Origin of the Solar System

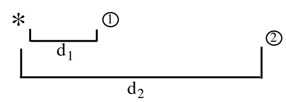
Look for General Properties

Dynamical Regularities

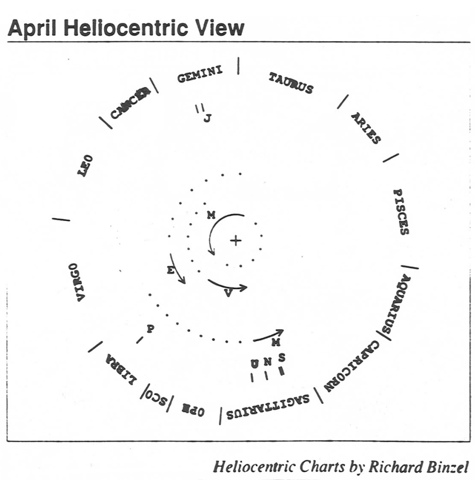
- Orbits in plane, nearly circular
- Orbit sun in same direction (CCW from N.P.)
- Rotation Axes ⊥ to orbit plane
- (Sun & most planets; Uranus exception)
- Planets contain 98% of angular momentum

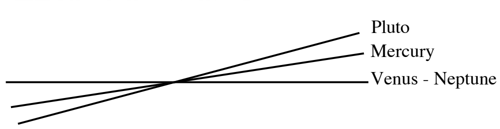
Spacing and Composition

- Spacing increases with distance
  - (roughly logarithmic)
- Composition varies with distance
  - inner 4: rocky, small, thin atmospheres
  - outer 4: gaseous, large, mostly atmosphere
- Sun contains 99.9% of mass



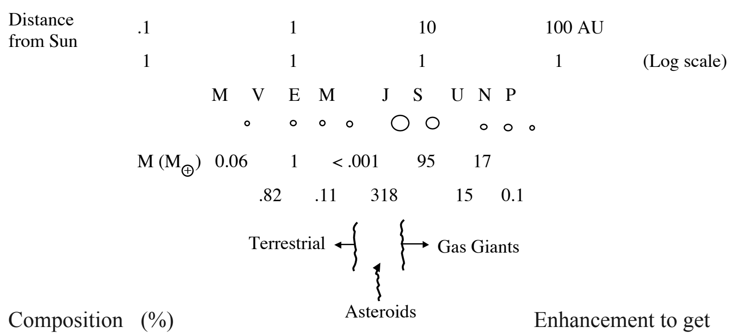
$$\frac{d_2}{d_1} \simeq 1.5 - 2$$





Side View

The Solar System



Composition (%)

	Rocky	"Icy"	Gaseous	Enhancement to get ⊙ abundance
Terrestrial	100	<1	0	300-500
Jupiter	6	~13	~81	2-40
Saturn	21	~45	~34	10-60
Uranus	~28	~62	~10	30 –140
Neptune	~28	~62	~10	30-115
Comets	~31	~69	~0	

Rocky - iron, silicates, …
"Icy" - at time of formation (H_2O, NH_3, CH_4, …)
Gaseous - H, He

Theory of Solar System Formation

All start with rotating disk

Minimum mass: 0.01 $M_\odot$

Sum of planets ~ 0.001 $M_\odot$ but most of H_2, He lost

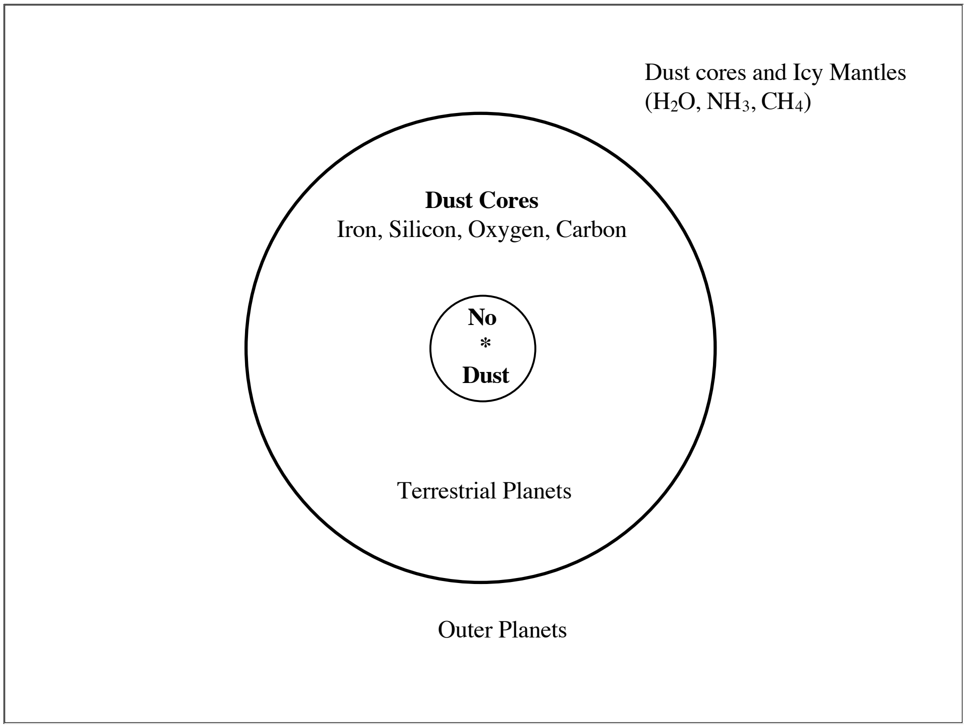
Note: Similar to masses of disks around forming stars

Some models assume more massive disks

Temperature, Density decrease with distance from forming star

(Observations suggest slower decrease than models usually assume)

DUST PLAYS A KEY ROLE



David W. Hughes

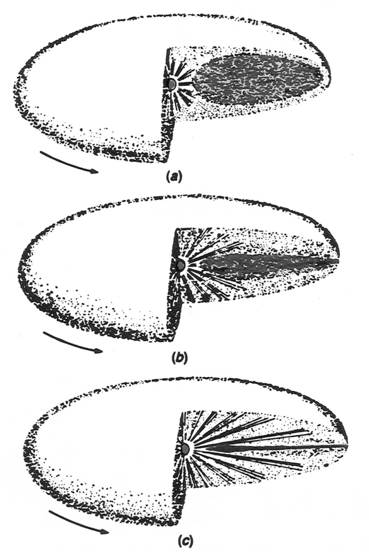
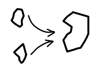


Fig.2.13. **In the spinning preplanetary solar nebula the dust retreats to the equatorial plane due to the energy losses that occur in the collision process illustrated in Figure 2.12 (from Boris Levin, *The Origin of the Earth and the Planets*, Foreign Languages Publishing House, Moscow, 1956).**

Dust Processes

Dust sinks to midplane

~10^4yr {
- Gravitational instability ⟶ planetesimals (~ 1 km in size)
- and/or
- Accretion of dust grains ↗



10^6 - 10^8 yr (problem) Collisions between planetesimals ⟶ rocky planet cores

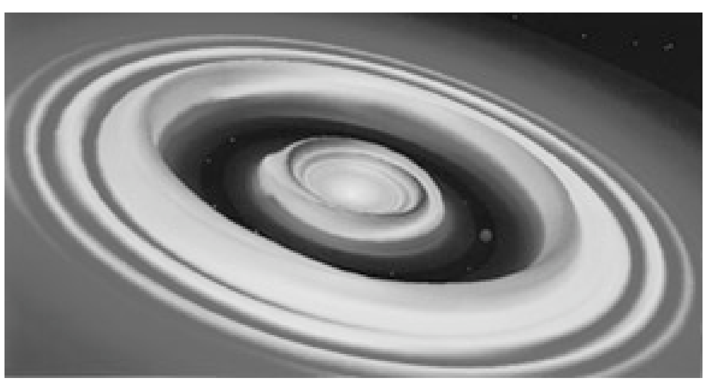
Gas Processes (Outer Planets)

Accretion of gas/gravitational collapse onto rocky cores

⟶ H, He in atmosphere

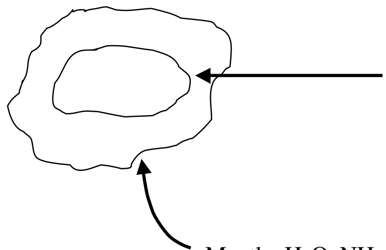
Rings, moons (minature solar system)

Planet Forming in a disk



Dust and Ice

Interstellar dust - core + mantle



$\xrightarrow{?}$ Planet types

Inner: Only rocky cores, little or no ice survives → rocky planets

Outer: Ice survives → comets, icy moons of outer planets

Outgassing

Planet heats internally → ice → gas → thin atmosphere
(if pressure, T ok → liquid → ocean)

Conclusions

1. Planet formation in a rotating disk with icy dust can explain most of the general facts about our solar system
2. Planetary systems are likely to be common since disks with $M \gtrsim M_{min}$ are common around forming stars.

If we are typical,

3. Expect other planetary systems will have ~10 planets, logarithmic spacing, different planet types

Caveats

- Other planetary systems are quite different
  - Big planets in close
  - But this is probably due to selection effect
- Locations may differ with mass of star
  - Ices survive closer to lower mass star
  - May get ice giants in close
  - Also planets may migrate inwards
  - May prevent formation of terrestrial planets

Formation of Earth

Solid particles → silicate + iron

No gas collected → atmosphere outgassed

Radioactive heating → molten core

→ ice → gas

H_2O → gas → liquid (oceans)

CO_2 → dissolve in oceans → carbonate rocks

N_2 → gas

Early Earth Atmosphere

N_2, CO_2, H_2O (CH_4, NH_3, H_2 ?)

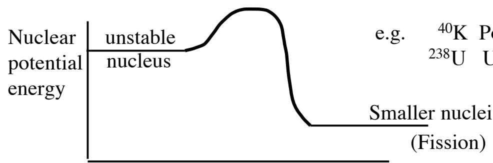
Reducing (No free O_2) Neutral ?

Energy Sources

Differentiation of the Earth

Impact heating by planetesimals (release of gravitational potential energy)

Radioactive nuclei decay (release of nuclear potential energy)



e.g. ^{40}K Potassium
^{238}U Uranium

(Fission)

Also emit ▯ particles (He)
electrons, gamma-rays

⟶ Kinetic energy ⟶ heat

Result: molten Earth

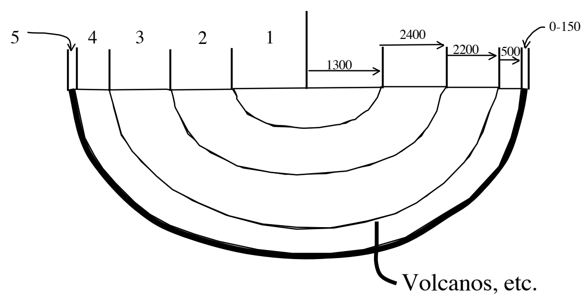
Iron-Nickel ⟶ center (core)

Silicates float ⟶ upper levels (mantle)

Differentiation released Grav. Potential energy ⟶ hot core

Radioactive heating continues

Results in layered Earth (like a soft-boiled egg)



Egg

Yolk
1. Inner solid core
2. Outer liquid core

} T ~ 4500 K, iron, nickel, … (maybe 7200 K)

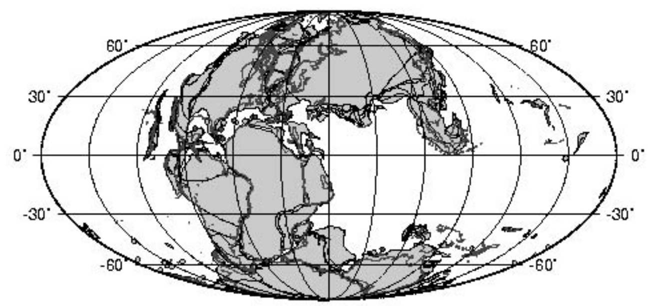
White
3. Lower mantle - iron rich silicates, solid
4. Asthenosphere (upper mantle) pliable

Shell
5. Lithosphere - rigid silicates (crust)

Lithosphere can "float" on asthenosphere

⟶ Continental Drift, Earthquakes, Volcanos

Continental Drift Reconstructed



150 My Reconstruction

Shows motion of continental plates over last 150 Myr.
Red and green dots show locations of ocean drilling.

http://www.odsn.de/odsn/index.html

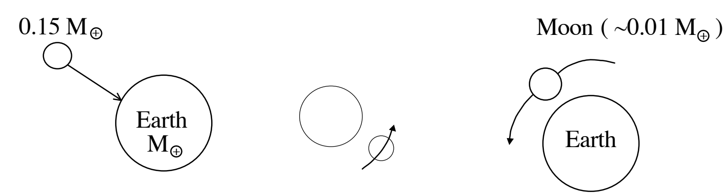
Formation of Earth and Moon

$\frac{M_{Moon}}{M_{Earth}}$ Larger than all but Pluto

Most terrestrial planets have no moons

(Martian moons are captured asteroids)

Moon most likely resulted from giant impact



Earth gets more iron $\rho_\oplus = 5.5$ g cm^{-3}

Moon mostly silicate $\rho_{Moon} = 3.3$ g cm^{-3}

Temperature was very high after impact (10,000 - 60,000 K)

Any icy material left?

Origin of Atmosphere

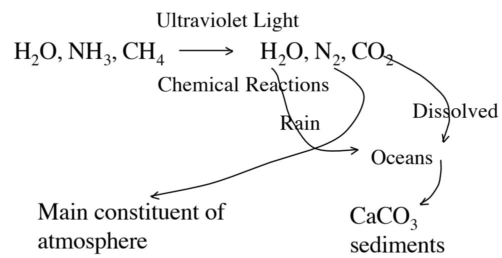
Certain “Noble” gases (e.g. Neon) are more rare in Earth atmosphere than in solar nebula. Atmosphere not collected from gas

Reason: Earth is small gravity is weak

Temperature in solar nebula is high - atoms moving fast, harder to hold

Outgassing: “Icy” material vaporized by high temperatures

→ vents, volcanos



No O_2 on early Earth; No ozone (O_3), so no protection from ultraviolet light

Alternative: Icy materials brought by comets.