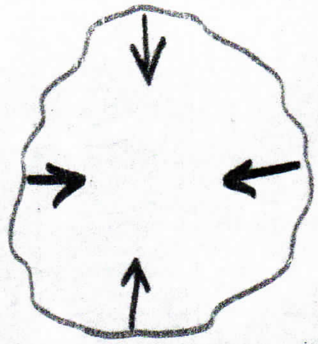
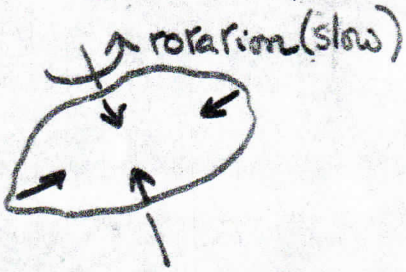
FORMATION OF PLANETARY SYSTEMS AS PART OF STAR BIRTH

- Read – Jastrow/Thompson Ch. 13

Stage 1 Interstellar gas cloud begins to contract under gravity
"Pushed" by turbulence from distant stellar explosions?



Stage 2 Flattening of gas cloud due to amplification of (chance) initial rotation
CONSERVATION OF ANGULAR MOMENTUM (ice skater analogy)
CENTRIFUGE EFFECT

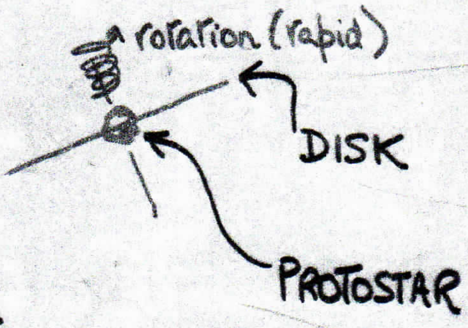


- **Stage 3** Accumulation of material at mass centres:

TWO CASES:

WHICH OPTION CHOSEN DEPENDS ON THE CLUMPING OF THE ORIGINAL CLOUD

A. Single mass centre dominates
→ PROTOSTAR plus flattened disk of centrifugally supported matter



— OR —

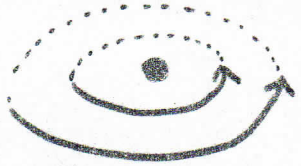
B. Fragmentation into multiple mass centres
→ MULTIPLE PROTOSTARS

- Observation → 3(B) has happened for about $\frac{1}{2}$ of all stars near Sun.

CAN 3(A) MAKE SOMETHING LIKE SOLAR SYSTEM?

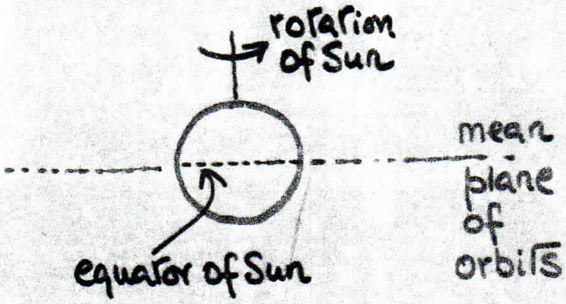
Observed Organisation of Motions in the Solar System.

1. Planets all circulate around Sun in same direction.

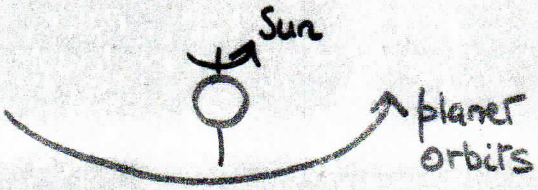


2. Orbits of planets are well aligned (8 of 9 within 7° of common plane)

3. Average plane of planetary orbits is within 1° of Sun's rotational equator



4. Rotation of Sun on its axis is in same sense as revolution of planets in their orbits



5. Most (not all) secondary motions in Solar System
   - rotations of planets
   - revolutions of satellites of planets (27 of 33)
   - orbits of minor planets (asteroids)

   share sense of Solar rotation and planet revolution

ALL AS EXPECTED IF PLANETARY MATERIAL FORMED FROM CENTRIFUGALLY-FLATTENED DISK WITH SAME ROTATION AS PROTOSUN

Some Further Organised Aspects of Solar System

1. Outer planets (Jupiter, Saturn, Uranus, Neptune) are MUCH MORE MASSIVE than inner planets
2. Average density of planets decreases with distance from Sun.
3. Planets are at non-random distances from Sun (Titius-Bode relation)

Average distance of planet from Sun = $4 + 3 \times 2^n$

PLANET	AVERAGE DISTANCE FROM SUN	TITIUS-BODE RELATION	n
Mercury	3.9	4	$-\infty$
Venus	7.2	7	0
Earth	10	10	1
Mars	15	16	2
Ceres	27.7	28	3
Jupiter	52	52	4
Saturn	95	100	5
Uranus	192	196	6
Neptune/Pluto	301/395	389	7

Not an exact law but an indication of non-randomness.

CAN THESE ORGANISED ASPECTS BE EXPLAINED BY MODEL OF ORIGIN OF SOLAR SYSTEM ?

CAN DIFFERENCES AMONG PLANETS BE EXPLAINED ?

SOLAR SYSTEM DATA

Planet	Semimajor axis of orbit around sun: A.U.[b]	Semimajor axis of orbit around sun: Titius-Bode	Orbital Period[c]	Rotation Period[c]	Diameter (Earth=1)	Mass (Earth=1)	Mean Density (gm/cm^3)	Mean Density Corrected for Effect of Gravity[d]	Surface Gravity (Earth=1)	Inclination of orbit to Earth's
Mercury	0.3871	0.4	87.97d	59d	0.38	0.053	5.1	5.5	0.39	7°02'
Venus	0.7233	0.7	224.70d	242.9d	0.95	0.815	5.3	4.8	0.89	3°24'
Earth	1.0000	1.0	365.26d	23h56m04s	1.00	1.00	5.52	4.4	1.00	0°
Mars	1.5237	1.6	1.88y	24h37m23s	0.53	0.108	3.94	3.7	0.38	1°51'
Ceres[a]	2.7673	2.8	4.60y							
Jupiter	5.2028	5.2	11.86y	9h50m to 9h55m	11.19	317.9	1.33		2.35	1°18'
Saturn	9.5388	10.0	29.46y	10h14m to 10h38m	9.47	95.16	0.69		0.93	2°30'
Uranus	19.182	19.6	84.01y	10h45m	3.71	14.67	1.56		0.99	0°46'
Neptune	30.058		164.79y	16h?	3.97	17.21	2.27		1.38	1°47'
Pluto	39.439	38.8	247.69y	6.4d	0.47	0.18	∼6?		?	17°6'

[a] Typical minor planet (asteroid)

[b] 1 A.U. (astronomical unit) = 92,956,000 miles

[c] y=years, d=days, m=minutes, s=seconds

[d] Planetary interiors are compressed by gravity. This column gives estimates of mean densities with this effect removed, assuming material basically similar to Earth rocks.

Physical Properties of Planets

PLANET	MASS (EARTH=1)	DIAMETER (EARTH=1)	MEAN DENSITY (WATER=1)	CORRECTED MEAN DENSITY
Mercury	0.053	0.38	5.5	5.5
Venus	0.815	0.95	5.3	4.8
Earth	1	1	5.53	4.4
Mars	0.108	0.53	3.94	3.7
Jupiter	317.9	11.19	1.34	
Saturn	95.16	9.47	0.69	
Uranus	14.67	3.71	1.56	
Neptune	17.21	3.97	1.52	
Pluto	0.18?	0.47?	~6?	

↑ Mass: measured by timing satellite orbits and/or artificial spacecraft orbits, then applying gravity theory

↑ Diameter: measure apparent (angular) size and distance to planet

↑ Mean density: mass/volume

EVOLUTION OF PRE-PLANETARY DISK

Denser than original pre-stellar cloud. → More collisions between all particles in cloud → fluctuations more likely to aggregate and grow.

Collisions eventually → big fluctuations accrete smaller ones.

Possible disc materials.

Heaviest elements — fine particles, dust, grit, rocks } Solidify at temperatures ~500 — 2000 K
iron, silicates, common minerals, carbon

Lighter elements — fine particles, ices — e.g. water H_2O, carbon dioxide CO_2, methane CH_4, ammonia NH_3 } solidify at 100 — 300 K

Lightest elements — gases e.g. hydrogen, helium, nitrogen, oxygen, neon } mostly solidify below 100 K

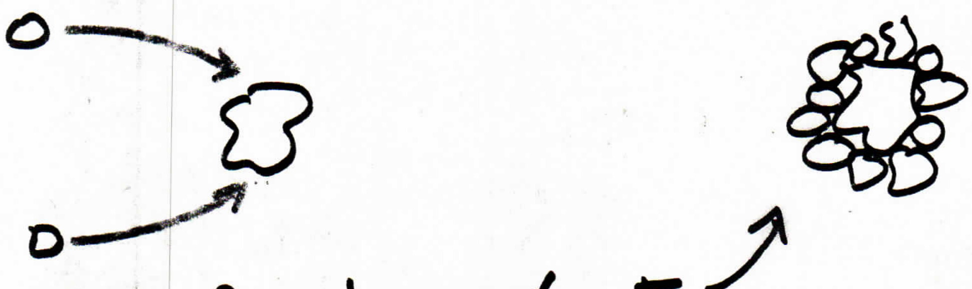
Solids aggregate more easily than gases.

Different materials solidify in different temperature ranges

Temperature decreases away from star.

GROWTH OF MASS CENTRES IN DISC

1. Formation of all scales of debris
2. Largest pieces attract smaller ones.



Grow by accretion to

3. Arrival of new pieces } warms accreting masses
Trapping of radioactivity heat }

4. Ignition of nuclear fusion in central star

<u>A. Far from central star</u> ROCKS] aggregrate, large masses
ICES]
Retain GAS atmospheres

Composition more ICY than ROCKY
Formation of massive "Jupiter-like" planets.

<u>B. Close to central star</u> ICES evaporate
Only ROCKS aggregate
Vaporised ices and GASES lost.

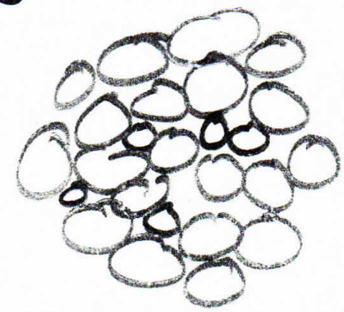
Composition more ROCKY than ICY
Formation of less massive, "Earth-like" planets.

5. Stellar radiation sweeps light gases outwards ?

Planet Formation in Outer Solar System

ROCKY } materials solid
ICY }

Aggregate into planets.



GASES retained by gravity of large masses

Abundant, low-density materials incorporated into planets

→ Massive, low-density, giant planets

e.g. **JUPITER**
$318 M_\oplus$
$11.2 R_\oplus$

Biggest protoplanet in Outer Solar System, by chance.

Greatest mass → strongest gravity.

Retained biggest % gases } low average density
smallest % rocks }

Observations: Mean density 1.34 × water (greater than density of Saturn)

But Jupiter's larger mass → greater self-compression than for Saturn.

Atmosphere mainly HYDROGEN
HELIUM
\+ ACETYLENE (C_2H_2)
METHANE (CH_4)
AMMONIA (NH_3)
ETHANE (C_2H_6)

Cloud layer temperature ~ -300°F

Pioneer Spacecraft (1974-75) → Jupiter radiates ~ 6×10^{14} kilowatts in infrared. Total solar radiation striking planet ~ 3×10^{14} kilowatts! Jupiter has net energy emission. Still contracting like very low-mass protostar?

SATURN

Smaller protoplanet than Jupiter, lower final mass
Also retained gases.
Mean density ~0.68 x water
 - less self compression than more massive Jupiter, similar composition.

Ring system — icy and rocky fragments prevented from accumulating into satellite by pull of Saturn.

URANUS
NEPTUNE

Smaller masses
Less gases retained
Higher average densities → denser composition
Dominated by ICY materials, residual gases.
 - methane, ammonia, etc.

SATELLITES
ASTEROIDS

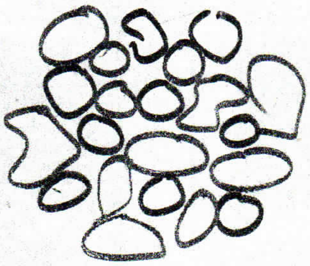
Much denser than planets of outer Solar System — much less gases retained by small masses. Densities ~ 2-3 x water?
 - ICY / ROCKY composition, little gases? (expected, space probes yet to verify)

COMETS

Normally beyond Pluto (a few remain closer in)
Small collections of rocky / icy debris
Volatiles stream behind on close approach to Sun

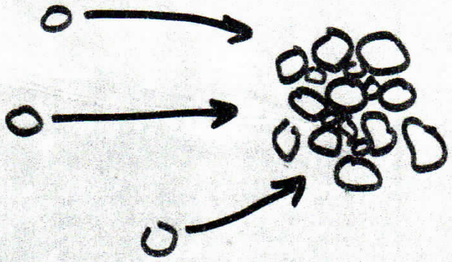
Development of Near-Star Planet

1. Before Sun "turns on", ROCKY and ICY materials solid. First aggregations contain both. Too small to retain gases by gravity



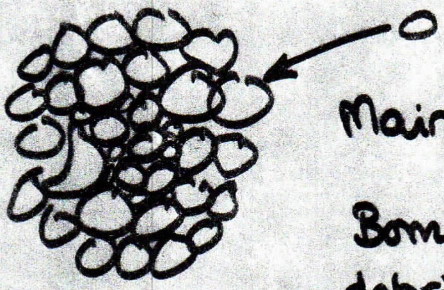
2. After Sun turns on, ICES evaporate. Ice vapours and gas heated and expelled towards <u>outer</u> Solar System

3. Accretion to planets :-



Some trapped icy material protected from vaporisation

4. Growth of small, low-mass, high-density planets:

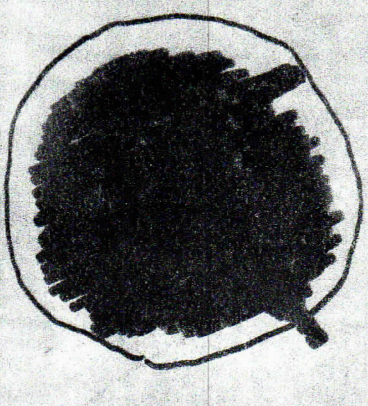


While planet forms (~500 million yrs) Main <u>heating</u> is surface bombardment.

Bombardment decreases with time as debris gets smaller, or accreted elsewhere.

5. Release of heat from radioactivity throughout planet melts interior:

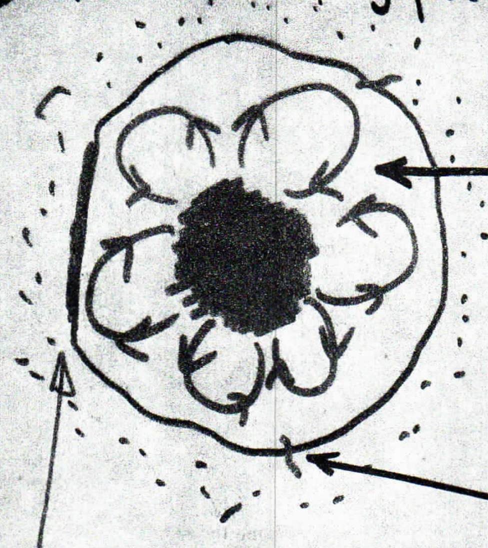
Importance increases with mass of planet



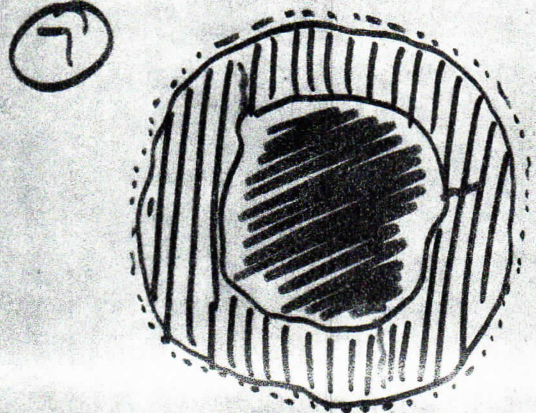
Interior molten rock (magma)
Dissolved ice vapours (gases)

Heaviest elements (Iron) settle to centre. Volcanism through crust. Volcanic gases retainable by final mass → atmosphere.

(6) Gradual cooling from surface



(7)



Quiescent planet – final stage

Final equilibrium atmosphere/oceans

EARTH, VENUS } Most massive inner planets. Longest radioactive-heating period → longest volcanism, densest atmospheres

MOON, MERCURY } Least massive. Shortest volcanism. Least atmospheres.

MARS Intermediate between extremes ?

- Do <u>Details</u> fit this General Picture ?