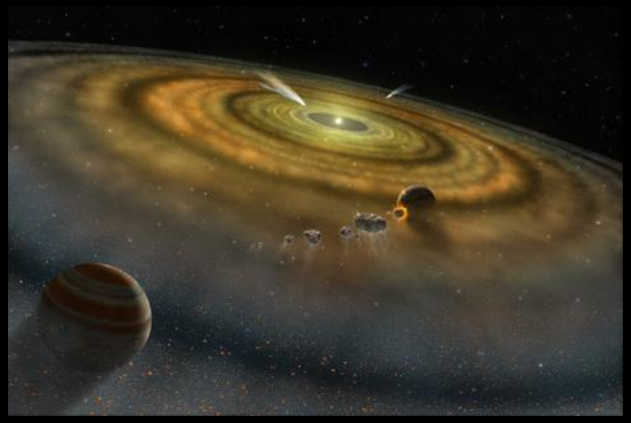
Formation of the Solar System



Q: What must formation theories account for?

• *consider* our ***solar system***

Patterns of Motion

• ***most*** planets have *nearly circular orbits*
• ***most*** planets have ~ *same orbital plane* (***ecliptic***)
• ***most*** planets *rotate* in *same direction* as *they orbit*

Characteristics of Planets

• ***inner planets*** *small, rocky;* lots of *metals*
• ***outer planets*** *large, gaseous;* lots of *volatiles*

• *exceptions* to above are important! ***Why?***

Nebular Theory

• ***4.6 Gy ago***, *our solar system* formed from a *cloud of gas & dust* ***within*** galaxy

• ***nebulae***: *nubes*, L. *"cloud"*

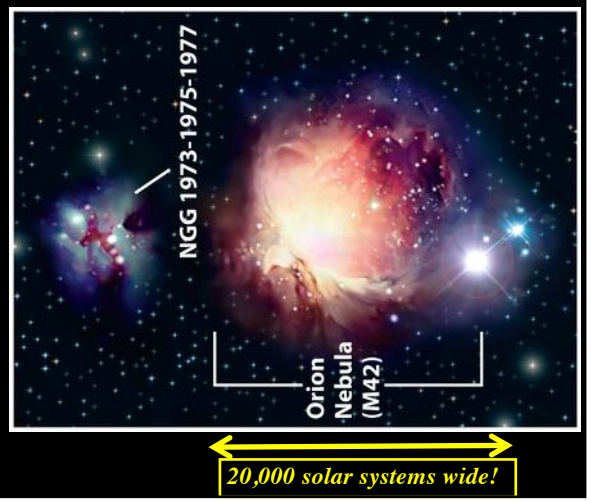
• ***nebulae*** are **mostly** *hydrogen, helium* (***98%+***)

(eg) Great Orion Nebula (M42)

Orion

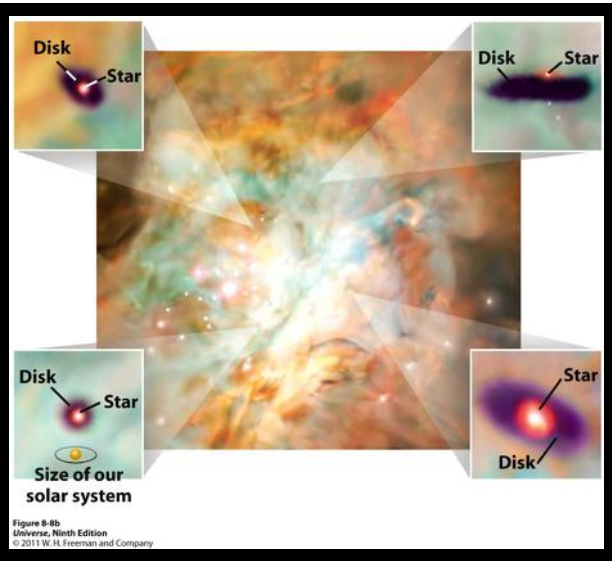
Great Orion Nebula ***M42***

(1500 ly)

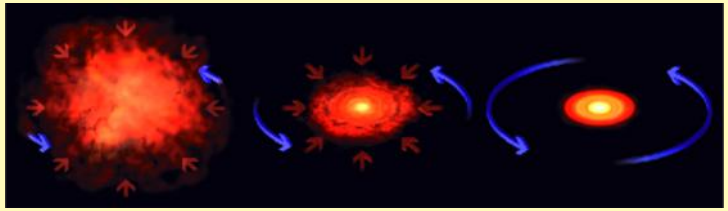


Solar Systems in *M42*

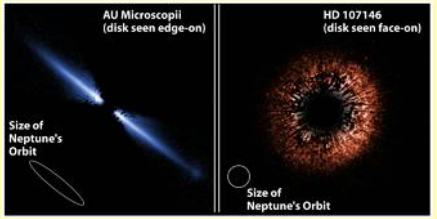
Solar Systems in Orion



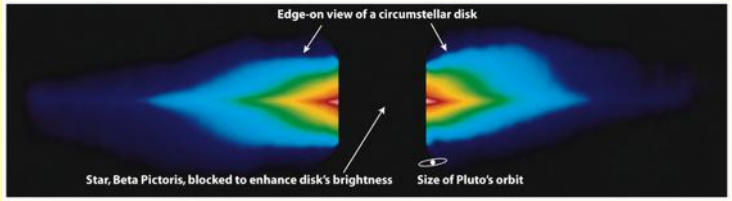
- *portion* of ***nebula*** collapsed ⇒ ***solar nebula***
- *collapse*: due to *shock wave* from ***supernova***?
(*radioactive* ^{26}***Al*** ⇒ ^{26}***Mg*** found in ***Allende*** *meteorite*)
- objects in space have ***rotation***
- as *nebula collapsed* ⇒ rotated *faster*
(eg) *like skater - conservation of angular momentum*
- *flattens* into "pancake-like" ***protoplanetary disk***



- *most mass* ends up at *center* of disk, forms ***star***
- *leftover* material forms ***planets***



(eg) *AU Microscopii (M1V), Beta Pictoris (A5V)*



CLICKER: Why does the solar nebula become flat?

(a) gravity wants to pull the material into a plane

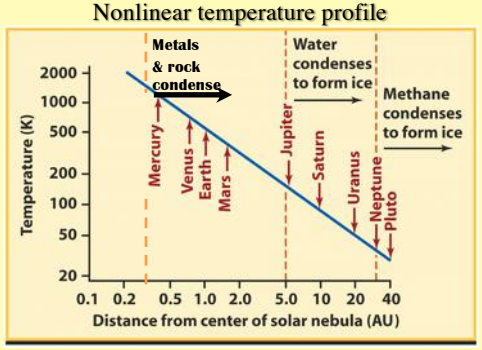
(b) the (increasing) rotation rate

(c) collisions between nebular materials

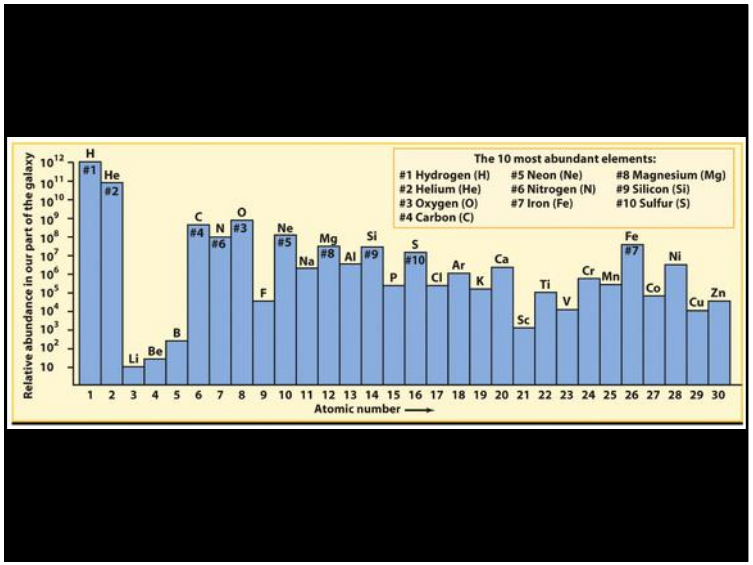
(d) Kepler's 2nd Law requires orbits to be coplanar

Formation of Planets

- ***planets*** form when material *collides* & *sticks together* (***accretion***)
- materials ***condense*** based on ***temperature***

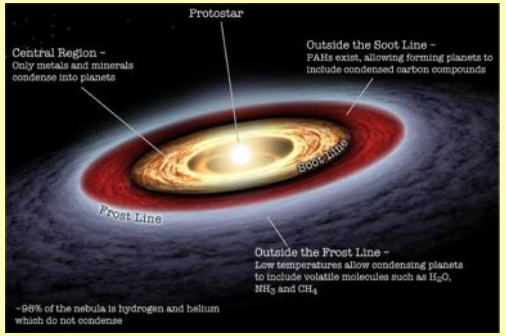


- *rocks, metals* ***condense*** at *high temps (1200+ K)*
- *ices & gas (**volatiles**)* ***condense*** at *low temps*



Frost Line

- *imaginary line* between ***Mars*** & ***Jupiter***
- location beyond which ***volatiles condense*** ~ *150 K*

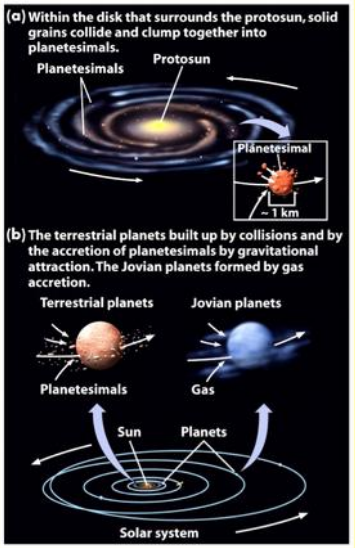


• ***volatiles vaporized inside Frost Line***, leaving mostly *rock & metal*

• ***volatiles*** survived ***beyond Frost Line***

Q: *What result did this have?*

• *more* material further out (*solids **AND** ices*); faster growth, bigger planets



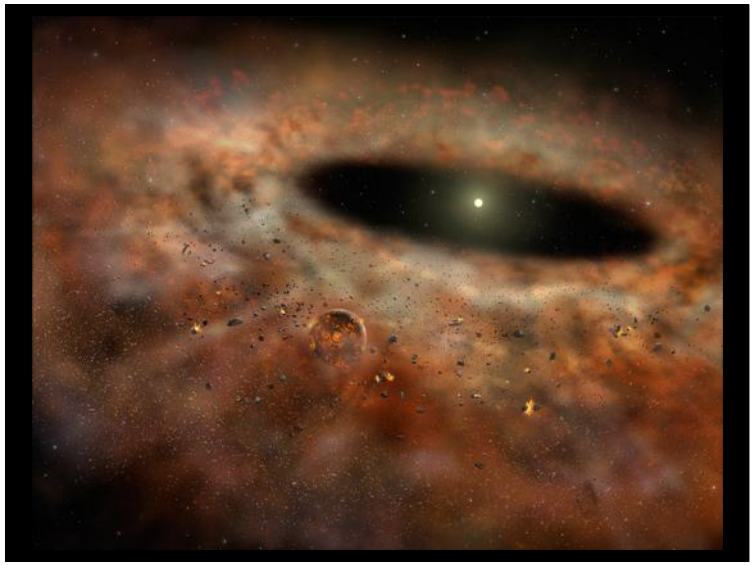
• matter in ***solar nebula*** began to *accrete*

• formed ***planetesimals*** (up to ~*10 km*)
• ***start*** of *planets*
• ***grow*** *over time*

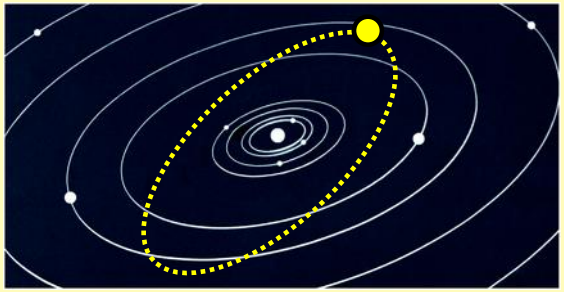
• *attracted* nearby material & *cleared orbits* within disk

• *trillions* of ***planetesimals*** formed: *where did they go?*

• most *collided* & formed ***protoplanets***

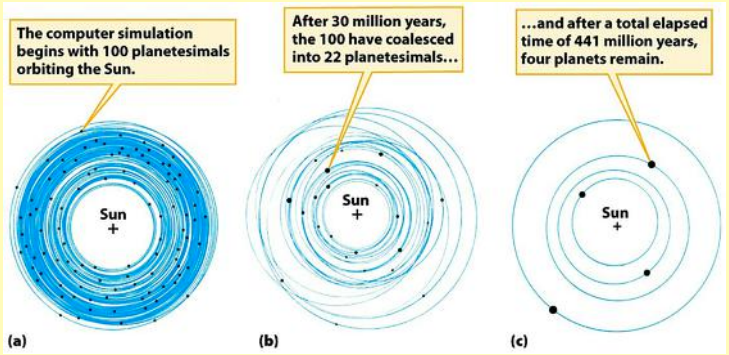


• ***protoplanets*** with nearly *circular orbits* survived to form *planets* - *why?*

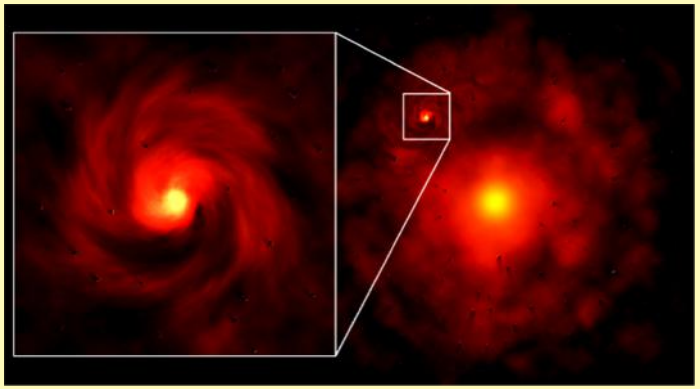


• ***protoplanets*** with highly *elliptical* orbits *cross other orbits more often* & are more *likely* to *collide*

• simulation of evolution of ***100 planetesimals***



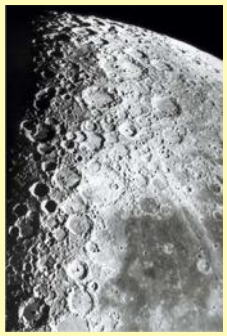
• ***outer planets*** grew ***large*** because of extra material
• many moons - *like* miniature ***solar systems***



• ***outer planets*** likely ***migrated*** orbits

• ***planetesimal***⇒*planet* ***~few hundred million years***
• ***crust*** had to *cool* to become solid

• frequent, major impacts: LHB (***late heavy bombardment period***) ended ~***3.8 Gy*** *ago*

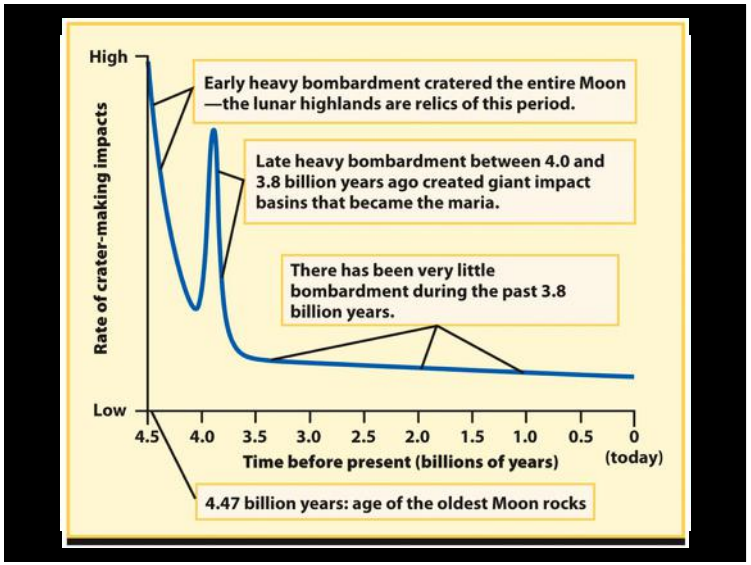


• ***Earth ~ 4.5 Gy*** old

• ***solar system ~ 4.6 Gy*** old

Q: *How do we know?*

• ***radioactive dating*** of *rocks, meteorites*



CLICKER: Nebular Theory is able to explain…

(a) (nearly) common orbital plane of the planets
(b) common direction of orbital motion
(c) variations in size of the planets
(d) variations in composition of the planets
(e) all of the above

Planets (*IAU*, Aug 2006)

- ***planets*** obey the following:
  1) orbit the Sun
  2) spherical (by self-gravity)
  3) dominant in orbit ("cleared" its region)

(eg) *Mercury* through *Neptune*

- ***"dwarf" planets*** obey the above except (3), and may ***not*** be a satellite of another object

(eg) *Pluto, Ceres, Eris (formerly Xena)*

- ***"small solar system bodies"*** are the rest

(eg) *most asteroids, comets, most TNO's*

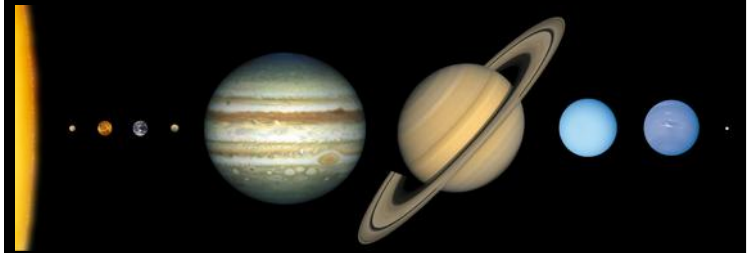
Planetary Groupings

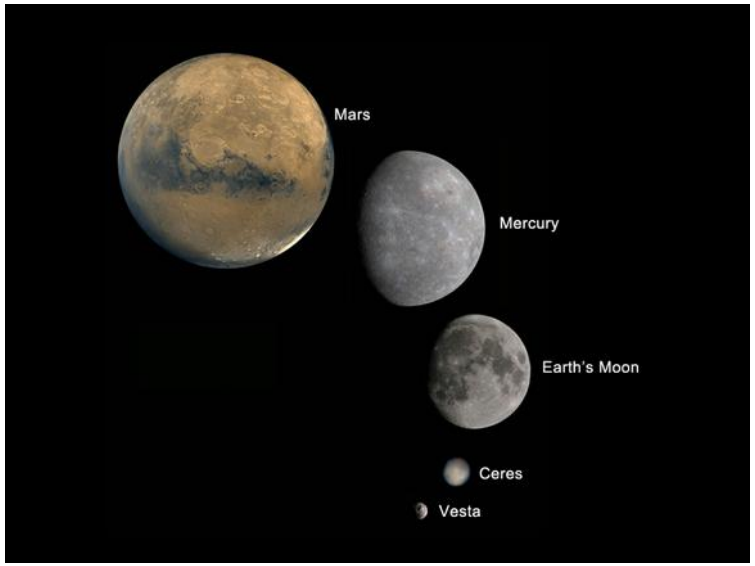
*Inner (**Terrestrial**) planets:* higher density, solid surfaces,small, few or no moons
(eg) *Mercury, Venus, Earth, Mars*

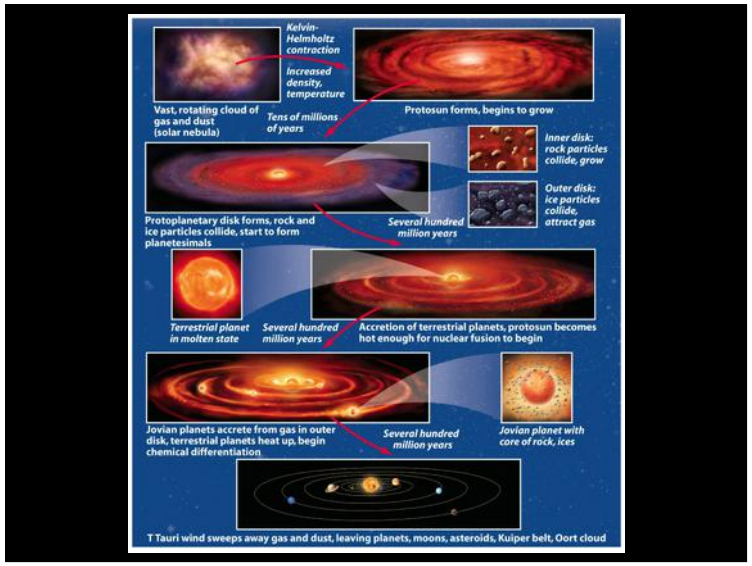
*Outer (**Jovian**) planets*: lower density, gaseous, much larger, lots of moons
(eg) *Jupiter, Saturn, Uranus, Neptune*

"Other": ***(eg)*** *asteroids, comets, Pluto, Eris*

Relative Sizes




Mars
Mercury
Earth's Moon
Ceres
Vesta


Kelvin-Helmholtz contraction
increased density, temperature
Vast, rotating cloud of gas and dust (solar nebula)
Tens of millions of years
Protosun forms, begins to grow
Inner disk: rock particles collide, grow
Outer disk: ice particles collide, attract gas
Protoplanetary disk forms, rock and ice particles collide, start to form planetesimals
Several hundred million years
Terrestrial planet in molten state
Several hundred million years
Accretion of terrestrial planets, protosun becomes hot enough for nuclear fusion to begin
Jovian planets accrete from gas in outer disk, terrestrial planets heat up, begin chemical differentiation
Several hundred million years
Jovian planet with core of rock, ices
T Tauri wind sweeps away gas and dust, leaving planets, moons, asteroids, Kuiper belt, Oort cloud