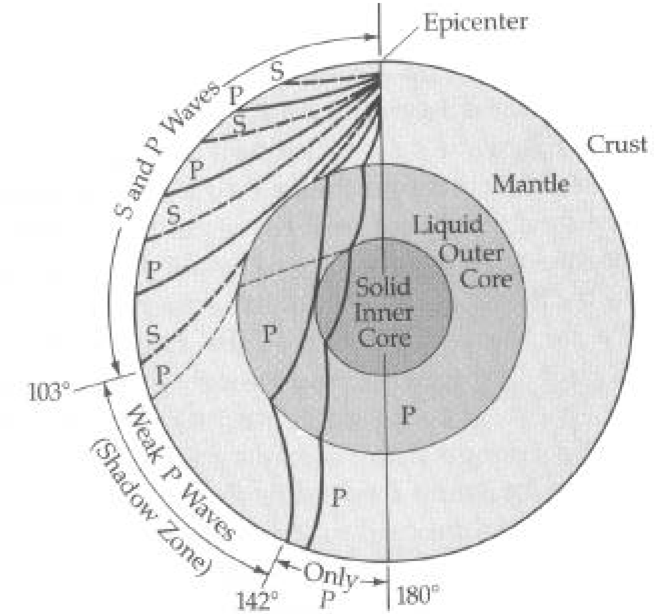
A Closer Look at Planetary Interiors

Hydrostatic balance:

$$\frac{dP}{dr} = -r(r)\frac{GM}{r^2}.$$

Also $M = \frac{4}{3} p\, r^3 \left\langle r \right\rangle.$ Integrate assuming $r(r) = \left\langle r \right\rangle, P_s = 0.$

$$\int_{P_c}^{0} dP = -\left\langle r \right\rangle^2 \frac{4}{3} pG \int_0^R r dr \Rightarrow P_c = \frac{2}{3} pG \left\langle r \right\rangle^2 R^2$$



Earth: $R \approx 6400$ km, $\left\langle r \right\rangle = 5500$ kg/m^3

$\Rightarrow P_c \approx 1.7 \times 10^{11}$ Pa $= 1.7 \times 10^6$ atm.

crust ρ = 3300 kg/m^3,

mantle ρ = 3400-5500 kg/m^3,

liquid outer core ρ = 9900-12000 kg/m^3,

solid inner core ρ = 13000 kg/m^3.

Heavier elements at bottom => Earth probably molten in past.

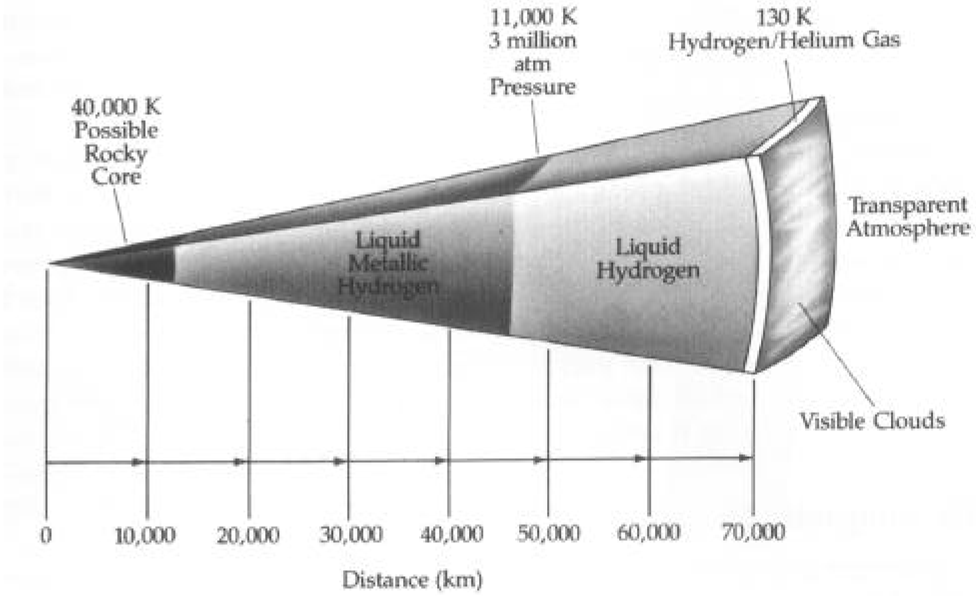
A Closer Look at Planetary Interiors

Jupiter: $R \approx 70{,}000\,\text{km}, \langle r \rangle \approx 1300\,\text{kg/m}^3 \Rightarrow P_c \approx 1.2\times10^{12}\ \text{Pa} = 1.2\times10^{7}\ \text{atm.}$

Mostly H and He.

At high pressures, H => p + e, liquid metallic hydrogen.

Internal weight supported by internal electron repulsion due to Coulomb force.



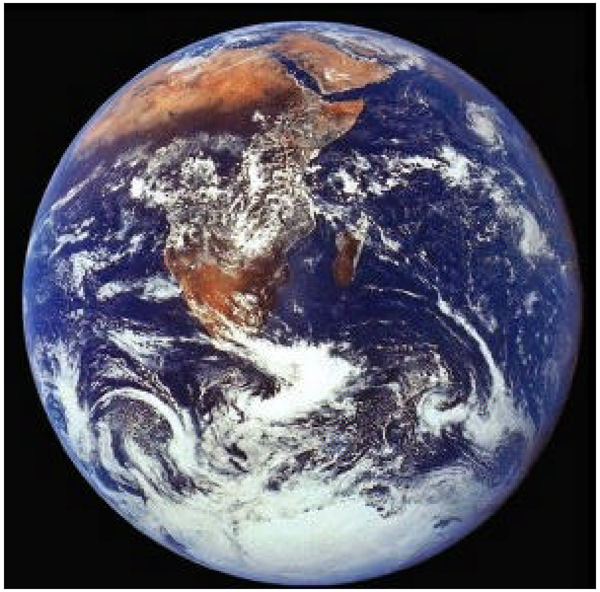
A Closer Look at Planetary Atmospheres

Earth: Lost initial atmosphere of H, He, and H compounds. Secondary atmosphere due to volcanism and outgassing; include H_2O, CO_2, N_2, and Ar. Later modification by life on Earth. Current composition 78% N_2, 21% O_2, 0.93% Ar, 0.033% CO_2 + other trace molecules. Atmospheric CO_2 + H_2O => greenhouse effect.

Scattering of light by atmospheric molecules ($L << \lambda$) described by Rayleigh Scattering law:

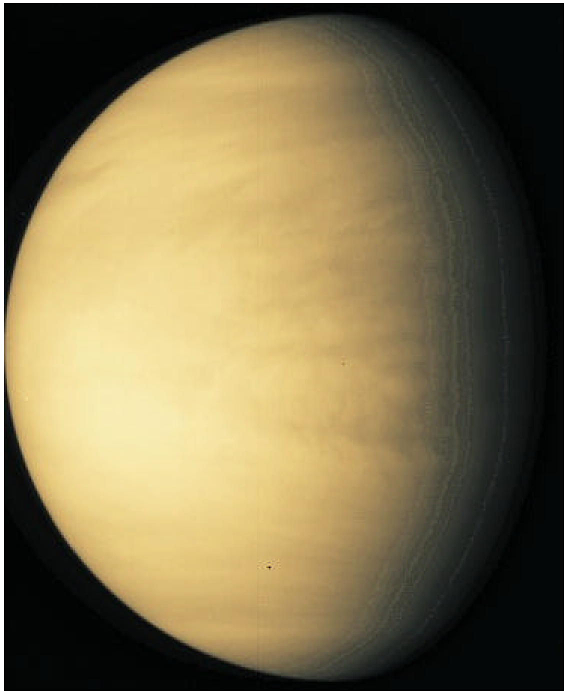
$$I_{scat} \propto \frac{1}{l^4}$$

=> sky is blue!

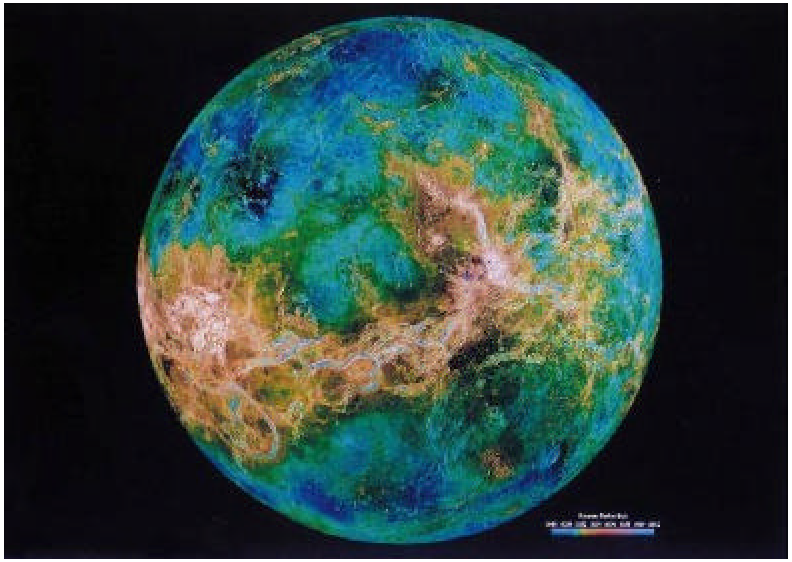


A Closer Look at Planetary Atmospheres

Venus: Runaway greenhouse effect. All CO_2 and H_2O released to atmosphere. Thick atmosphere absorbs more photons. Comparison: Earth has most CO_2 in rocks; carbonate rocks, e.g., $CaCO_3$, (limestone).



Visual

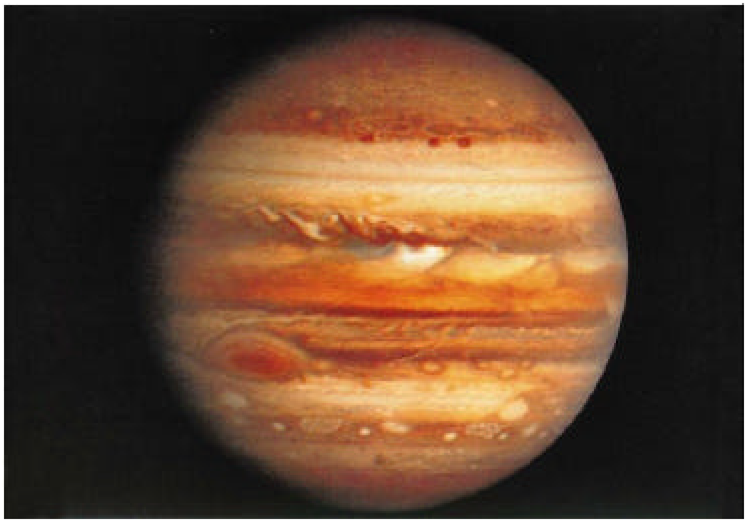


Radar

A Closer Look at Planetary Atmospheres

Jupiter: Different atmospheric composition, e.g., H_2, He, CH_4, NH_3, NH_4HS (ammonia hydrosulfide). Colors depend on molecular structure. Bands due to rising high pressure regions (zones) and descending low pressure regions (belts) being deflected by the Coriolis force.

Red spot: cyclonic motions due to local high pressure region and Coriolis force.



Magnetospheres

Earth, Jupiter, Saturn, Uranus, Neptune: $B_{\text{surface}} = 0.1\text{-}4 \times 10^{-4}$ T.
Mercury, Venus, Mars: $B_{\text{surface}} = 5\text{-}300 \times 10^{-9}$ T.

Planets have dipolar magnetic field (like bar magnet), due to flow of charged particles in metallic core. Magnetic "field lines" point along local ***B*** direction; spacing gives strength.

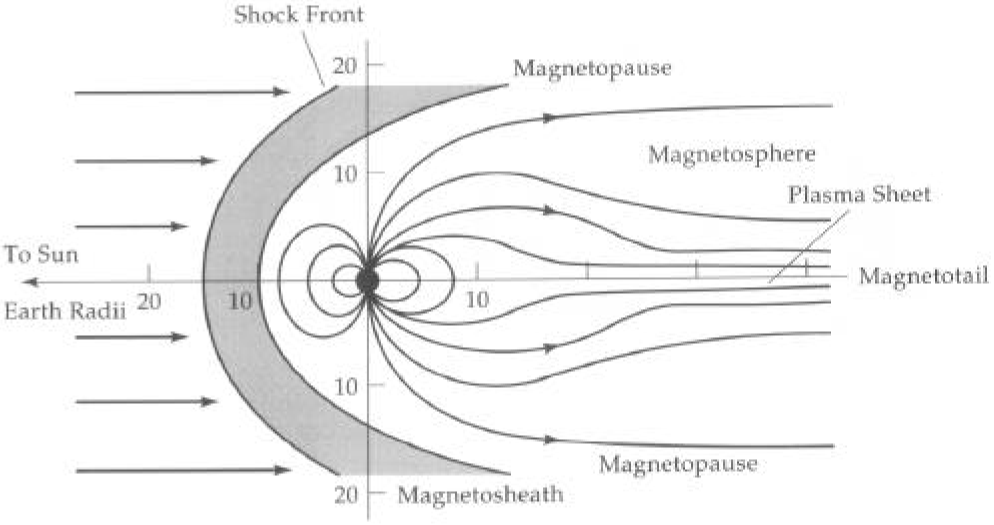
Magnetic (Lorentz) force $\mathbf{F}_m = q\,\mathbf{v} \times \mathbf{B}$.

Earth's field reverses every ~ 10^4 - 10^5 yr; not well understood.

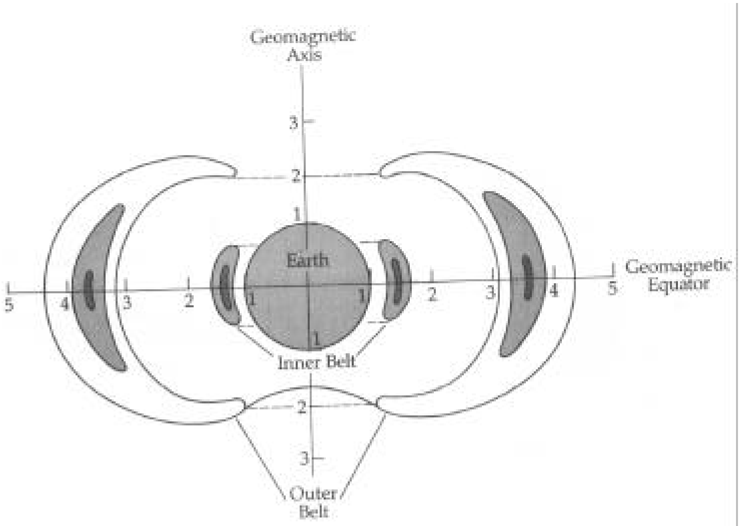
Dipolar field decreases as $1/r^3$, much less rapid than exponential decrease of atmospheric density => magnetic forces dominate interactions far from planet. Planets have a magnetosphere, where the planetary magnetic field interacts with the charged particles of the solar wind.

Magnetospheres

Interaction with solar wind
=> shock front and long tail
of magnetic field lines.



Van Allen radiation belts: charged particles trapped in magnetosphere. Inner belt interacts with atmosphere => <u>auroras</u>, the light produced in aftermath of collisional excitation or ionization of atmospheric gases.



Auroras

(COURTESY TOM EKLUND)

(COURTESY JOUNI JUSSILA)

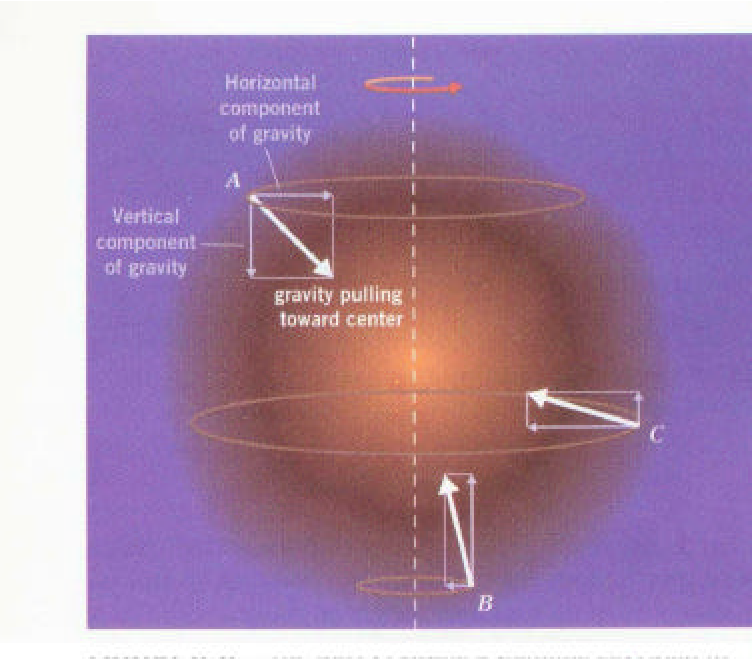
Green light from electronic transitions in oxygen, red light from nitrogen and oxygen.

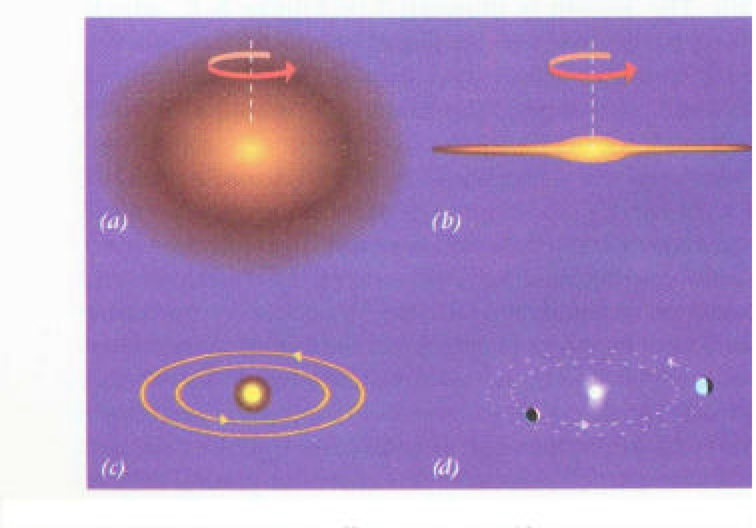
Formation of the Solar System

Dynamical properties to explain:

- Planets revolve ccw around Sun; Sun rotates in same direction
- Orbits nearly coplanar
- Very nearly circular orbits
- Planets rotate ccw, same direction as orbit (two exceptions)
- Small spacing for terrestrial planets, large spacing for gas giants
- Most satellites orbit in same direction as planet, with orbital plane close to planet’s equatorial plane
- Sun has > 99% of mass but < 1% of angular momentum
- Comets come inward from all directions and angles

Nebular Hypothesis





Rotating cloud of gas and dust => flattened disk => central object and disk => Sun forms in center, planets form by accretion of planetesimals.

Nebular Hypothesis

- Explains coplanarity and common direction of planets’ revolution and rotation

- But, how to understand angular momentum distribution?

  – internal friction causes matter to spiral in but angular momentum to move outward

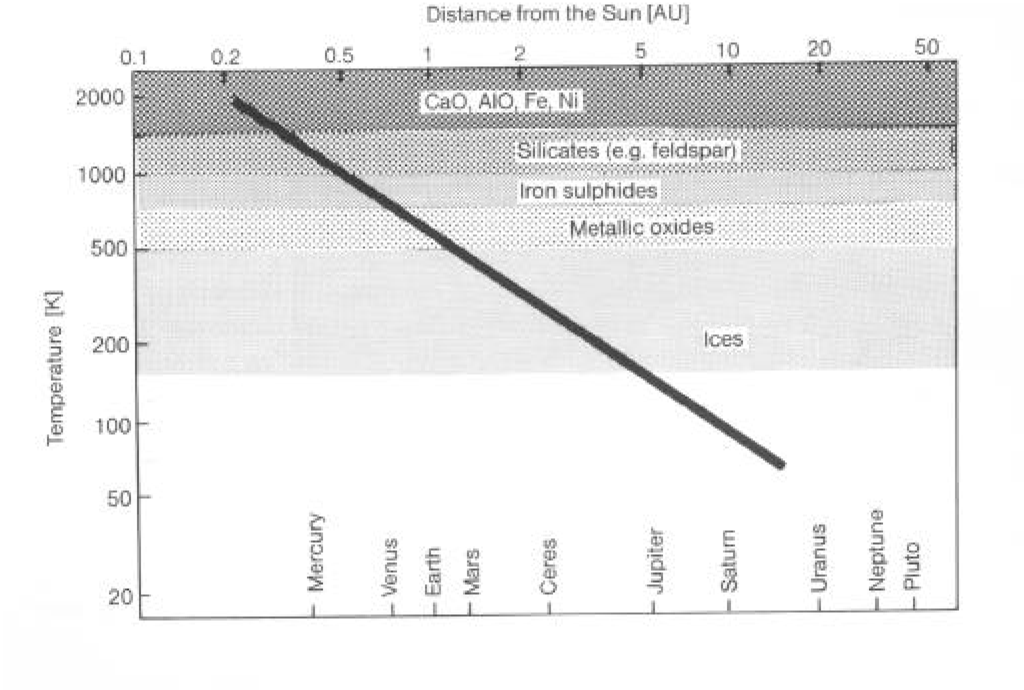
  – ***B*** threads Sun and gaseous disk => acts to slow down Sun’s rotation and transfer its angular momentum to disk

- Planet formation: dust grains => planetesimals => protoplanets

- Satellites form in mini planet formation scenario

- But, what about the different composition of terrestrials and gas giants?

The Condensation Sequence



A temperature gradient in early solar system allows condensation of lighter elements only at large radii.

The Condensation Sequence

- Early solar nebula is hot, due to energy from gravitational contraction. As nebula cools, center remains hottest due to the Sun.

- As nebula cools, metals and silicates condense first (highest condensation temperature) to form rocky cores.

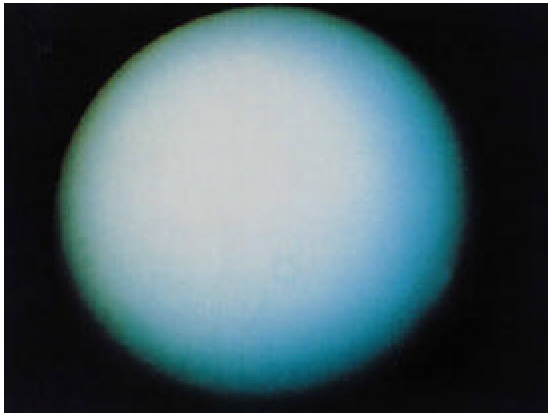
- First cores form in outer solar system (lower relative temperature) and get a head start in mass accumulation. Accrete from larger zones than inner cores which form later.

- Volatiles (ices of H_2O, CH_4, NH_3) condense only in outer solar system, contributing a much larger supply of condensed matter for outer planets.

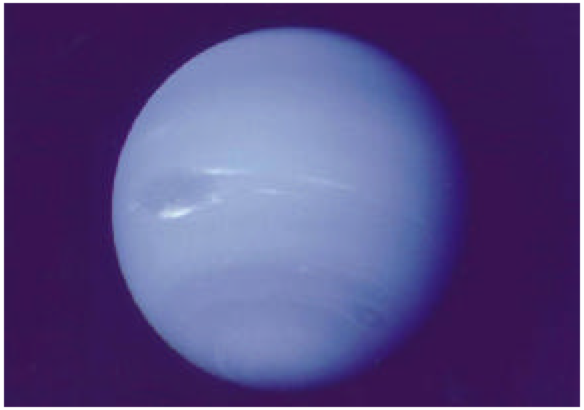
Formation of the Giant Planets

- Jupiter and Saturn: Planetary cores became larger due to condensed ices at these radii. Planetary cores eventually large enough to trap significant amounts of nebular gas, H and He. Therefore, planetary atmospheres similar to that of Sun. Heating of interior due to gravitational contraction of protoplanet.

- Uranus and Neptune: Large amounts of icy materials. Not as much nebular gas (H and He) captured.



Uranus



Neptune

Asteroids and Comets

- Asteroid belt (2.3-3.3 AU): Planetesimals that did not accrete to form planets. Due to tidal effects of Jupiter? Composition at different radii consistent with condensation sequence. Mostly S-type (silicates) in inner belt and C-type (carbon) in outer belt.

- Kuiper belt (~30-100 AU): Icy planetesimals beyond Neptune’s orbit which also did not form planets.

- Comets: Remnant icy planetesimals near outer planets which were ejected in random directions by gravitational interactions. Results in formation of spherical Oort cloud.

- Finally, expect clearing of remaining planetestimals by accretion onto planets. Clearing of remaining gas in solar nebula by solar wind.

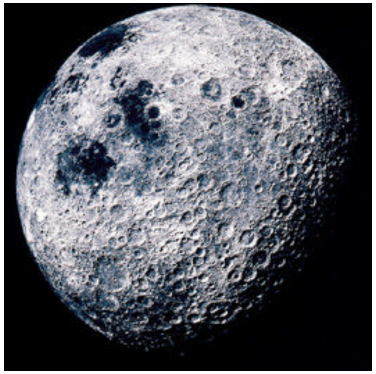
Formation of the Earth-Moon System

Earth

- Accretion from small bodies ~ 4.6×10^9 yr ago. Atmosphere H, He.
- Radioactivity (e.g., $^{238}U \rightarrow {}^{206}Pb + \ldots$) melts interior. Interior differentiates to dense core and light crust.
- Outgassing by volcanoes yields H_2O, CO_2, NH_3, SO_2,… Ocean basins formed, rain falls and fills them.
- Surface cools and crust thickens => plate activity. Atmosphere affects surface features. Presence of life affects atmosphere.

Moon

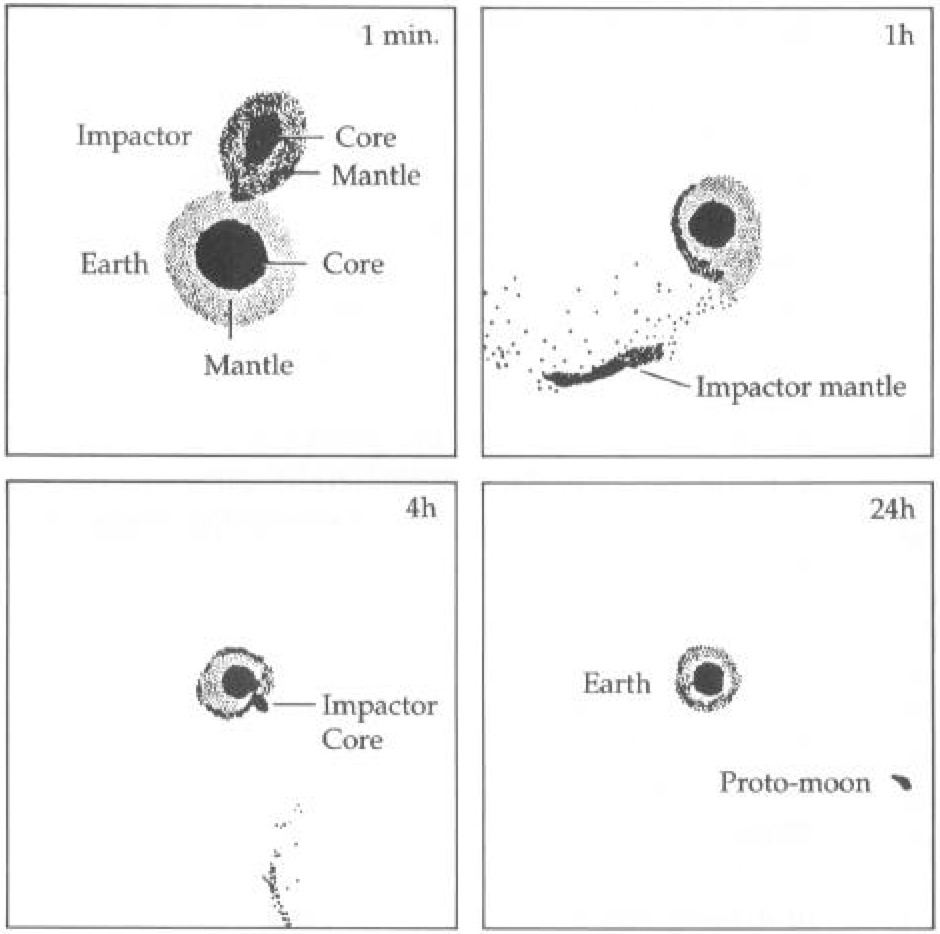
- Formation by accretion or impact
- Melting of outer shell and some differentiation
- Solidification of crust => cratered highlands ~ 4.1 - 4.5 x 10^9 yr ago
- Large basins formed by impacts
- Lava punctures thin crust in basins and fills them. Forms dark regions known as “maria” ~ 3.0 - 3.9 x 10^9 yr ago
- After this, not much internally driven evolution or cratering. Intense period of bombardment by planetesimals ends.



The far side of the Moon

The Giant Impact Hypothesis

Origin of the Moon could be from (1) fission, (2) capture, (3) binary formation, or (4) giant impact. Option (4) is most accepted today.



A giant impact model.

Accounts for both the similarities and differences in composition of the Earth and Moon.