massive enough, gravity will win

This is known as Jeans Collapse (after Sir James Jeans)

- Increased density -> increased gravity -> more material gets sucked in -> runaway process (Jeans collapse)

Collapsing cloud



M=mass ρ=density
k=Boltzmann's constant
μ=atomic weight
N=no. of atoms
T=temperature (K)

Gravitational potential energy $\sim \dfrac{GM^2}{R}$

Thermal energy $\sim kTN \sim kT\dfrac{M}{\mu}$

Equating these two and using $M\sim\rho R^3$ we get:

$$\boxed{\rho_{crit} \sim \frac{kT}{G\mu R^2}}$$

Does this make sense?

Francis Nimmo UCSC

Angular momentum conservation

- In an isolated system we expect angular momentum to be conserved
- This was one of the big problems that astronomers in the early 1900s found with the nebular hypothesis: what sort of collapse could end up with most of the angular momentum in the solar system in Jupiter (biggish mass, big radius) but not in the Sun?

Lower mass stars

High mass stars

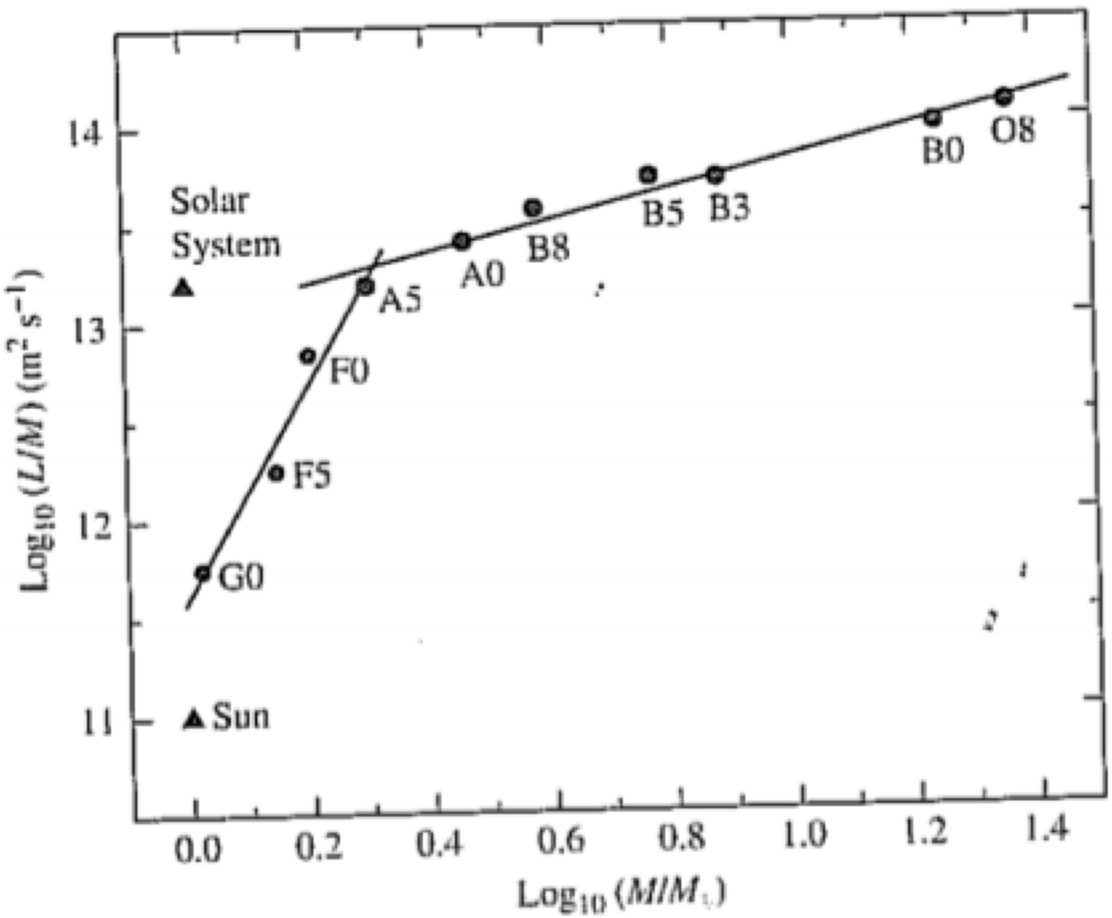


FIGURE 23.8 The average amount of angular momentum per unit mass as a function of mass for stars on the main sequence. The Sun's value and the total for the entire Solar System are indicated by triangles. Best-fit straight lines have been indicated for stars A5 and earlier, as well as for stars A5 and later (not including the Sun).

From Carroll and Ostlie

Angular momentum 2

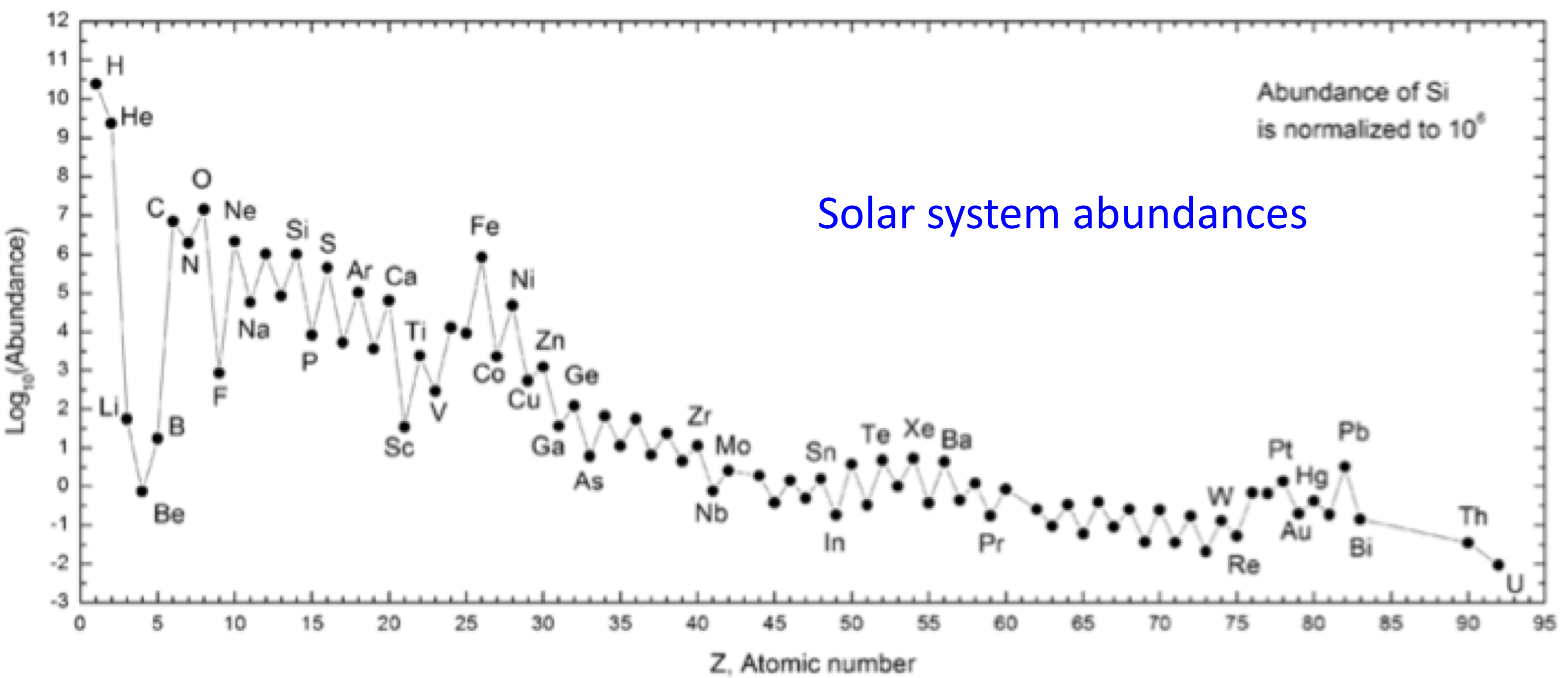
- The fact that the composition of meteorites is very close to that of the heavy elements in the Sun (and the abundance of different stars is different) was the reason astronomers returned to the nebular hypothesis
- BUT angular momentum can be exchanged between different parts of the early solar system and we now think that is what happened, with the Sun losing a.m. via mass loss, magnetospheric interactions.

History of SS Formation theories 2

Theories of type (ii):

- A passing star pulled some of the Sun's atmosphere off via tidal forces. This former atmospheric material then coalesced and formed the planets (early 1900s)
- The Sun captured material from passing interstellar clouds (1940s)

In ~1930 we learned that the Sun is almost all composed of H and He. If the early solar system had a similar makeup, gas might have escaped the early solar system, so the objection about the density being too low for gravitational collapse went away



Paths to planet formation

Two possibilities:

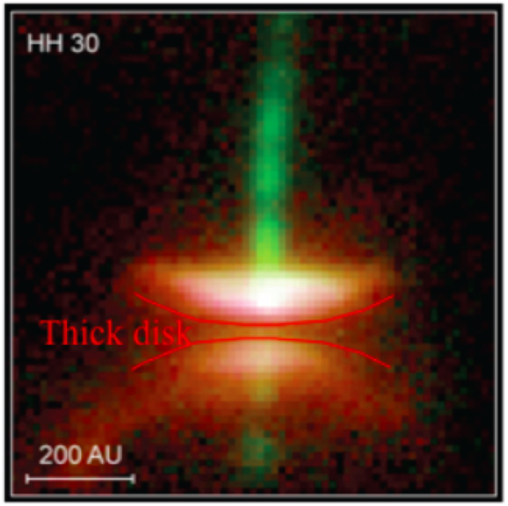
(i) Planets form like stars, from the gravitational collapse of gas clouds

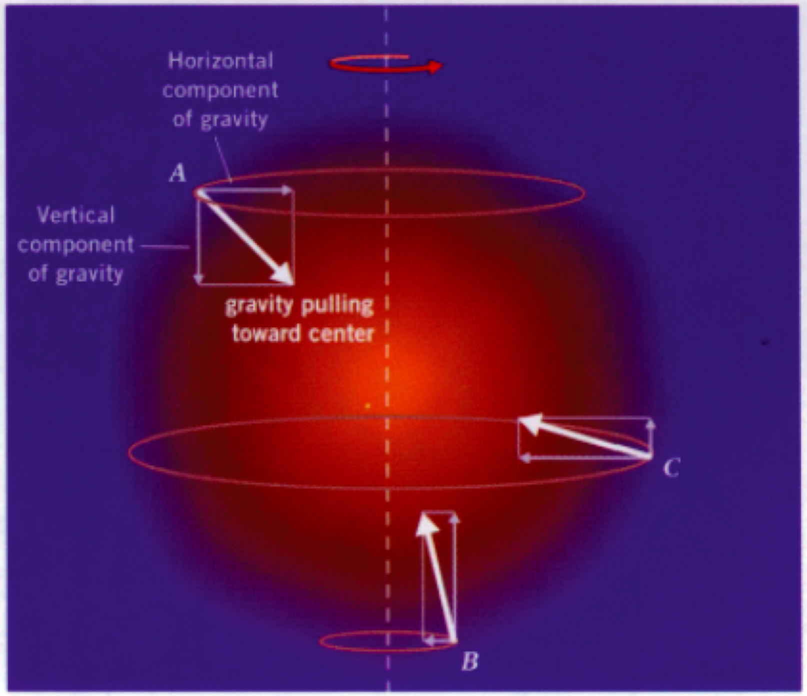
(ii) (now preferred) Planets form by the aggregation of solid particles in a disk around a star, with or without gas

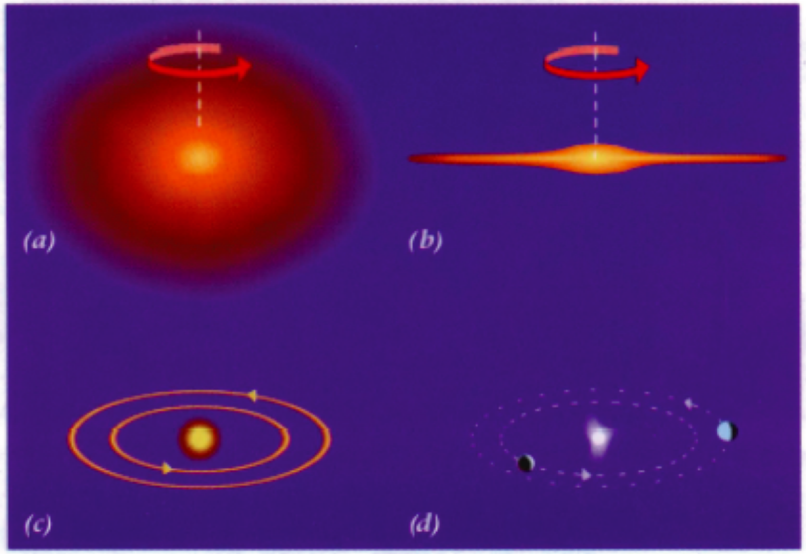
Nebular hypothesis

As the nebula that was to form the Sun collapsed, it spun up and formed a protoplanetary disk

We see disks around young stars today:







Common misconception:

The terrestrial planets are denser than the gas giants because the heavier elements in the early solar nebula fell toward the center

Question: give some everyday examples of heavy stuff falling faster than lighter stuff (think Pumpkin Drop…. then think of bubbles in champagne)

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

Mass of Sun / volume inside 40 AU

~ 10^{33} g / $(40 \times 10^{13}$ cm$)^3$ or 10^{-11} g/cm^3

(Density of water in cgs units is 1.0)

This is equivalent to a good vacuum on Earth.

There is no liquid phase at these densities and pressures; solids sublime directly to gas and vice versa.

We can model temperature gradient in young protoplanetary disk quite well:

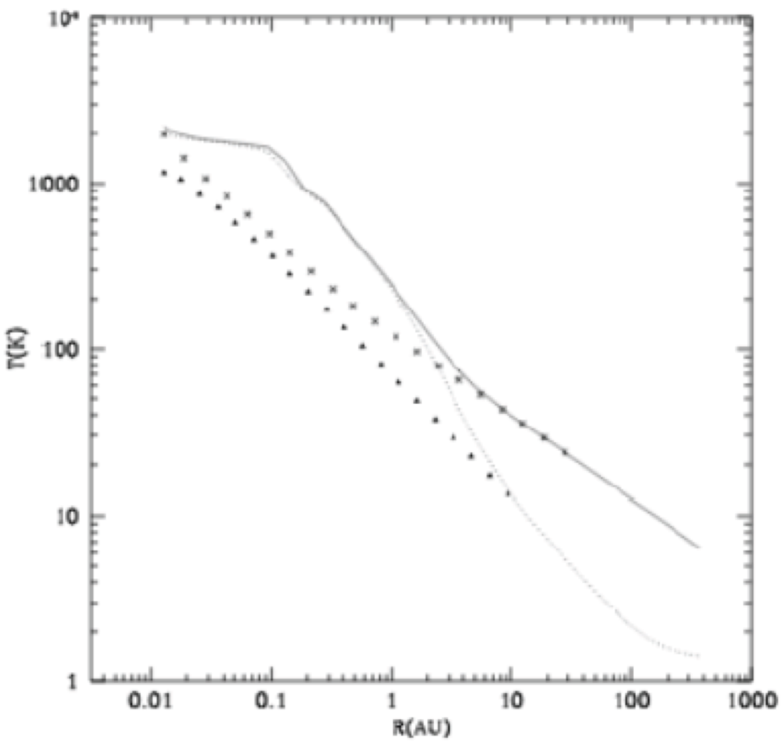


FIG. 3.—Radial distribution of the midplane T_c and photospheric T_{phot} temperatures for an irradiated and a nonirradiated disk model. The plotted

D'Alessio et al 1998 model of a disk around a young 2M_sun star

Nebular Composition

- Based on solar photosphere and chondrite compositions, we can come up with a best-guess at the nebular composition (here relative to 10^6 Si atoms):

Element	H	He	C	N	O	Ne	Mg	Si	S	Ar	Fe
Log_{10} (No. Atoms)	10.44	9.44	7.00	6.42	7.32	6.52	6.0	6.0	5.65	5.05	5.95

- Blue are volatile, red are refractory
- Most important refractory elements are Mg, Si, Fe, S

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Condensation sequence

Some elements will always be gaseous at solar nebula temperatures, pressures (eg H, He)

Some elements will condense out only at low temperatures, far away from Sun (volatiles such as H_2O)

Some elements will condense out almost anywhere in the solar system (refractory elements and compounds such as Fe, FeS, minerals)

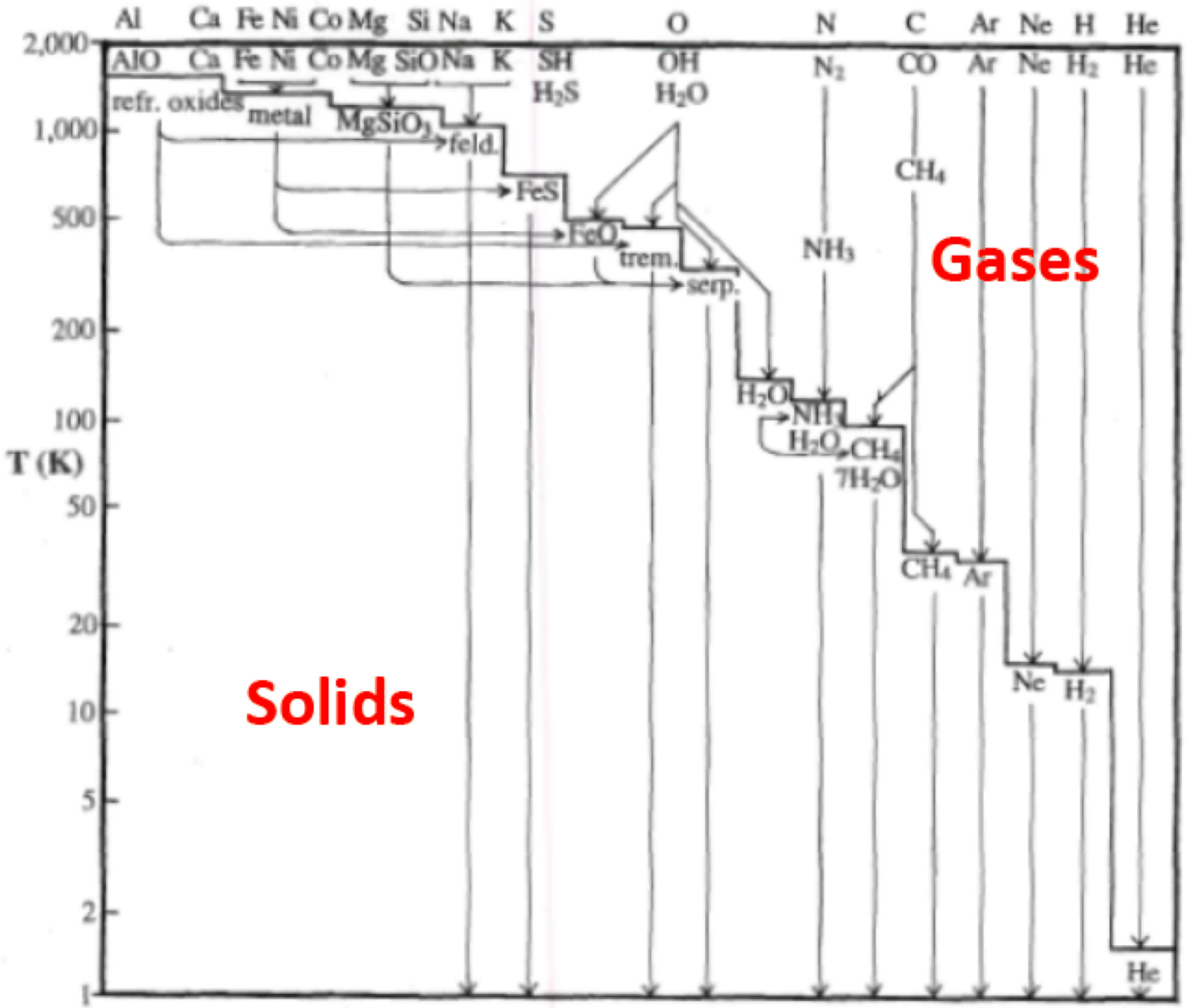


Figure IV.26 Major element flow chart for equilibrium condensation. The sequence of reactions of gases (above the solid line) and condensates (below the solid line) in solar material cooling at equilibrium. A pressure of 10^{-2} bar is assumed.

Phase diagrams

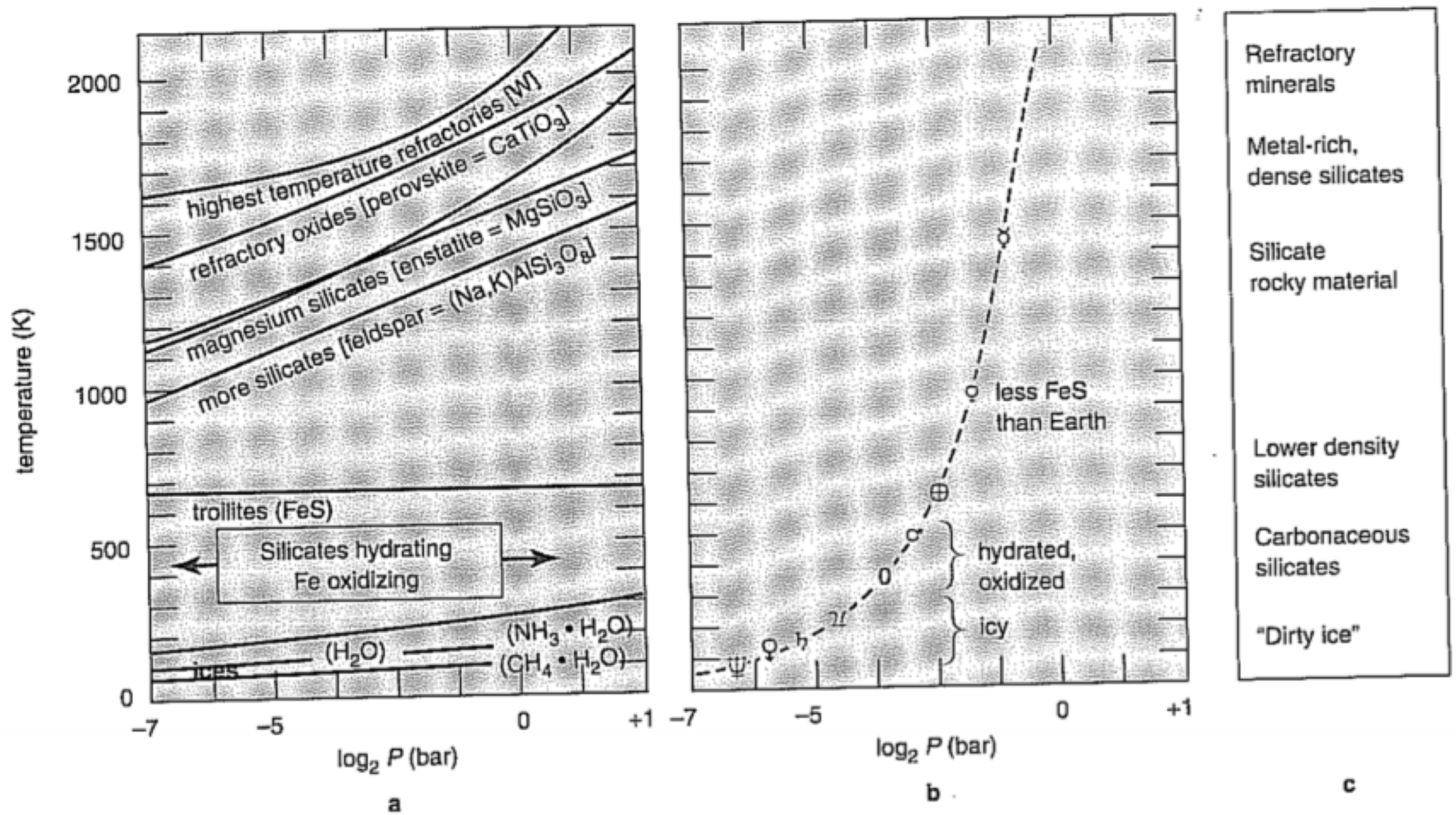
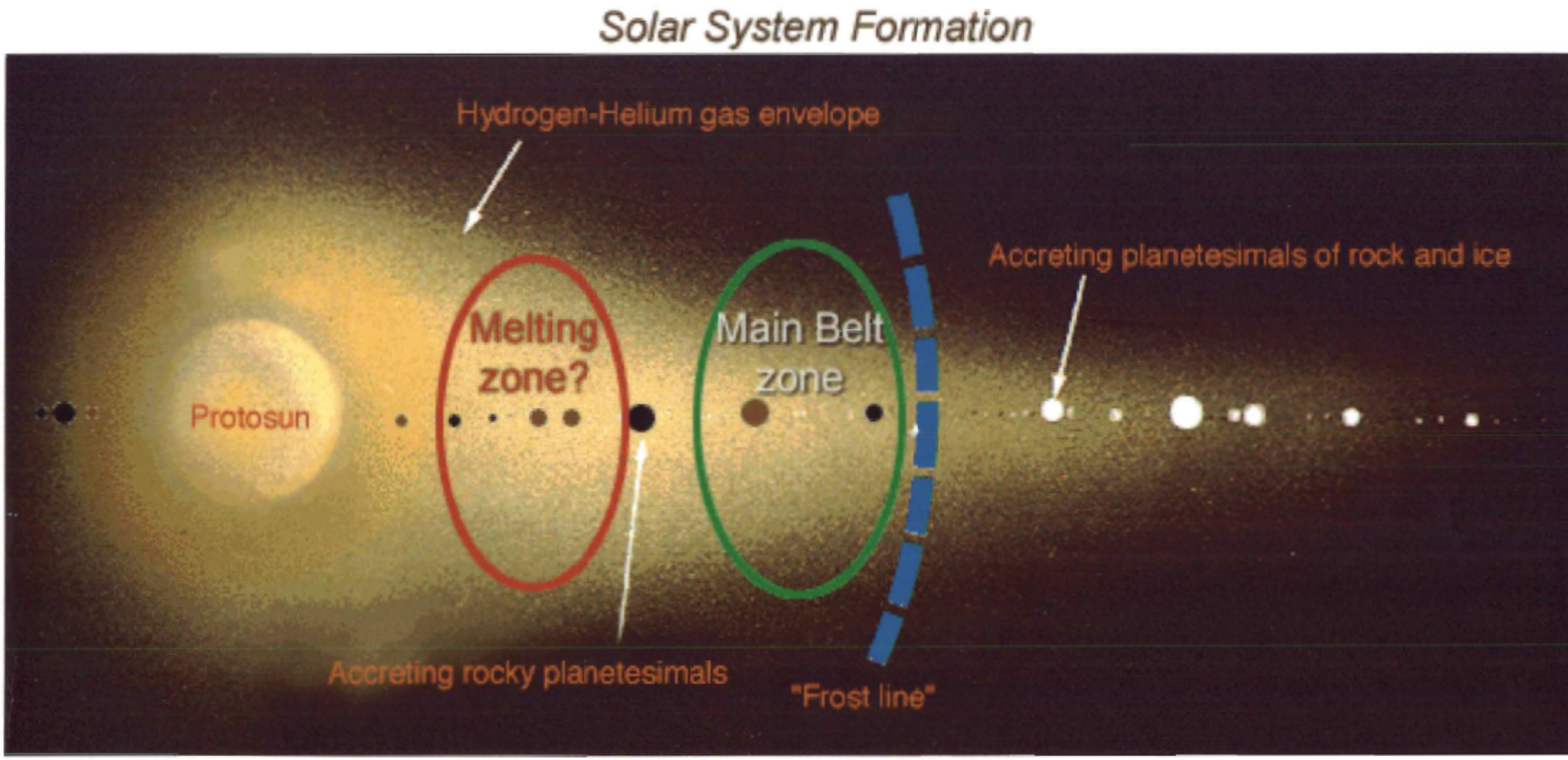


Figure 5-5. (**a**) The types of minerals condensing as the temperature declines, for different pressures. Curves indicate locations for various mineral groups, and brackets give most prominent examples. (**b**) The dashed curve gives a plausible adiabatic distribution of temperature and pressure in the solar nebula at a given moment, with the relative positions of the planets given. If the gas were suddenly blown away, the mineral grains remaining would have compositions given in part (a), which approximately agree with observed planetary properties. (**c**) The bulk composition of solid material that would dominate at various temperatures. (Adapted from Lewis, 1972a, 1972b)

Hartmann "Moons and Planets"

The Ice line



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

by Bottke & Martel

Giant planet formation

- The giant planets started off with cores significantly larger than the terrestrial planets (say 10 Earth masses for Jupiter) since they live beyond the ice line and ices are much more common because they are made of lighter elements (H,C,N,O)
- This extra mass allowed them to attract more H and He from the protosolar nebula

Planetismals and accretion

Start with the solar nebula: a disk of gas and dust surrounding the sun, with a temperature gradient

Microscopic grains will condense out as temperature allows:

-- silicates and iron compounds everywhere

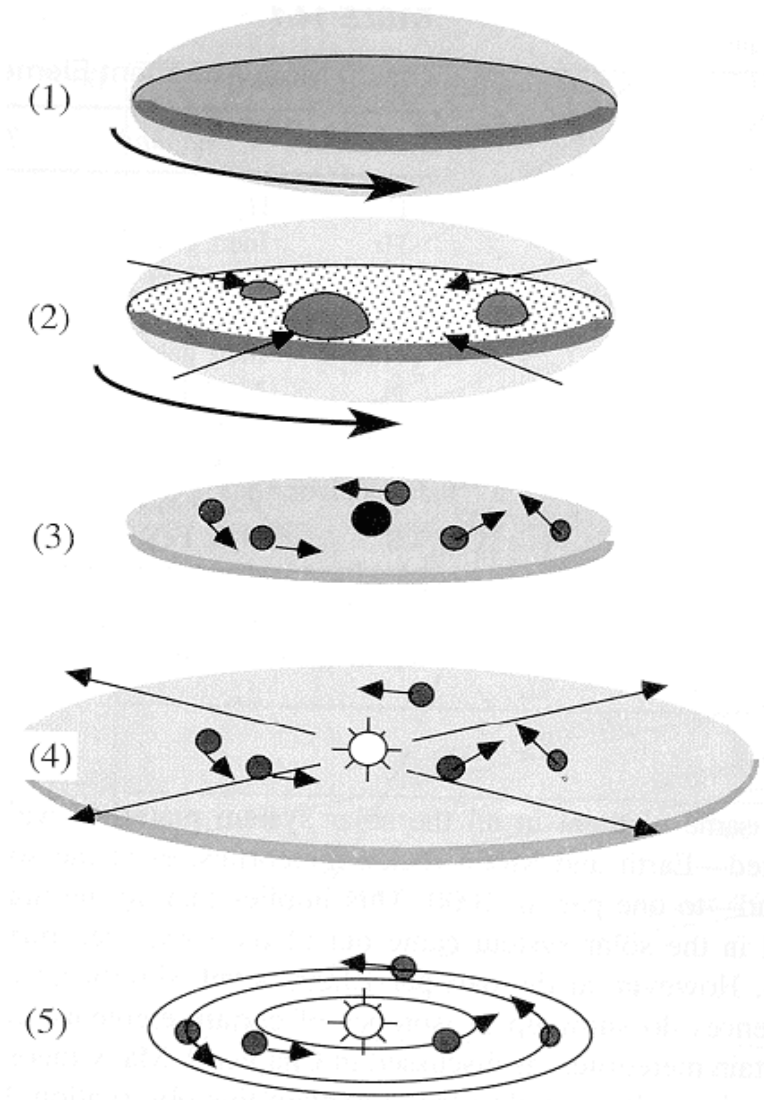
-- water and other ices outside 'ice line'

Grain sizes of order 1 micron

Grains settle to midplane of the nebula; collide, agglomerate, grow in size. In around 10^4 years, end up with km-sized objects: planetismals

Sequence of events

- 1. Nebular disk formation
- 2. Initial coagulation (~10km, ~10^4 yrs)
- 3. Runaway growth (to Moon size, ~10^5 yrs)
- 4. Orderly growth (to Mars size, ~10^6 yrs), gas loss (?)
- 5. Late-stage giant collisions (~10^{7-8} yrs)



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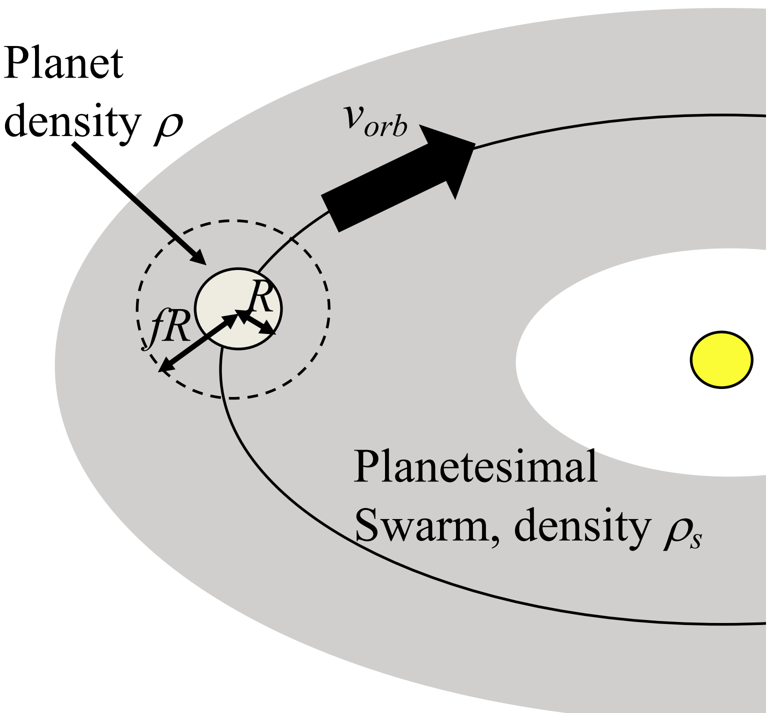
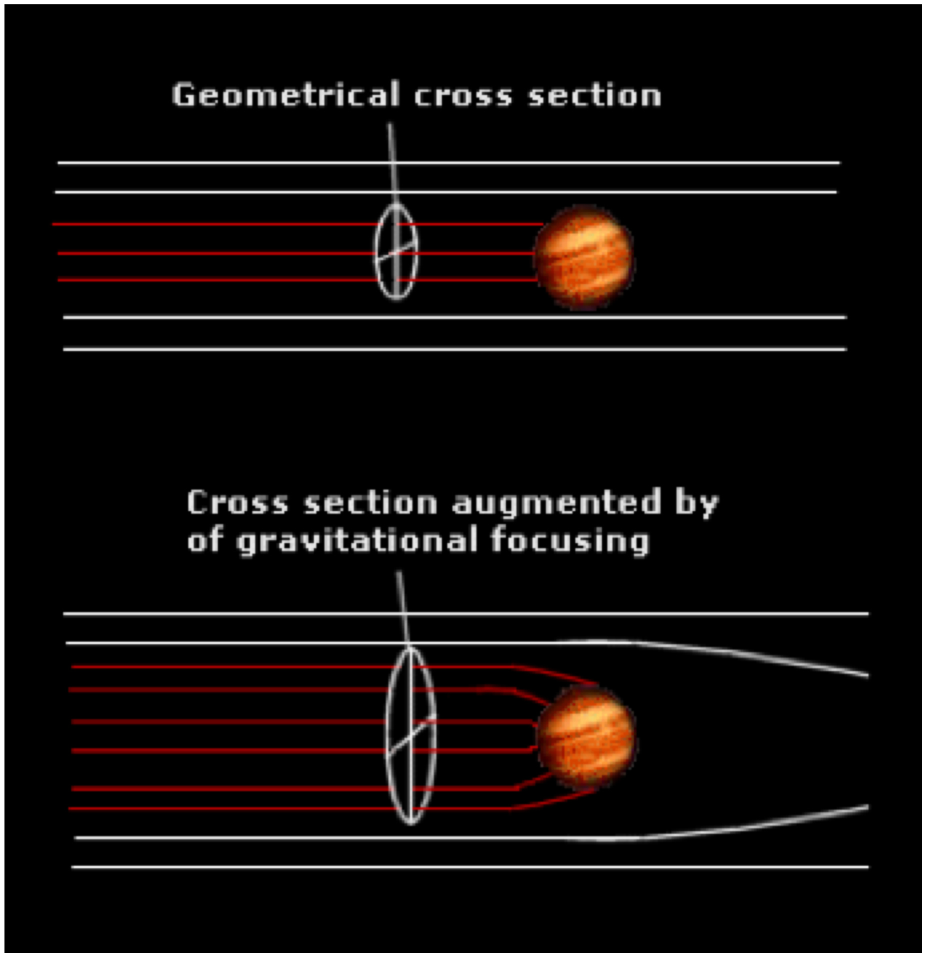
Accretion timescales



- Consider a protoplanet moving through a planetesimal swarm. We have $dM/dt \sim \rho_s v R^2 f^2$ where v is the relative velocity and f is a factor which arises because the gravitational cross-sectional area exceeds the real c.s.a.
- Question: why is it larger?

Gravitational focusing

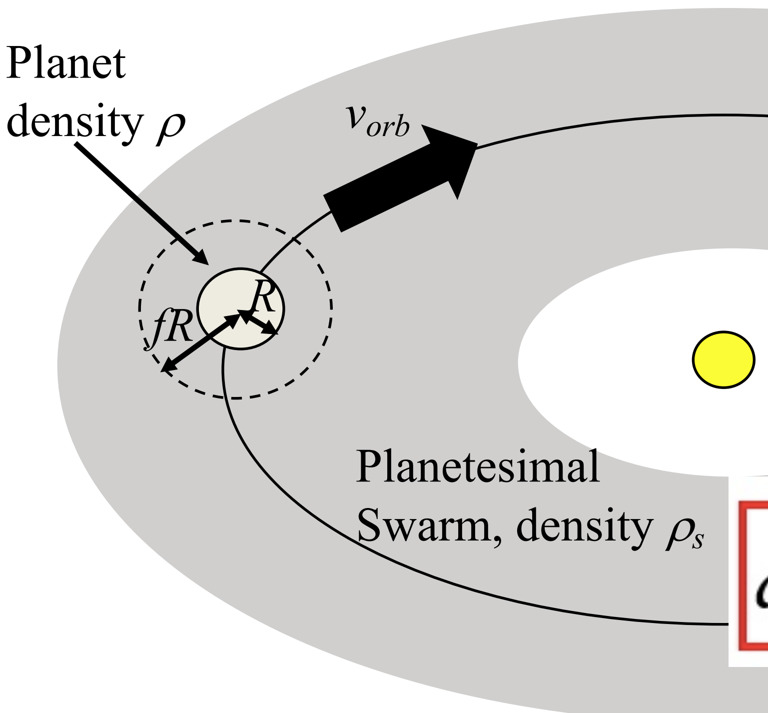


Gravity moves the orbits of planetismals toward the massive object, which increases its effective cross-section

Accretion physics

f accounts for the gravitational focusing:

$$f = (1 + (v_e / v)^2) \approx (1 + (8G\rho R^2 / v^2))$$



where v_e is the escape velocity, G is the gravitational constant, ρ is the planet density. So:

$$\boxed{dM / dt \sim \rho_s v R^2 (1 + (8G\rho R^2 / v^2))}$$

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Accretion timescales

- Two interesting cases:
  - $8G\rho R^2 << v^2$ so $dM/dt \sim R^2$ which means all bodies increase in radius at same rate – *orderly growth*
  - $8G\rho R^2 >> v^2$ so $dM/dt \sim R^4$ which means largest bodies grow fastest – *runaway growth*

  - So beyond some critical size (~Moon-size), the largest bodies will grow fastest and accrete the bulk of the mass

- This gas accretion became a runaway process, especially for Jupiter and Saturn: cores got more massive, accreted more gas, got even more massive, etc
- The process terminated when the solar system was cleared of gas

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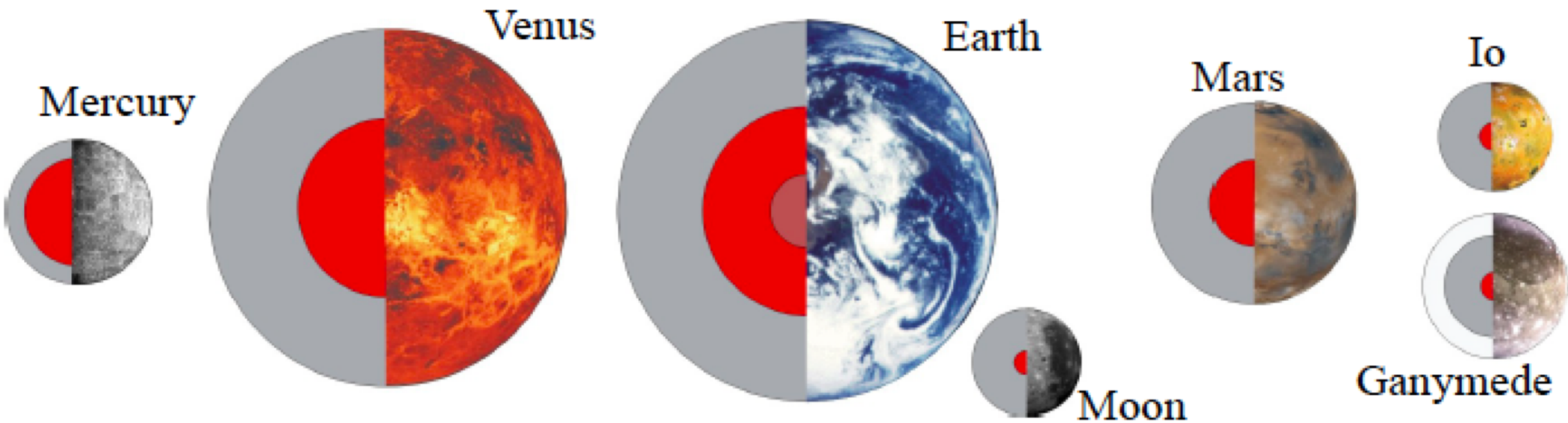
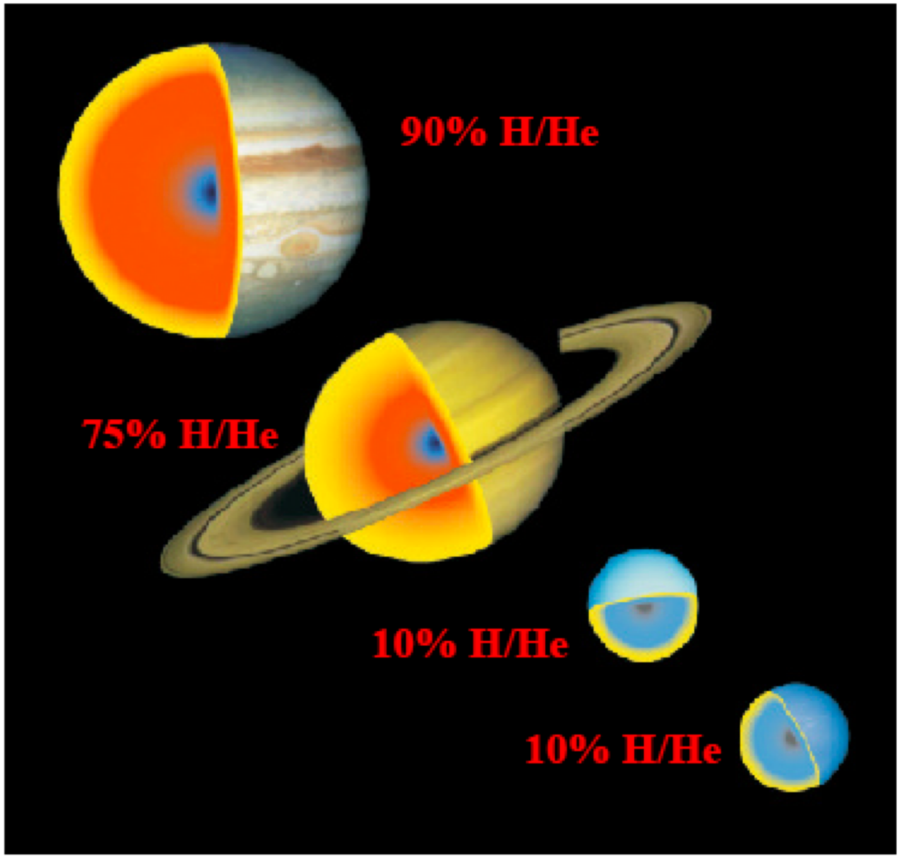
Terrestrial (silicate) planets



- Consist mainly of silicates ($(Fe,Mg)SiO_4$) and iron (plus FeS)
- Mercury is iron-rich, perhaps because it lost its mantle during a giant impact (more on this later)
- Volatile elements (H_2O,CO_2 etc.) uncommon in the inner solar system because of the initially hot nebular conditions
- Some volatiles may have been supplied later by comets
- Satellites like Ganymede have similar structures but have an ice layer on top (volatiles are more common in the outer nebula)

Gas and Ice Giants



- Jupiter and Saturn consist mainly of He/H with a rock-ice core of ~10 Earth masses
- Their cores grew fast enough that they captured the nebular gas before it was blown off
- Uranus and Neptune are primarily ices (CH_4,H_2O,NH_3 etc.) covered with a thick He/H atmosphere
- Their cores grew more slowly and captured less gas

Figure from Guillot, *Physics Today*, (2004). Sizes are to scale. Yellow is molecular hydrogen, red is metallic hydrogen, ices are blue, rock is grey. Note that ices are not just water ice, but also frozen methane, ammonia etc.

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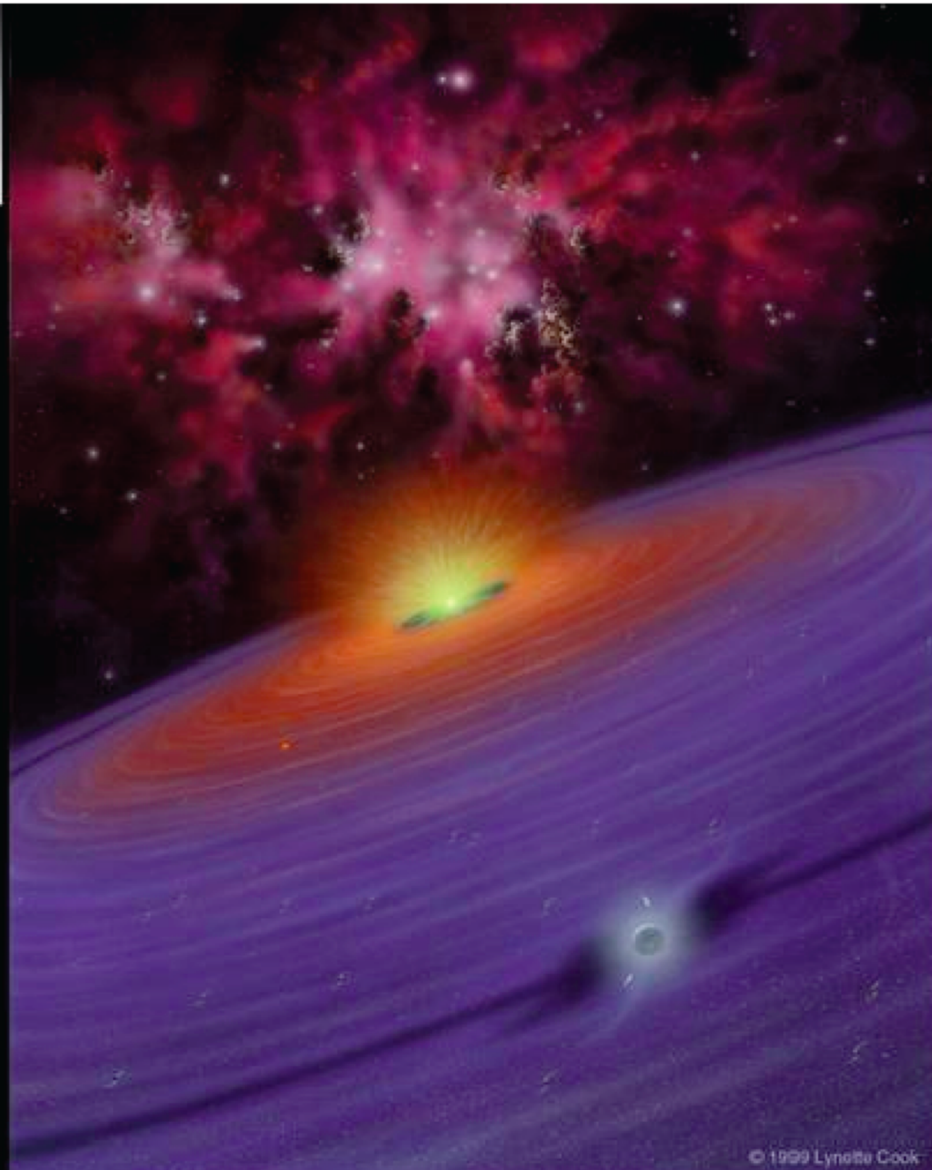
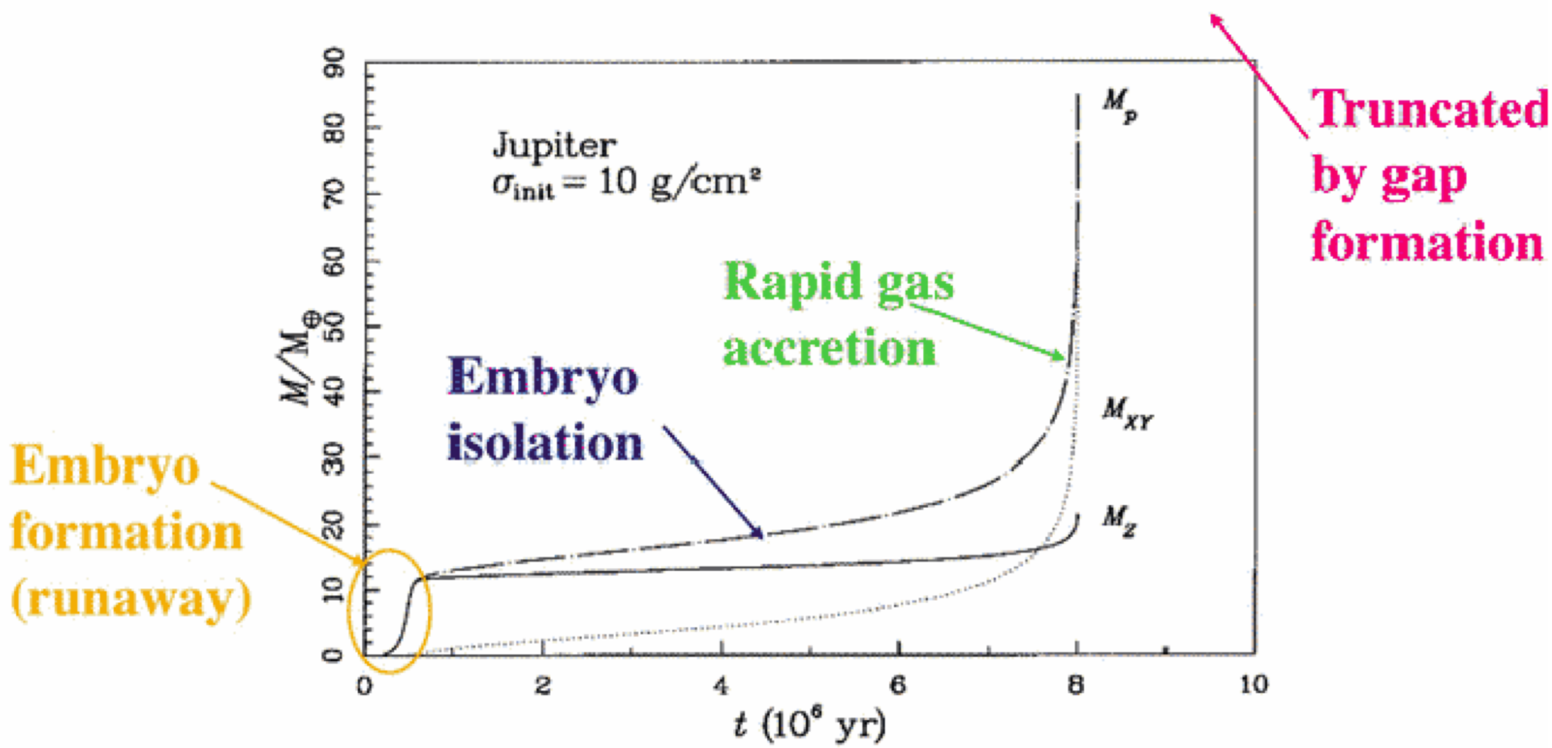
Jupiter
Saturn
Uranus
Neptune


© 1999 Lynette Cook

Core Nucleated Accretion ("Classical" Standard Case)



Pollack *et al*. 1996

- Question: the terrestrial planets probably accreted some gas too, but our current atmospheres are not H and He. What would have helped them lose these primordial atmospheres?

Summary

- Solar system formation tied closely to formation of the Sun
- Disk of dust and gas settles to midplane
- Planetismals accrete to form planets
- Position in solar system (ice line) determines whether

-- the more abundant ices form planetary cores which then accrete gas to form giant planets

-- the less abundant refractory elements form the smaller terrestrial planets

Summary 2

- The giant planets started off with larger cores because they included the more abundant volatile elements
- This allowed them to accrete even more gas in what became a runaway process
- The terrestrial planets lost any early atmospheres they had accreted because they were molten …. Energy gained from accretion

More questions

- Question: How did the planets get into mostly circular orbits?
- Hint: think of Kepler’s second law

- Answer:

Gravity is a weak force, so things need to stay near each other for a while to aggregate. (this works for colliding galaxies too).

Planetismals on elliptical orbits will both have a higher chance of intersecting other stuff, and will also collide at higher velocity, making aggregation less likely and disintegration more.

Meteorites

- Question: Given the current theory of solar system formation, how do you think that some meteorites are basically solid Fe?

Meteorites

- Question: Given the current theory of solar system formation, how do you think that some meteorites are basically solid Fe?

- Answer: Some body which was massive enough to become molten and then differentiate must have collided and broken into pieces