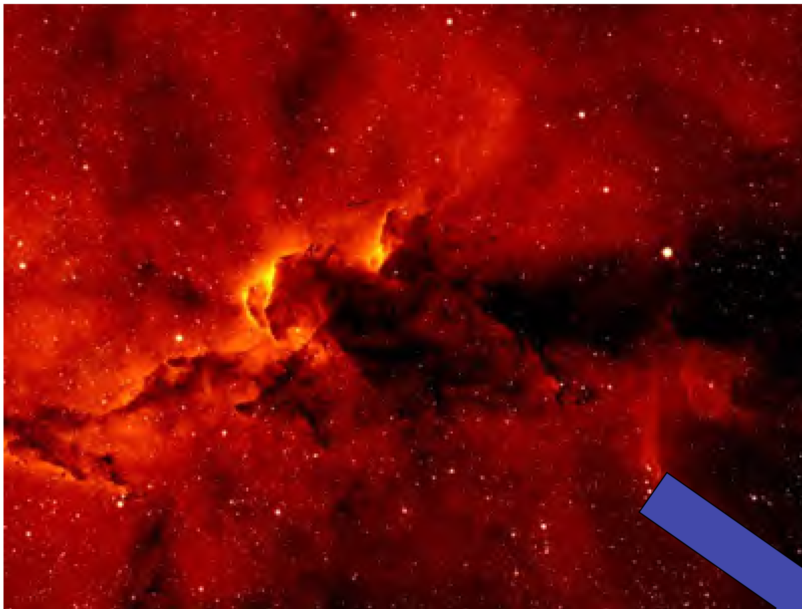


Formation & Habitability of Planets

Fran Bagenal
University of Colorado Boulder

Formation: Sources of Evidence

Star-forming regions

- Chemistry of source material

Our solar system

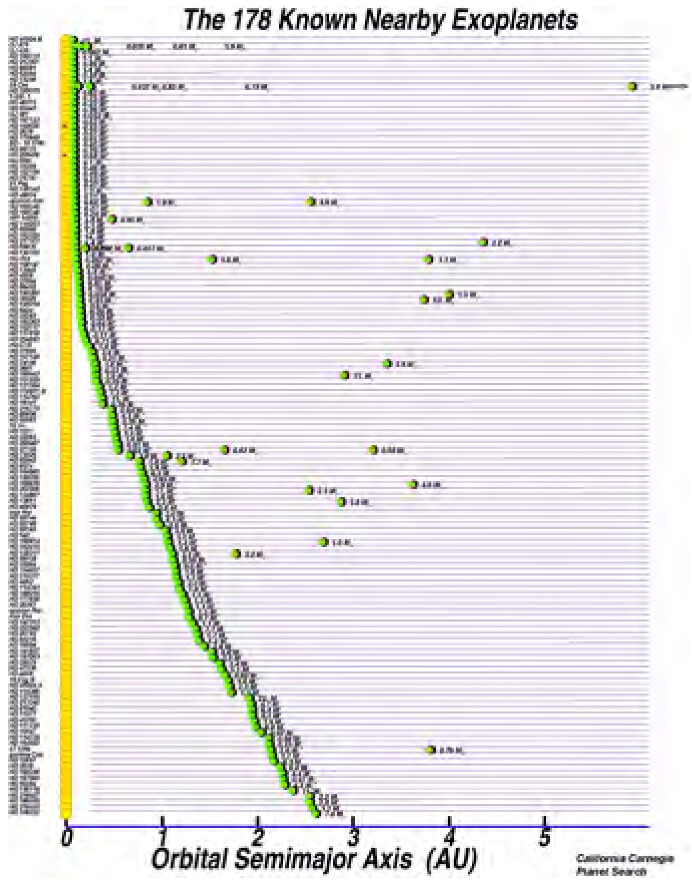
1. Patterns of motions
2. 2 types of planets
3. Asteroids and comets
4. Exceptions

Other solar systems

- Similarities and differences

To Date
- 454 planets

- 53 systems with 3 or more planets



http://exoplanets.org/table/

Collapse of the Solar Nebula

- Formation of the Sun seems a good place to start.
- Theories of star formation are based on observing millions of stars of different ages.
- Start with a **nebula** of gas and dust.

  - ***Nebula = noun = "cloud" (plural = nebulae)***
  - ***Nebular = adjective = "cloud-like"***

Section could have been called
Collapse of Nebular Solar Nebula.

How Big Was Solar Nebula?

- ~1% efficiency (guess)
- start with ~100 Mass of Sun = 10^{32} kg
- If Temperature of cloud ~1000K
  - density ~ 10^{-12} kg m^{-3}
  - R~2,500 AU
- If Temperature of cloud ~10K
  - density ~ 10^{-18} kg m^{-3}
  - R~250,000 AU

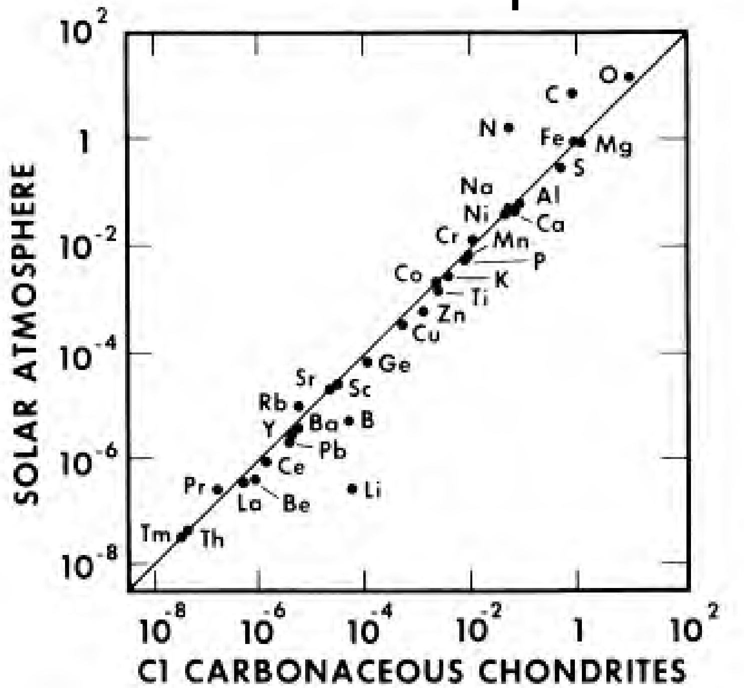
What was the solar nebular made of?

Cosmic Abundances of Elements

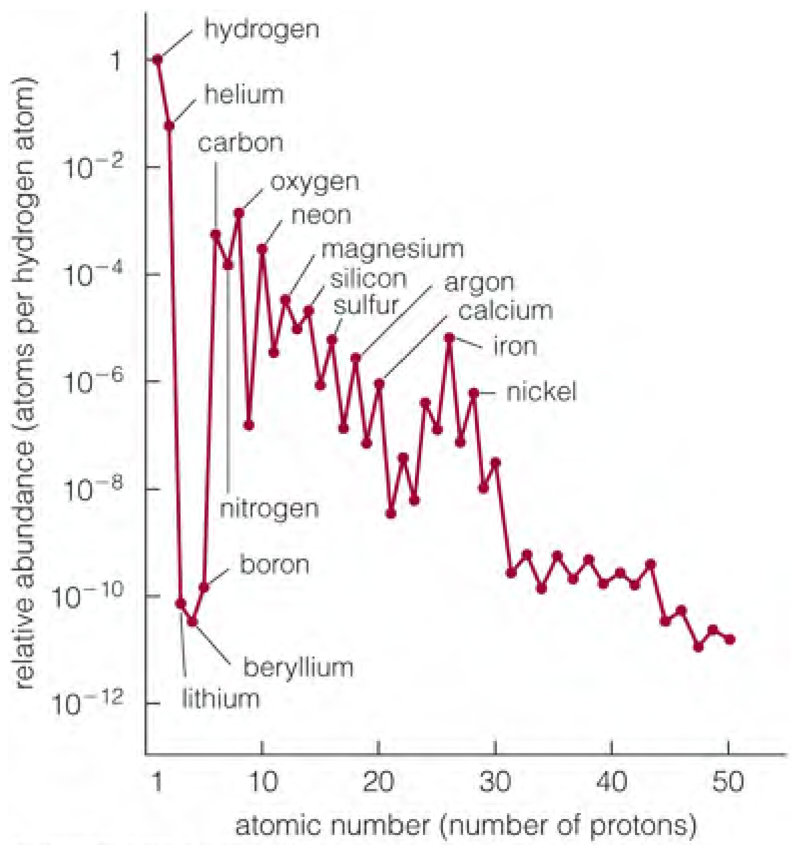
Element	Symbol	Atomic #	Relative Abundance
Hydrogen	H	1	1,000,000
Helium	He	2	80,000
Carbon	C	6	420
Nitrogen	N	7	87
Oxygen	O	8	690
Neon	Ne	10	130
Sodium	Na	11	2
Magnesium	Mg	12	32
Aluminum	Al	13	3
Silicon	Si	14	45
Sulfur	S	16	16
Argon	Ar	18	1
Calcium	Ca	20	2
Iron	Fe	26	32
Nickel	Ni	28	2

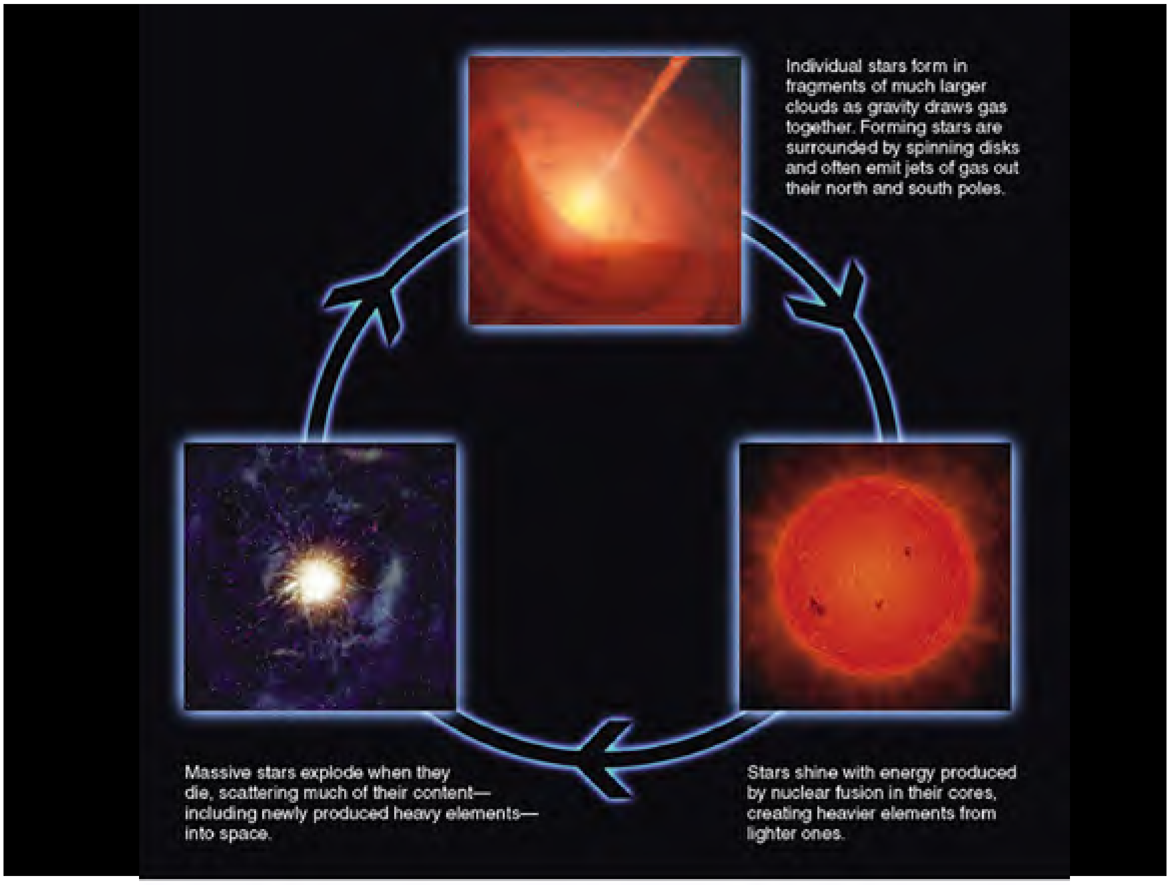
Meteorites vs. Solar Photosphere

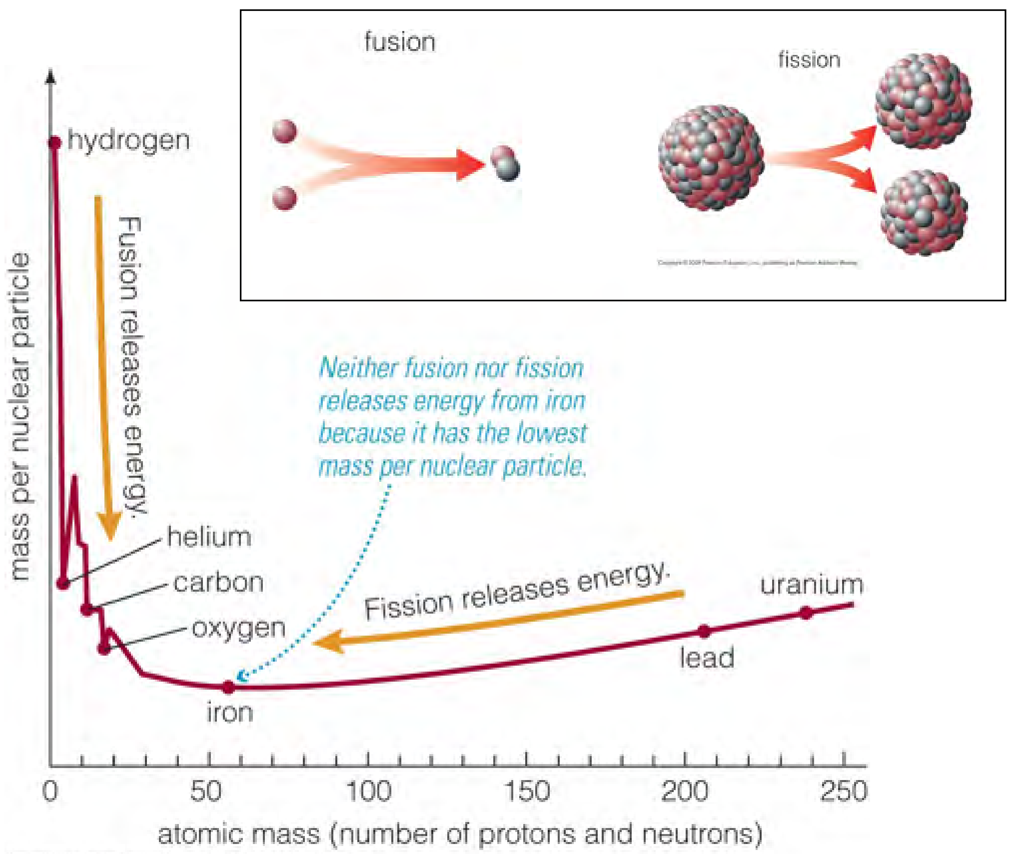
- Note the striking similarity between meteoritic and photospheric compositions
- Normally gaseous elements (N,C,O) are enriched in photosphere relative to meteorites
- We can use this information to obtain a best-guess nebular composition



Basaltic Volcanism Terrestrial Planets, 1981




Individual stars form in fragments of much larger clouds as gravity draws gas together. Forming stars are surrounded by spinning disks and often emit jets of gas out their north and south poles.
Stars shine with energy produced by nuclear fusion in their cores, creating heavier elements from lighter ones.
Massive stars explode when they die, scattering much of their content—including newly produced heavy elements—into space.


fusion
fission
hydrogen
Fusion releases energy.
Neither fusion nor fission releases energy from iron because it has the lowest mass per nuclear particle.
helium
carbon
oxygen
iron
Fission releases energy.
uranium
lead
mass per nuclear particle
0
50
100
150
200
250
atomic mass (number of protons and neutrons)
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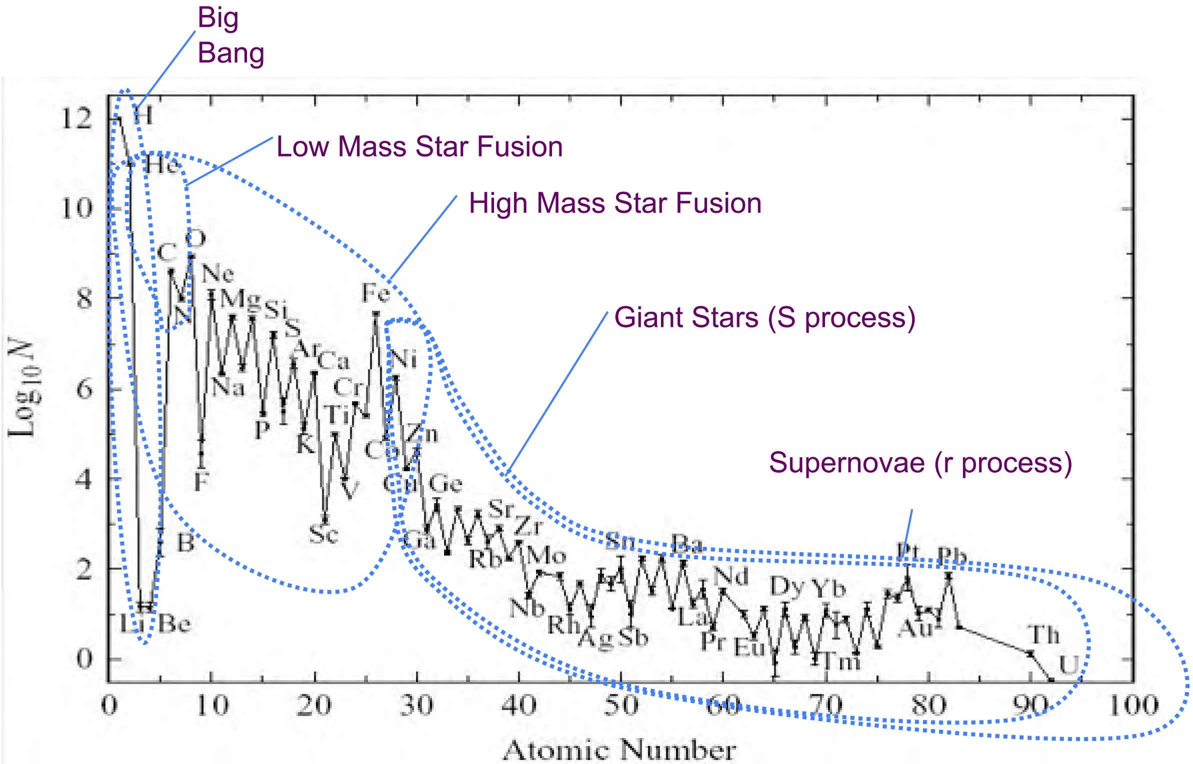


Galactic Recycling

- Many fusion products remain locked up in “stellar corpses”
- Stellar winds and explosions are the main ways fusion products escape
- Escaping gases mix in giant molecular clouds, enriching them in heavy elements (“metals”)
- More stars (and solar systems?) are born…
- …and die, continuing the recycling and enrichment

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
Condens. Temp (K)	180	--	78	120	--	--	1340	1529	674	40	1337

- Blue are volatile (easy to vaporize), red are refractory (hard to vaporize)
- Most important refractory elements are Mg, Si, Fe, S

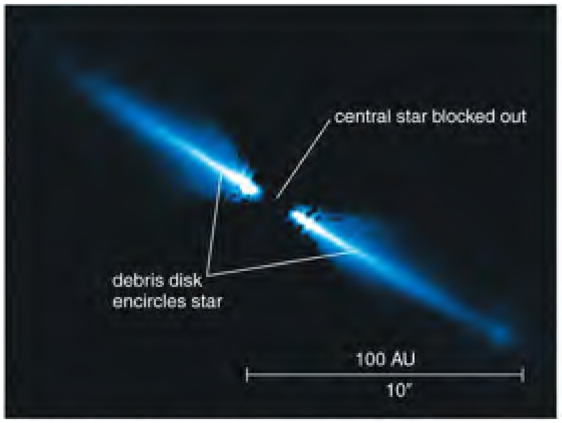
Data from Lodders and Fegley, *Planetary Scientist's Companion*, CUP, 1998
This is for all elements with relative abundances > 10^5 atoms.

TABLE 2.6.1. Interstellar molecules.

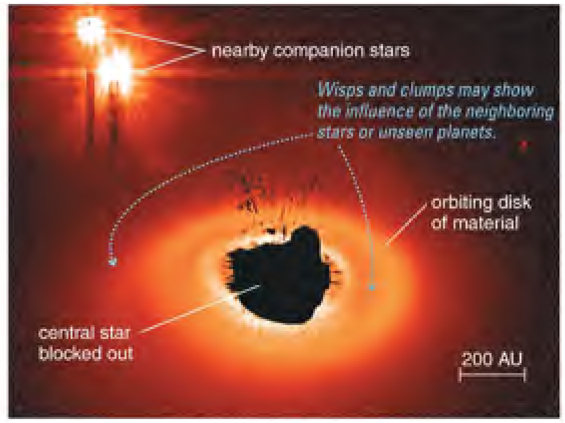
Simple Hydrides, Oxides, Sulfides, Halides, and Related Molecules				
H_2	CO	NH_3	CS	NaCl
HCl	SiO	SiH_4	SiS	AlCl
H_2O	SO_2	CC	H_2S	KCl
	OCS	CH_4	PN	AlF
Nitriles, Acetylene Derivatives, and Related Molecules				
HCN	$HC\equiv C-CN$	$H_3C-C\equiv C-CN$	H_3C-CH_2-CN	$H_2C=CH_2$
H_3CCN	$H(C\equiv C)_2-CN$	$H_3C-C\equiv CH$	$H_2C=CH-CN$	$HC\equiv CH$
CCCO	$H(C\equiv C)_3-CN$	$H_3C-(C\equiv C)_2-H$	HNC	
CCCS	$H(C\equiv C)_4-CN$		$HN=C=O$	
$HC\equiv CCHO$	$H(C\equiv C)_5-CN$		$HN=C=S$	
H_3CNC				
Aldehydes, Alcohols, Ethers, Ketones, Amides, and Related Molecules				
$H_2C=O$	H_3COH	$HO-CH=O$	H_2CNH	
$H_2C=S$	H_3C-CH_2-OH	$H_3C-O-CH=O$	H_3CNH_2	
$H_3C-CH=O$	H_3CSH	$H_3C-O-CH_3$	H_2NCN	
$NH_2-CH=O$	$(CH_3)_2CO$?	$H_2C=C=O$		
Cyclic Molecules				
C_3H_2	SiC_2	C_3H		
Ions				
CH^+	HCO^+	$HCNH^+$		
HN_2^+	$HOCO^+$	SO^+		
	HCS^+			
Radicals				
OH	C_3H	CN	HCO	C_2S
CH	C_4H	C_3N	NO	NS
C_2H	C_5H	H_2CCN	SO	
	C_6H			

Data from Irvine W. M. and Knacke R. F. (1989) in *Origin and Evolution of Planetary and Satellite Atmospheres* (S. Atreya p. 5, Fig. 1, Univ. of Arizona, Tucson.

Images of Protoplanetary Disks



a We see this disk edge-on around the star AU Microscopii, confirming its flattened shape.

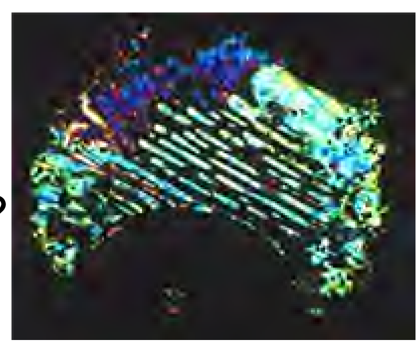


b This photo shows a disk around the star HD141569A. The colors are not real; a black-and-white image has been tinted red to bring out faint detail.

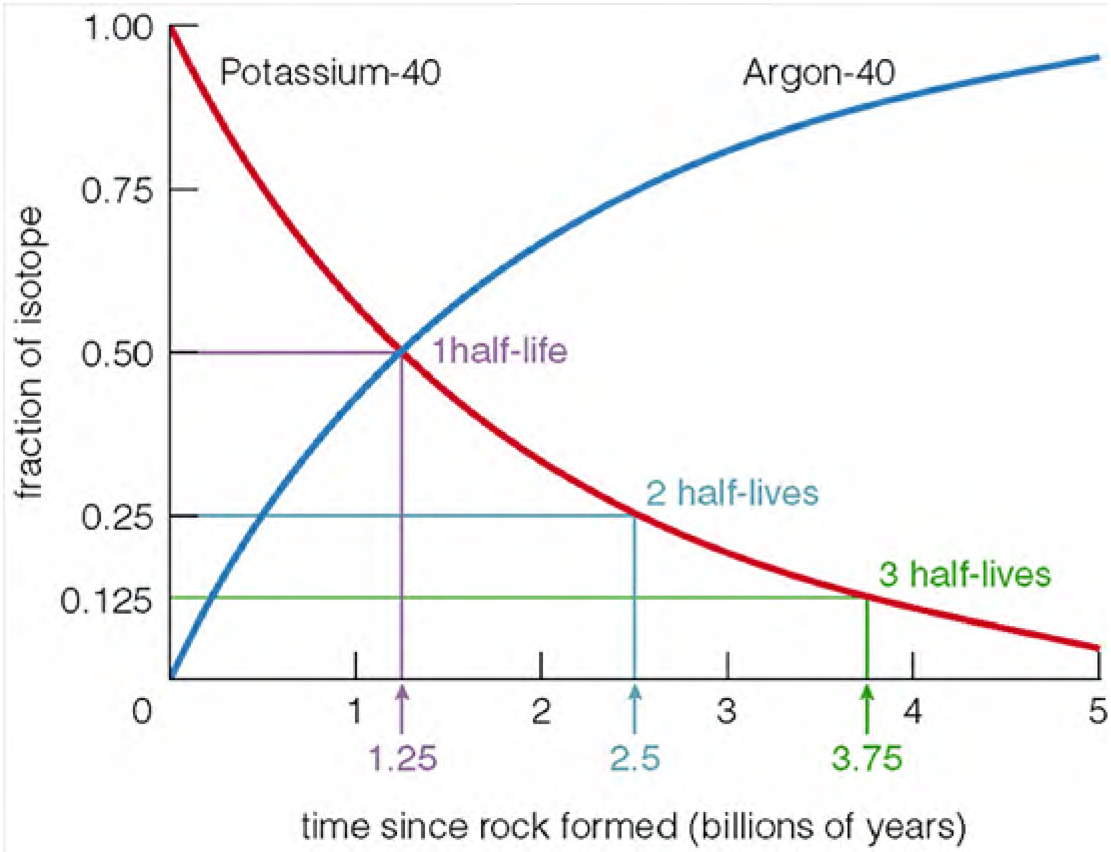
We can now watch solar systems being formed...

Oldest Meteorite

Allende - fell to Earth near Chihuahua, Mexico at 1:05am on February 8, 1969. Age: 4.5 BY old



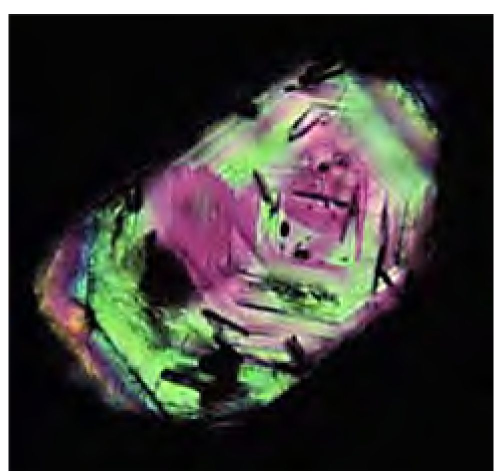
How do we know it's that old?



Oldest Rocks

The best age for the Earth (4.54 Ga) is based on Pb (lead) ratios in troilite from iron meteorites, specifically the Canyon Diablo meteorite.

Mineral grains (zircon) with U-Pb ages of 4.4 Ga have recently been reported from sedimentary rocks in west-central Australia.



Oldest Rocks

- The oldest dated lunar rocks have ages between 4.4 and 4.5 billion years and provide a minimum age for the formation of Moon
- The meteorites, and therefore the Solar System, formed between 4.53 and 4.58 billion years ago
- http://pubs.usgs.gov/gip/geotime/radiometric.html#table

4.54 BY to <1% accuracy

Collapse of the Solar Nebula

Collapse Spin-up Form Disk

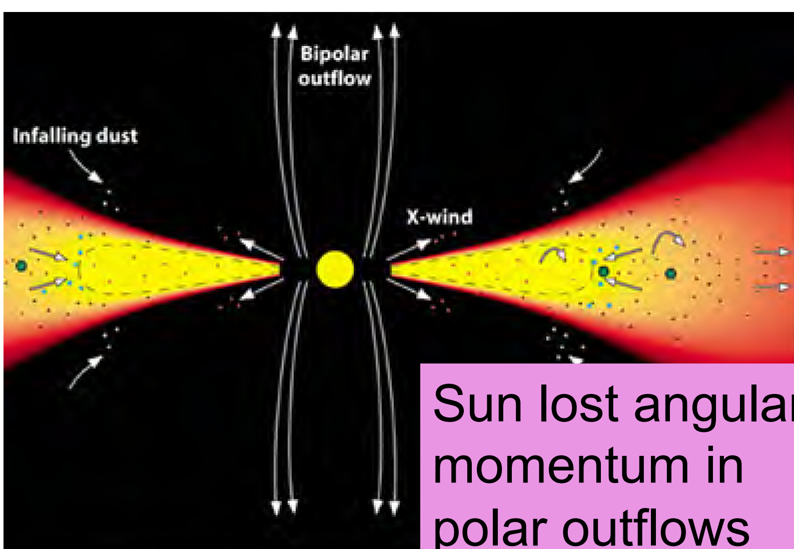
Spin up: Conservation of Angular Momentum MVR = Constant

Where did the angular momentum come from???

Small random motions averaging out to a tiny bulk motion

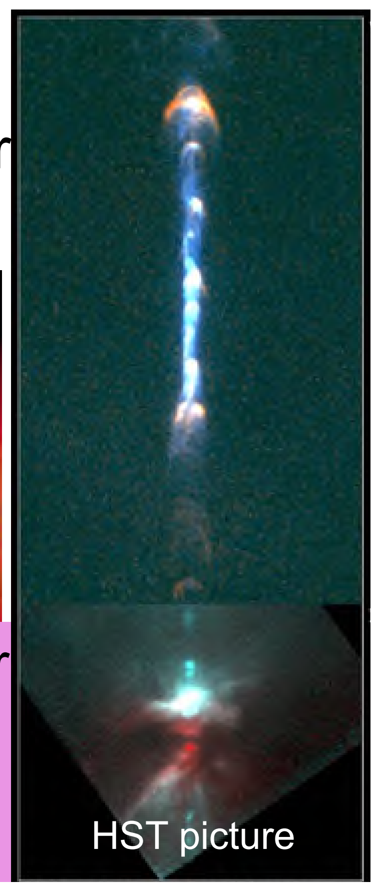
- this bulk motion is then “amplified” (due to conservation of angular momentum) as the cloud collapses

Spin Period of Sun ~ 26 days
What happened to the angular momentum?



(PSRD graphic by Nancy Hulbirt, based on a concept

Sun lost angular momentum in polar outflows


HST picture

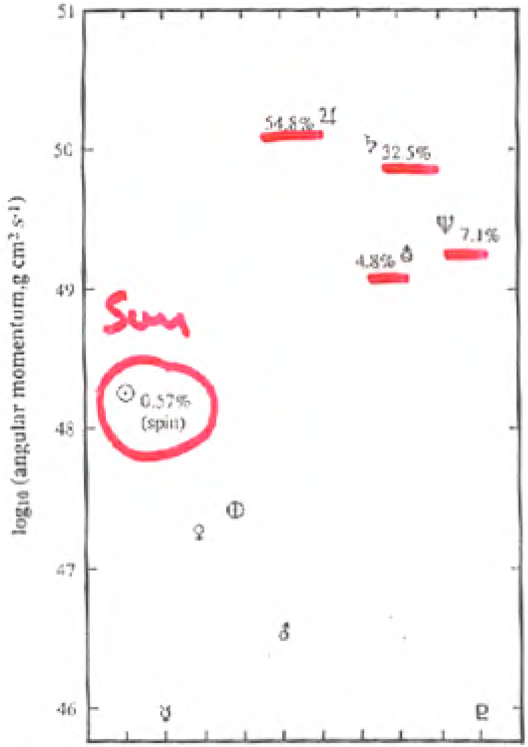
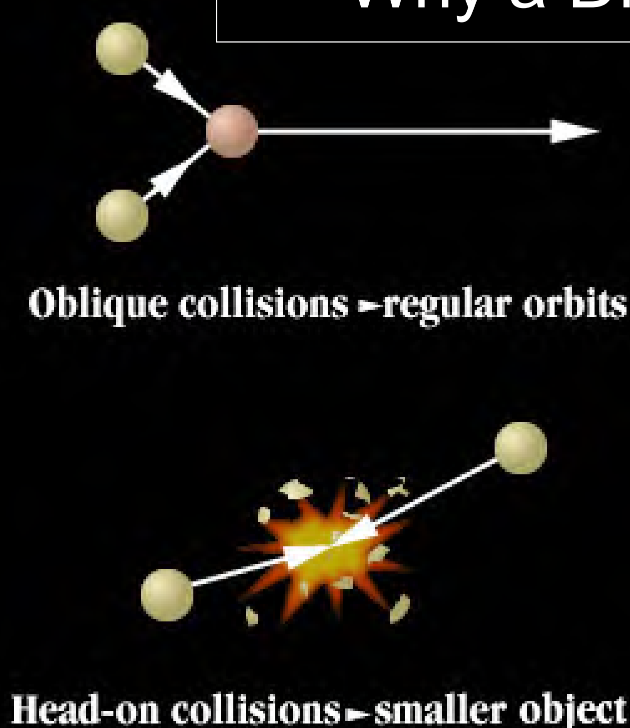


Figure III.7 Orbital angular momenta of the planets. Note the overwhelming importance of the Jovian planets.

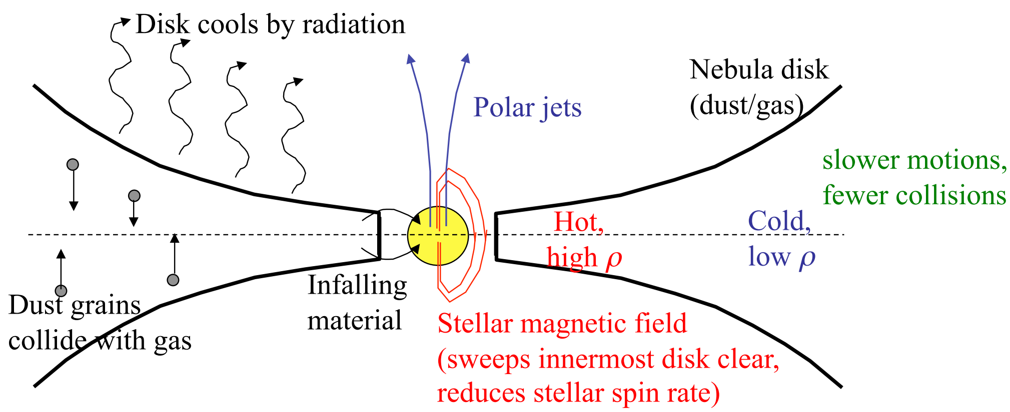
Sun lost most angular momentum - Most left in *orbital* momentum of Jupiter (& Saturn)

Why a Disk?

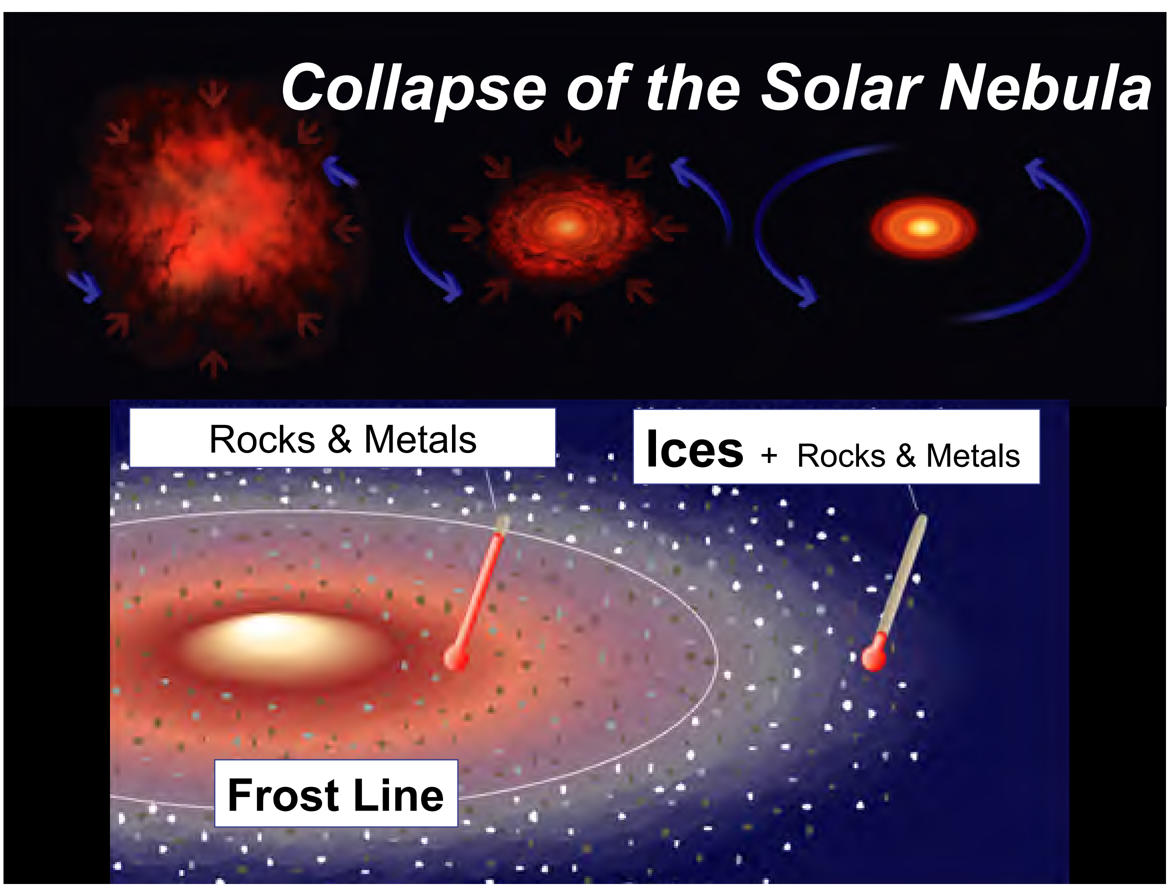


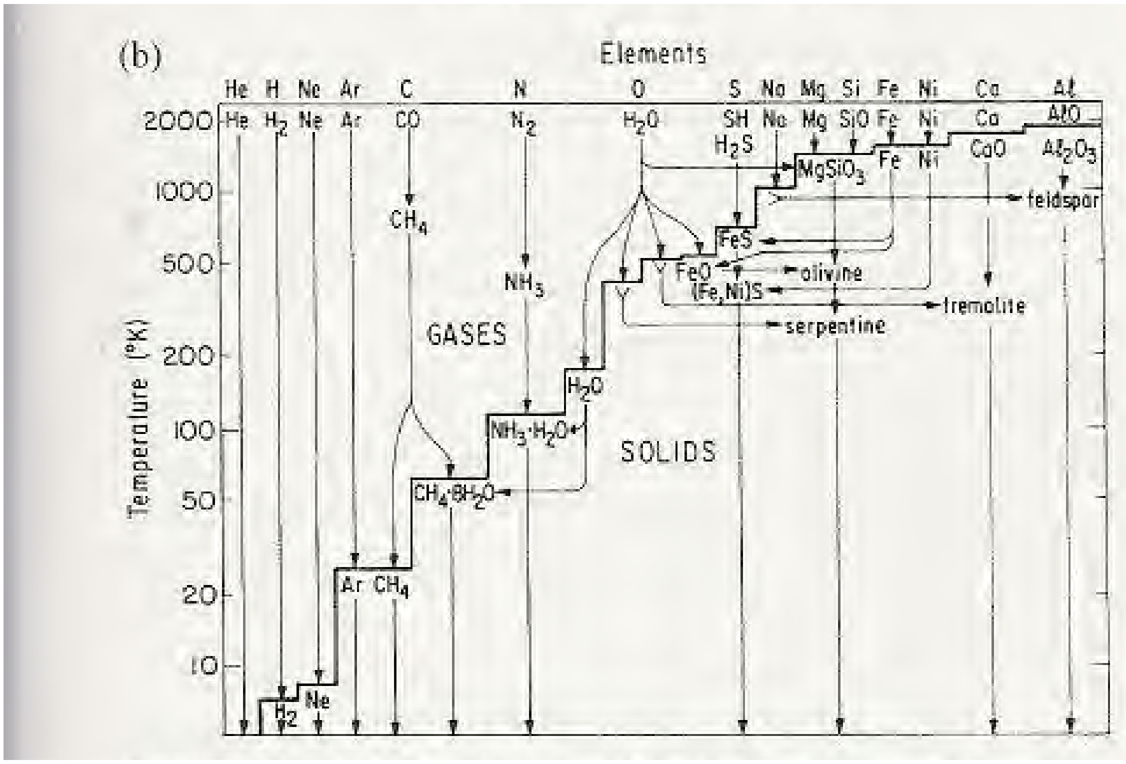
- As the cloud collapses (due to gravity) the gases, dust and stuff orbit the central mass.
- On the timescale of an orbit, gravity still balances the centrifugal force.
- The disk is not formed by being “flung out into a disk”.
- Nor does gravity of the disk “pull the material down onto a disk”.
- These are common misconceptions.

Cartoon of Nebular Processes



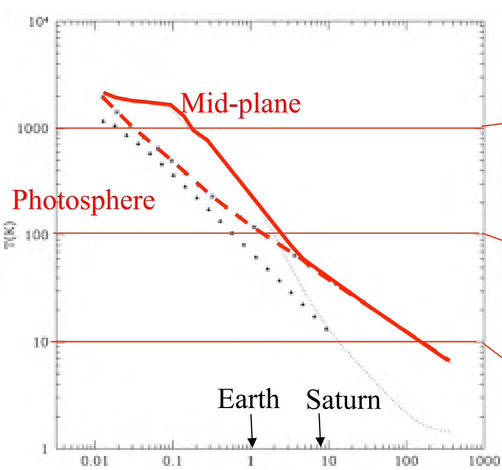
- Scale height increases radially
- Temperatures decrease radially – consequence of lower irradiation, and lower surface density and optical depth leading to more efficient cooling



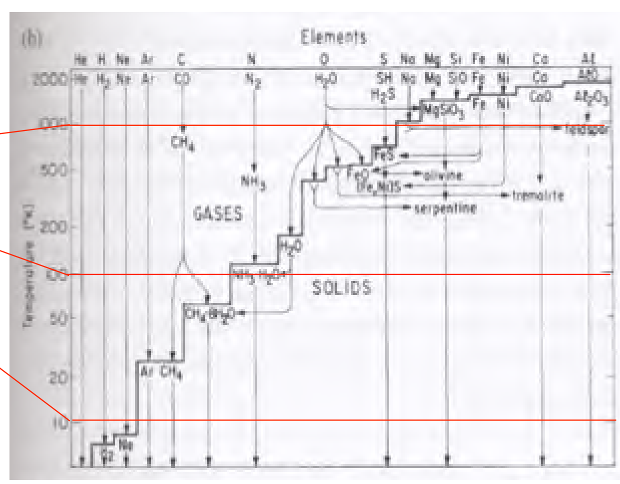


Temperature and Condensation

Nebular conditions can be used to predict what components of the solar nebula will be present as gases or solids:



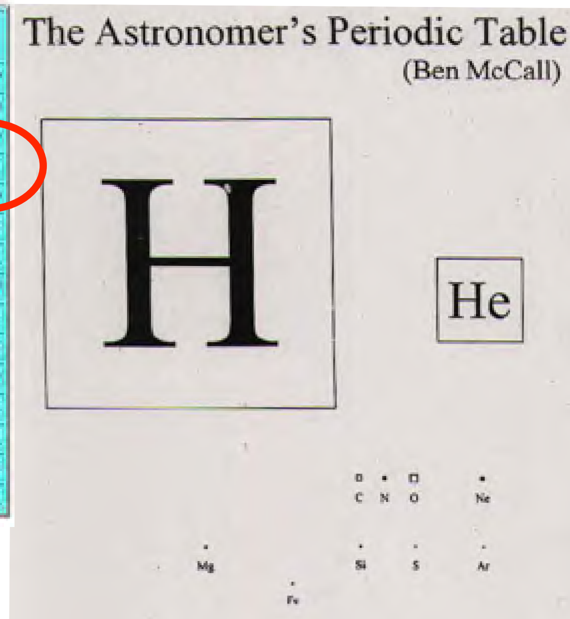
Temperature profiles in a young (T Tauri) stellar nebula, D'Alessio et al., *A.J.* 1998



Condensation behaviour of most abundant elements of solar nebula e.g. C is stable as CO above 1000K, CH_4 above 60K, and then condenses to $CH_4.6H_2O$. From Lissauer and DePater, *Planetary Sciences*

The Cosmic Abundance of Elements

Element	Symbol	Atomic Number	Number of Atoms per Million Hydrogen Atoms
Hydrogen	H	1	1,000,000
Helium	He	2	68,000
Carbon	C	6	420
Nitrogen	N	7	87
Oxygen	O	8	690
Neon	Ne	10	98
Sodium	Na	11	2
Magnesium	Mg	12	40
Aluminum	Al	13	3
Silicon	Si	14	38
Sulfur	S	16	19
Argon	Ar	18	4
Calcium	Ca	20	2
Iron	Fe	26	34
Nickel	Ni	28	2



H_2O NH_3 CH_4

Water, **A**mmonia, **M**ethane

CO_2 CO N_2

Ignore inert gases
He, Ne, Ar

Minimum Mass Solar Nebula

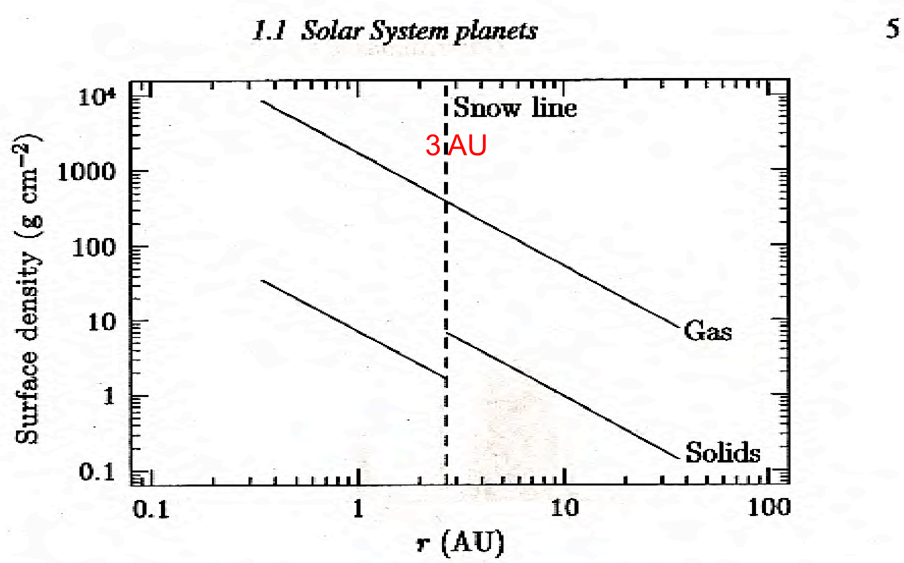
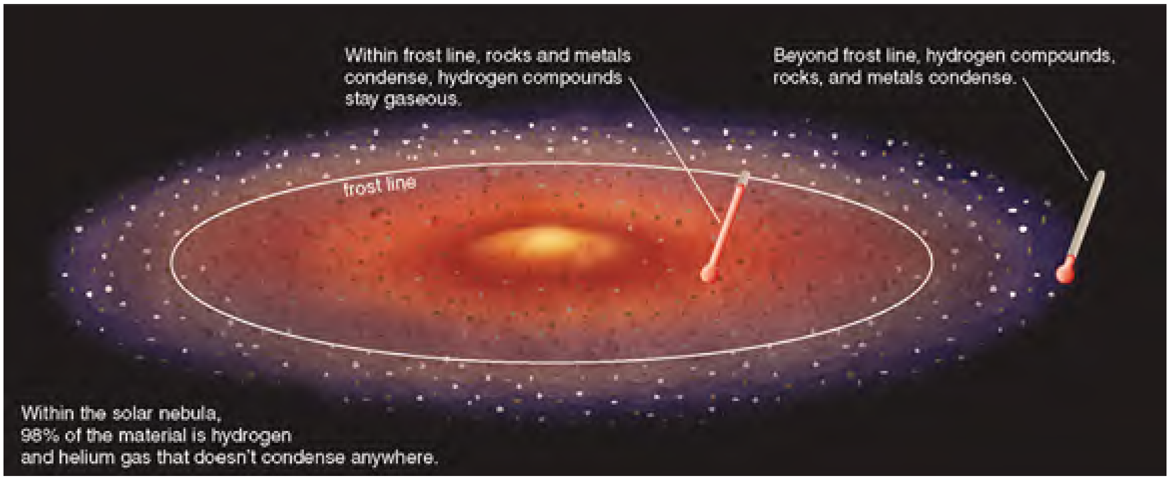
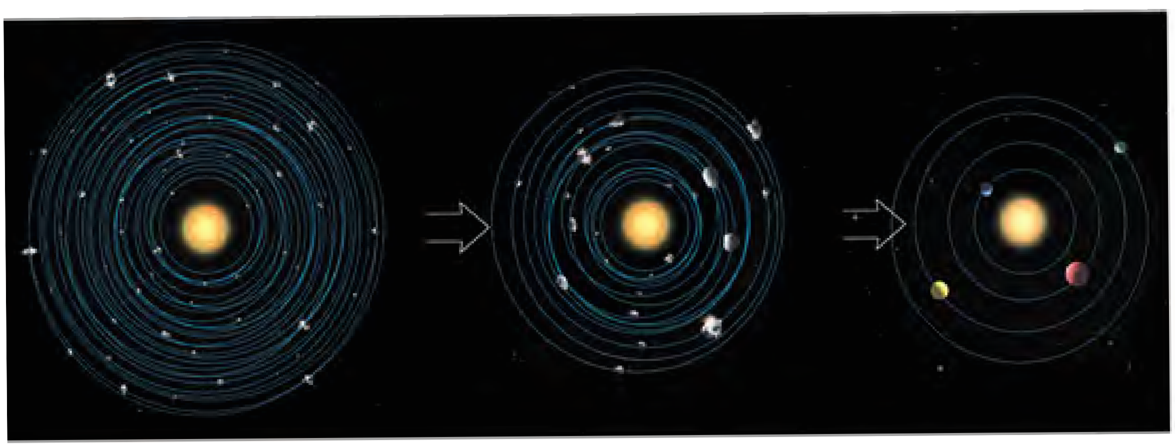


Fig. 1.1. The surface density in gas (upper line) and solids (lower broken line) as a function of radius in Hayashi's minimum mass Solar Nebula. The dashed vertical line denotes the location of the snow line.



• 98% of material - hydrogen & helium - does not condense.
• Inside frostline only refractory materials condense - rocks & metals
• Outside frostline volatiles also condense - WAM - AND rocks & metals too.

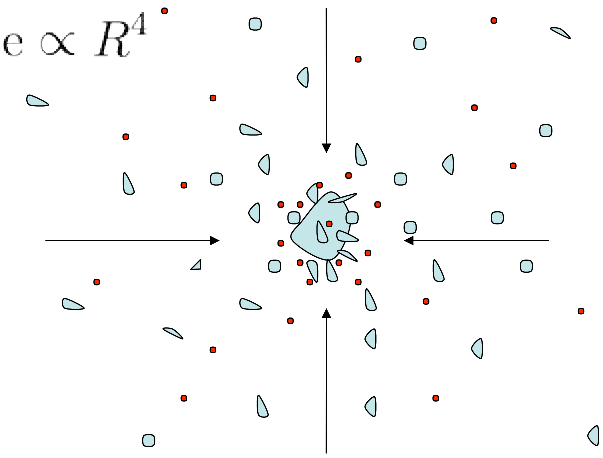


Planetesimals

- ***Oligarchic growth*** - the bigger get bigger
- Beyond the frost line – snowballs snowball....
- REALLY big (icy) planetesimals (~20 Rearth) gravitationally pull in hydrogen - the most abundant gas - and become GIANT.

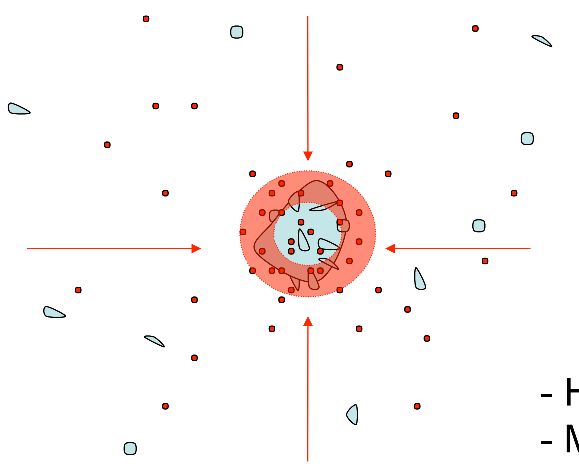
Stage 1: runaway accretion of solids

$$\text{Growth Rate} \propto R^4$$



- Lasts ~ 10^6 years or less near 5 AU
- Can produce 10 M_{Earth} cores
- Requires disk densities 2-3 times higher than that predicted by minimum mass solar nebula

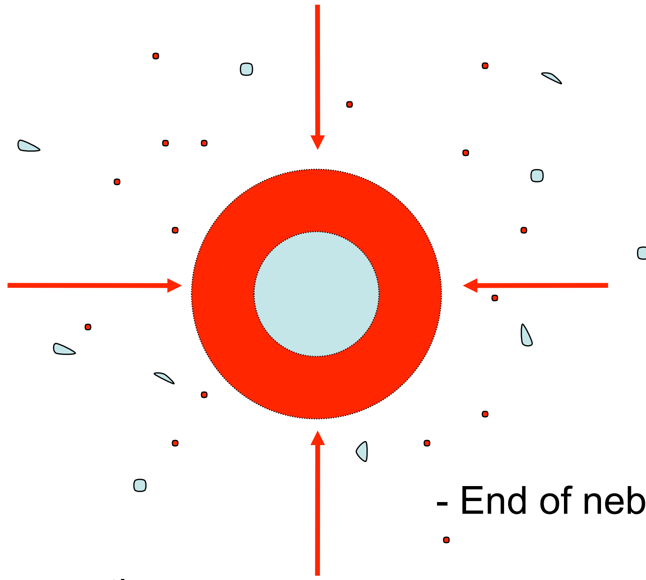
Stage 2: steady gas infall



- Heating
- $M_{core} > M_{envelope}$

• Controlled by balance of radiative cooling and heating from contraction and planetesimal accretion
• Continues as long as planetary envelope is in contact with protosolar nebula

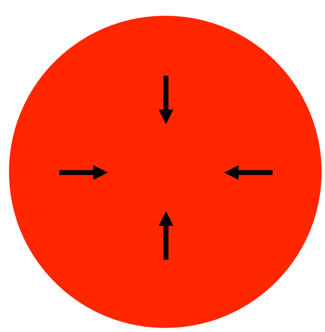
Stage 3: runaway gas infall



- End of nebular phase

Runaway gas accretion occurs when $M_{\mathrm{envelope}} \cong M_{\mathrm{core}}$

Stage 4: 'Isolation' phase

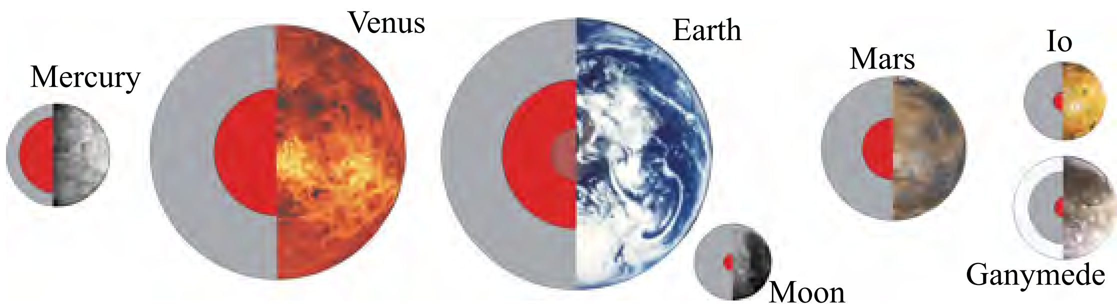


- Planet continues to contract and cool

Why Only ~~2~~ 3 Types of Planets?

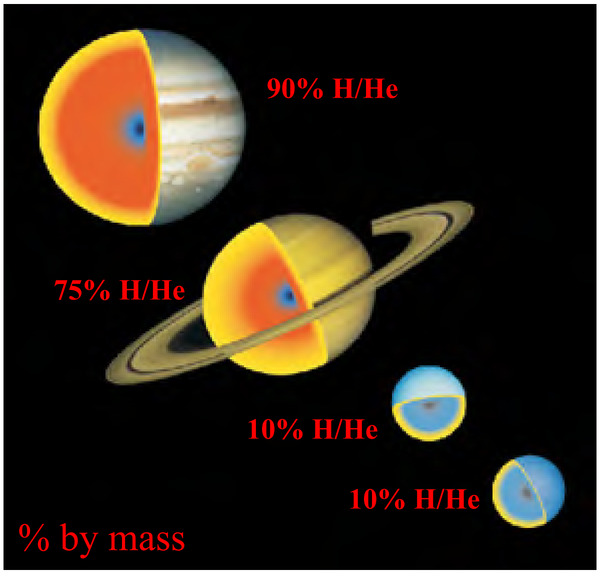
1. Cosmic Abundance of Elements
2. Temperature Colder Farther from Sun
   - Abundance ices condense beyond frost line
   - Snowballs -> bigger snowballs
   - Giant snowballs have enough gravity to hold H - most abundant element - > giant planets
   - Small amounts of rock & metal-> terrestrial planets
   - Ice dwarf planets, comets, asteroids = leftovers

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 Giant Planets

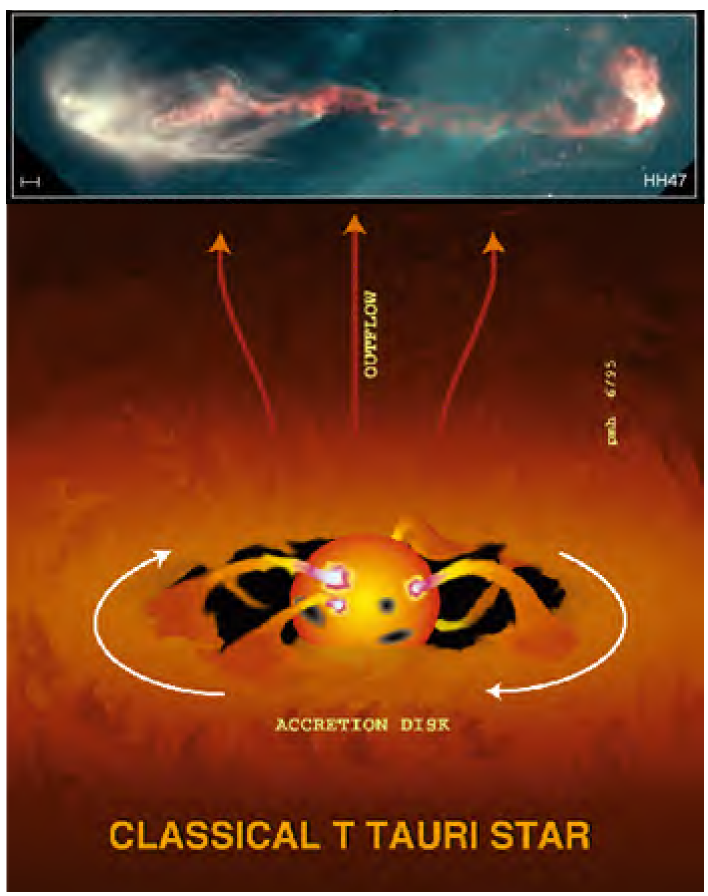


- Jupiter and Saturn consist mainly of He/H with a rock-ice core of ~10 Earth masses
- Their cores grew fast enough that they captured the nebular gas before it was blown off
- Uranus and Neptune are primarily ices (CH_4,H_2O,NH_3 etc.) covered with a thick He/H atmosphere
- Their cores grew more slowly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

Figure from Guillot, *Physics Today*, (2004). Sizes are to scale. Yellow is molecular hydrogen, red is metallic hydrogen, hydrogen compounds are blue, rock is grey.

But there's still **gas** between planets

- •What happens to the gas?
- •Young stars go through phase of v. strong solar wind
- •blows away gas



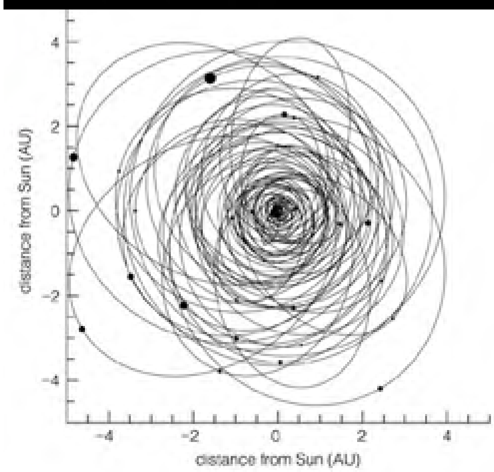
Phases of SS Formation

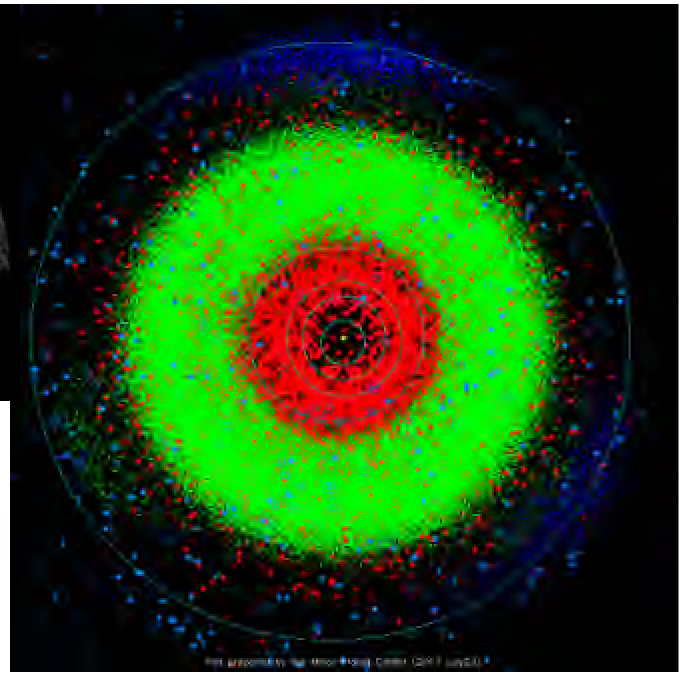
- Dense cloud collapse (0.1-0.5My)
- Disk dissipation (material falls onto disk & is transported onto Sun) (0.05 My)
- Protosun becomes a T Tauri star; accretion begins (1-2My)
- Nebular gas loss by T Tauri winds (3-30My)

But there's still **junk** between planets

What happens to the junk?

- Gets kicked about - mostly by JSUN
- Kicked out of solar system
- Herded - asteroid belt, Kuiper Belt
- Captured as moons
- Bashed into young planets -> Moon, Charon, others?
- Delivers water (+other volatiles) to Earth



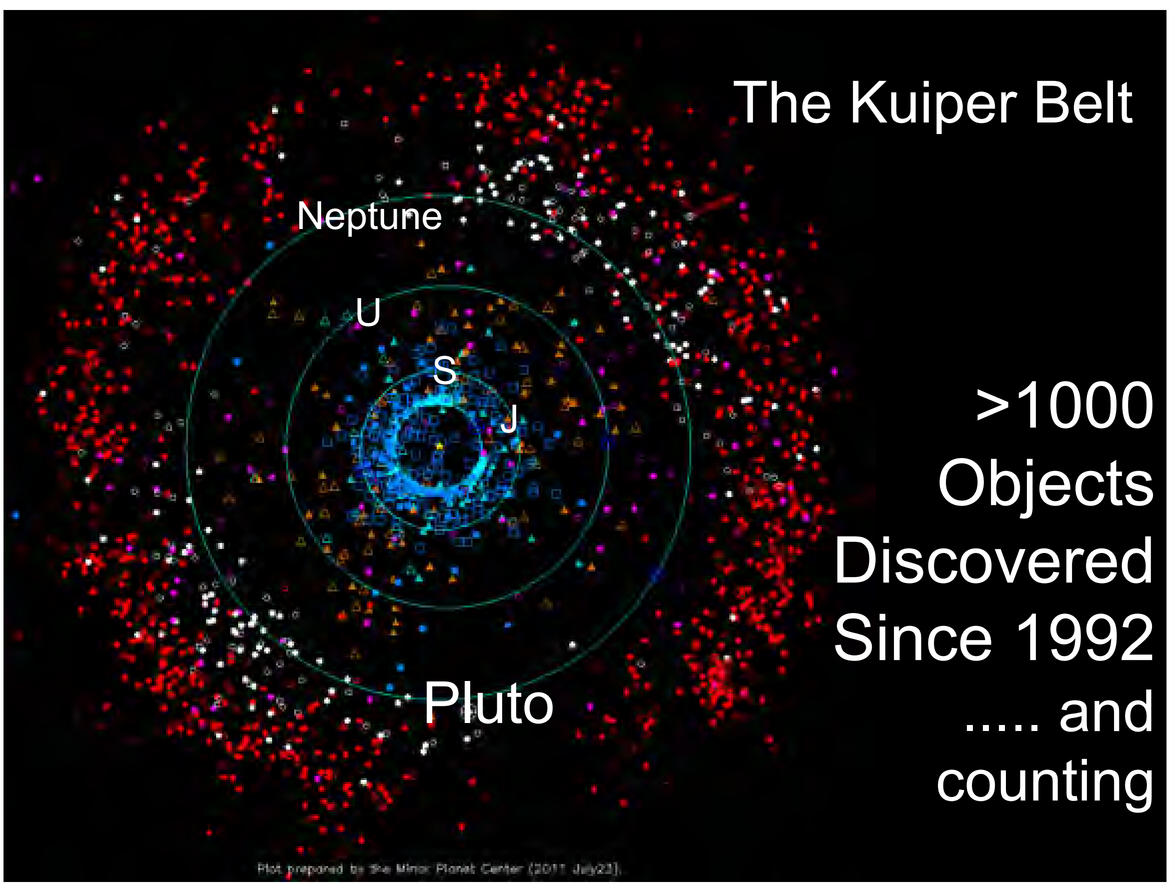


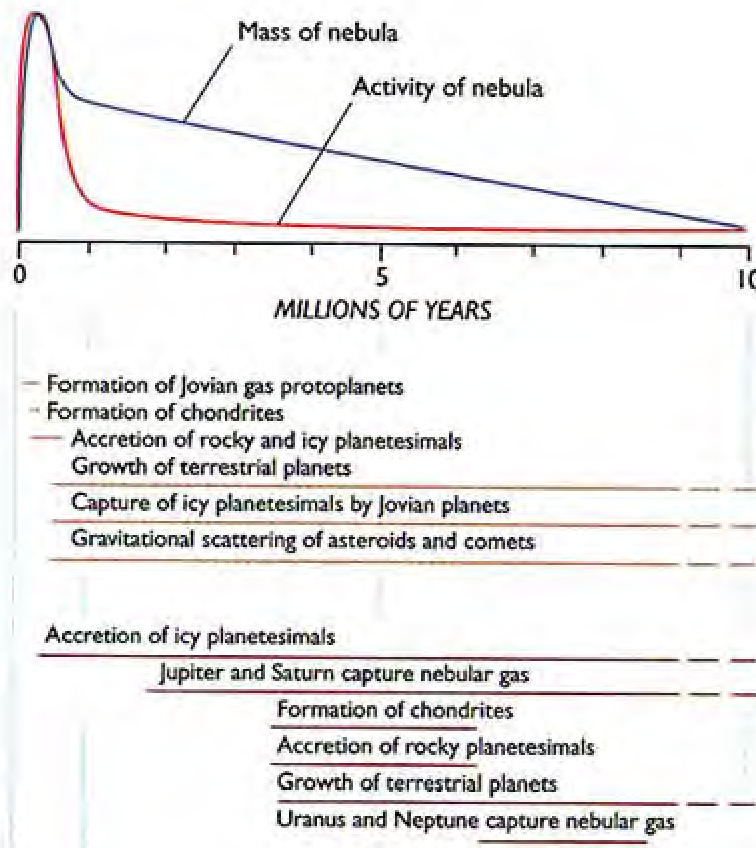
100s of thousands of asteroids

100s Near Earth Objects

100s Trojans ± 60° of Jupiter

http://www.minorplanetcenter.net/iau/lists/InnerPlot.html





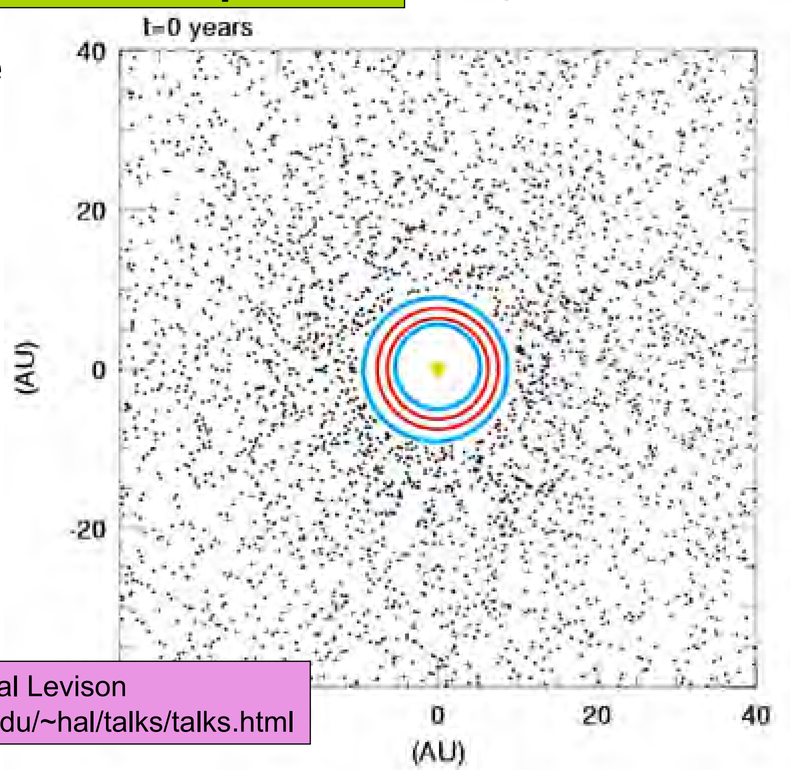
- Nebula collapse <1 MY
- planetesimal formation in 1MY
- J, S < 2 MY
- Terrestrials <4 MY
- Uranus & Neptune?

But it's not so simple…

Jupiter & Saturn
& Neptune Uranus

- Hard to make U & N at present orbits
- Where did earth's oceans come from?
- How to make Kuiper Belt?

=> Migration?



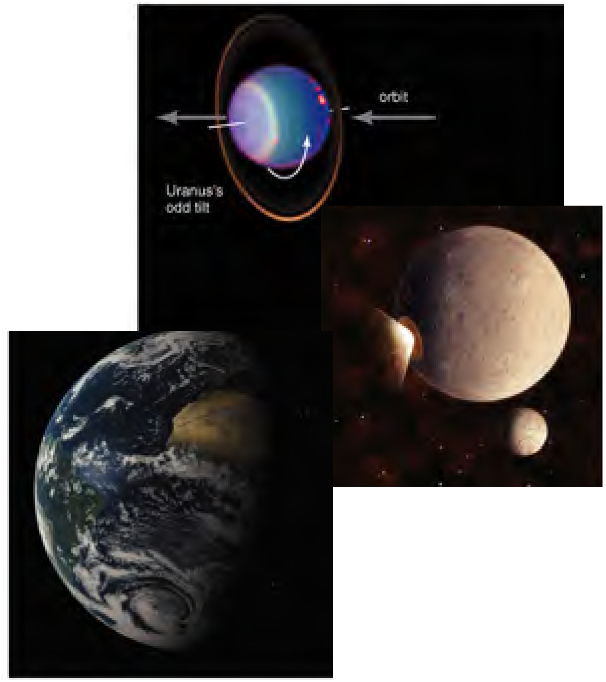
See movies in talks by Hal Levison
http://www.boulder.swri.edu/~hal/talks/talks.html

Can migration and planetesimal scattering explain the "exceptions"?

Uranus tipped on side

Late Heavy Bombardment: Leftover planetesimals bombarded other objects in the late stages of solar system formation

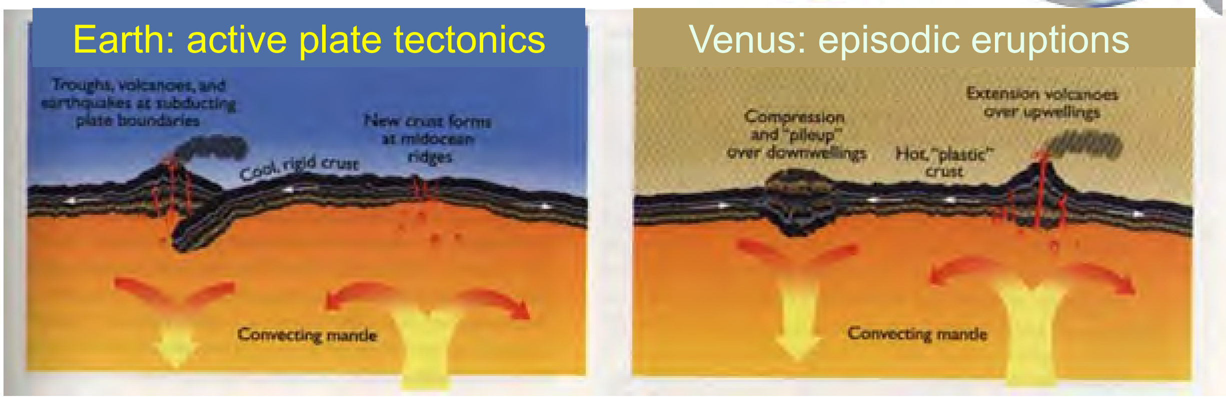
Earth oceans: Water & other volatiles must have come to Earth by way of icy planetesimals from beyond the frost line



Issues addressed:

1. Angular momentum distribution
2. Orderly motion
3. 3 types of planets
4. Time scale of formation
5. Asteroids, comets, Kuiper Belt
6. How Earth got oceans
7. Anomalies? Uranus tipped on side? Formation of Moon & Charon? Collisions can explain anything!

Why Are Venus and Earth So Different?

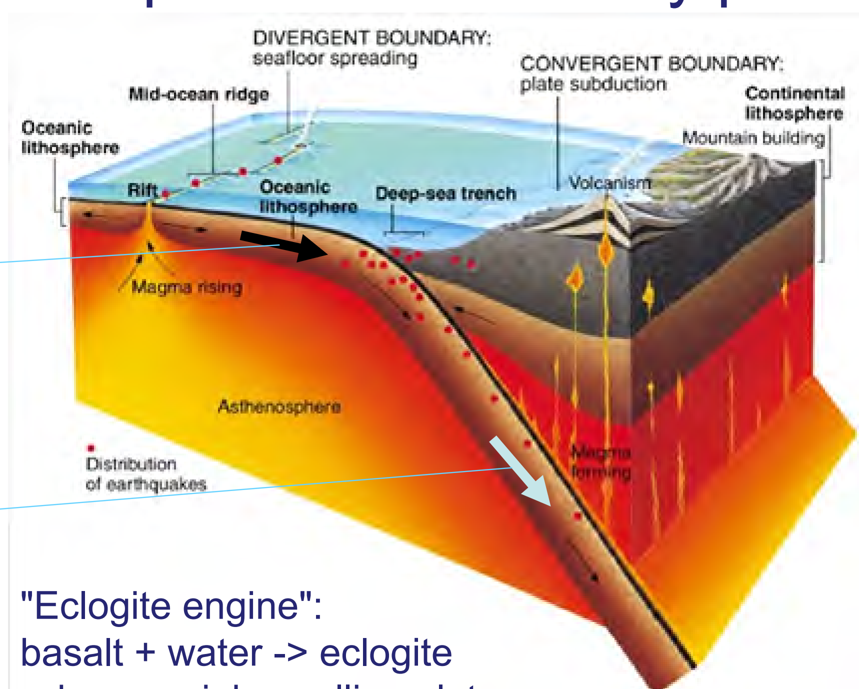


- Does Earth just have more vigorous convection or is something else involved?
- Could **liquid water** be involved? Earth has lots, Venus has none (lost due to run-away greenhouse, dissociation, ionization, solar wind stripping)

Are the plates pushed - or do they pull?

PUSH - away from expanding mid-ocean ridge

PULL - sinking, dense plate material



"Eclogite engine":
basalt + water -> eclogite
- denser, sinks, pulling plate
- lower melting point -> more volcanism

Differences in surface geology – and dynamo - due to their atmospheres?

- Watery Earth: vigorous recycling of crust / upper mantle - driven by "eclogite engine"

- Dry, hot Venus: static crustal lid holds in heat generated by radioactivity in mantle until erupts in (periodic?) episode(s?) of volcanic resurfacing

- Heat flux from core driven by mantle convection:
    - Earth – strong mantle convection, large temperature gradient, drives core convection -> dynamo
    - Venus – low temperature gradient, stably stratified core -> no dynamo

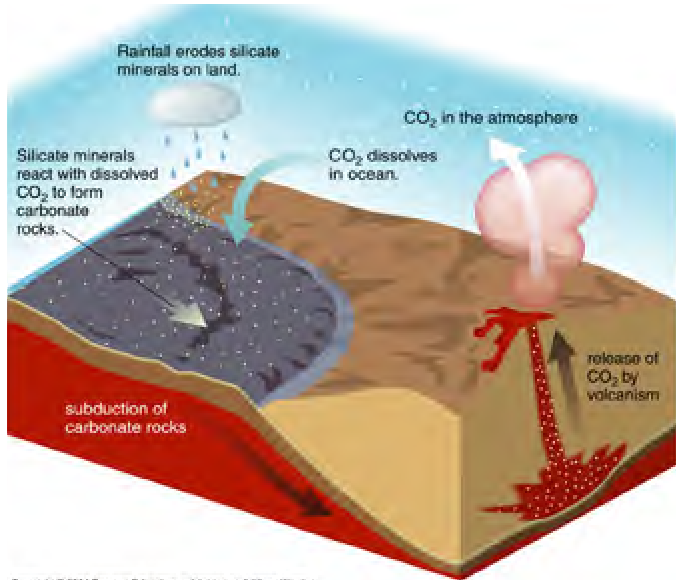
Requirements for Life*

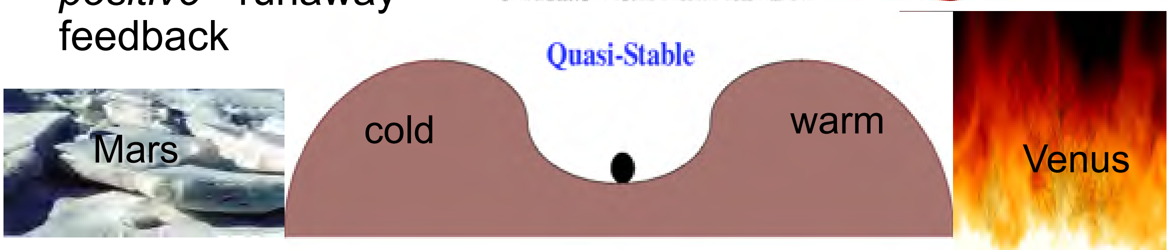
- Organic Chemicals
- Energy
- Liquid water
- Moderate stability
- over millions of years
- Nothing too nasty – radiation, changes in climate, mass destruction, epidemic diseases….

** based on extrapolation from one example - Earth!*

Stability vs. Instability

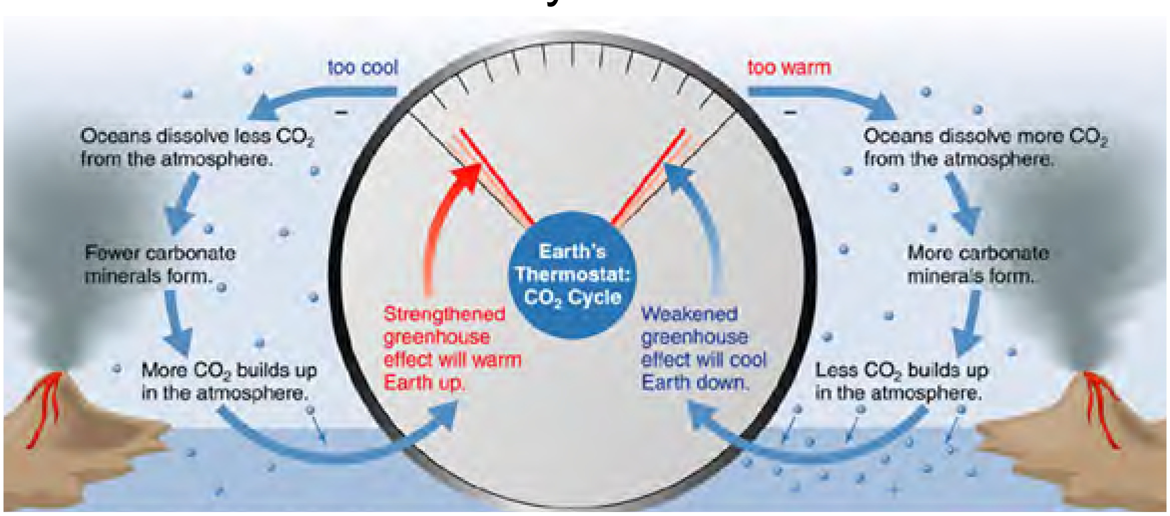
- The Carbon Dioxide Cycle causes *negative* feedback for **small** temperature changes, giving Earth a stable climate
- But **large**, **rapid** changes could lead to *positive* - runaway - feedback





Stability of Earth's Climate
thanks to the CO_2 cycle
& FEEDBACK MECHANSIMS

- Allowed Earth to stay 'habitable' despite Sun brightening over billions of years
- Takes half a million years to stabilize…



Why is Earth Habitable?

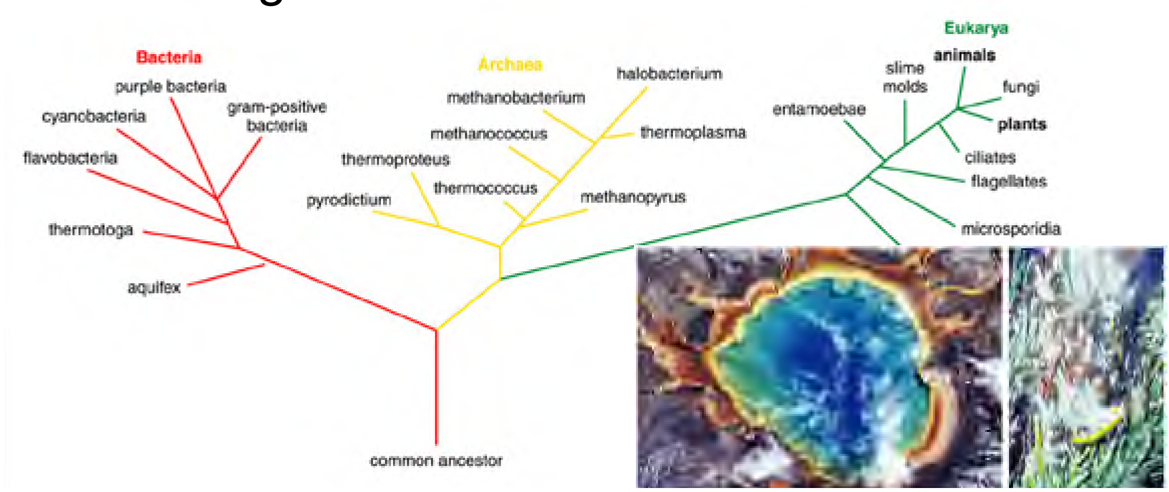
- Geology: plate tectonics, erosion
- Water: abundant and liquid
- Atmosphere: oxygen, stratosphere, little CO_2
- Stable climate (unlike Mars & Venus)
- Life: astonishing and planet-altering

All of these unique features are

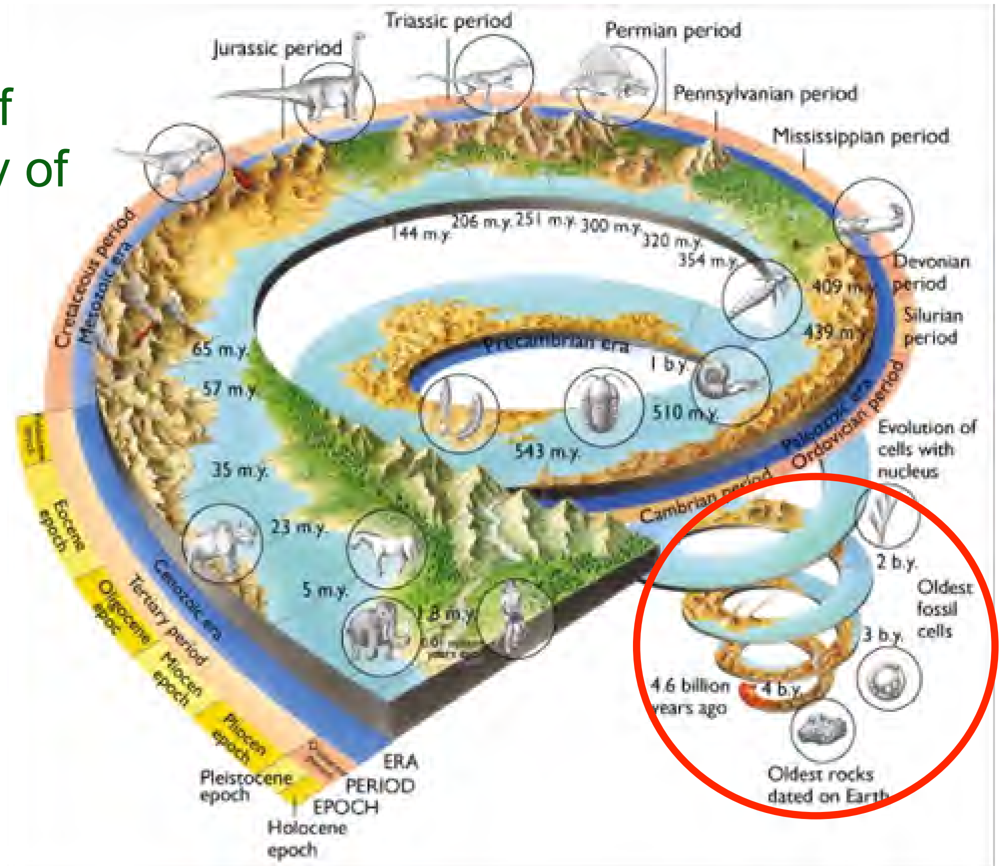
interrelated

Origin of Life

- Almost 4 billion years ago - early - often?
- Have evidence for early life
- No one knows how
- Experiments show nature can make life's building blocks



Brief History of Life



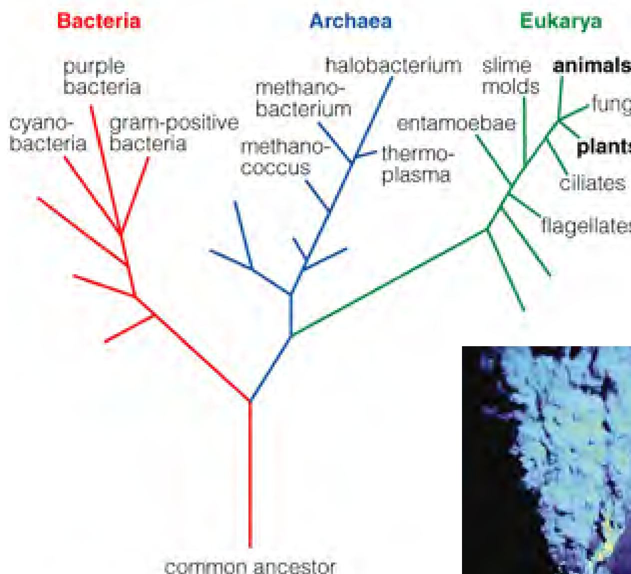
Earliest Fossils

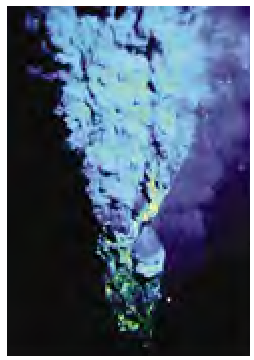
Fossil algae = stromatolites

- Oldest fossils (bacteria-like organisms)
- 3.4 billion yrs ago
- Carbon isotope evidence pushes origin of life to >3.85 billion yrs ago

➢ *Life arose about as soon as possible after bombardment!!!*

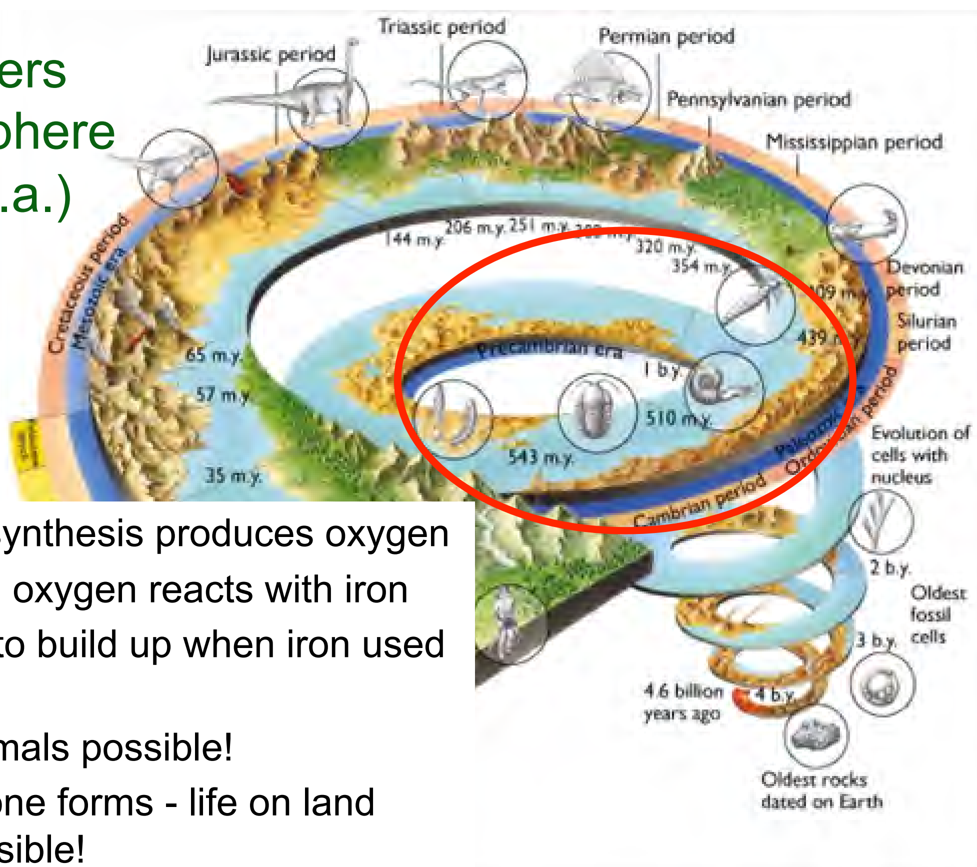
Tree of Life





- "tree of life" from DNA study
- Plants & animals a tiny part of tree. .
- Common Ancestor most likely arose at "black smoker" near a volcanic region of tectonic plate spreading

Life Alters Atmosphere (~2 b.y.a.)



- Photosynthesis produces oxygen
- At first, oxygen reacts with iron
- Starts to build up when iron used up
  - Animals possible!
  - Ozone forms - life on land possible!

65 million years ago in Colorado & around the world

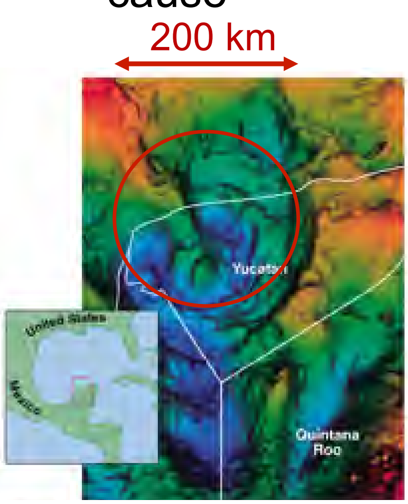
Most species alive, including dinosaurs, disappeared from earth

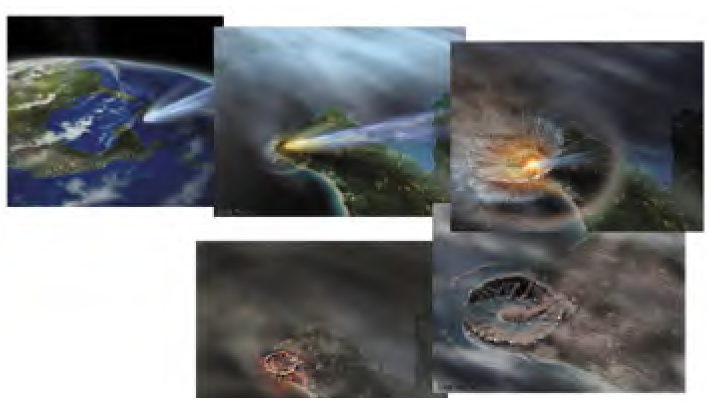
Sedimentary rock layer from that time shows:

- Iridium & other elements - *SO WHAT?? What makes iridium rare in Earth rocks? Hint: it's a dense metal…*
- grains of "shocked quartz" - *requires very high pressure*
- spherical rock droplets - *how does that happen?*
- soot from forest fires

Impacts and Mass Extinctions on Earth

1. debris in atmosphere blocks sunlight; plant die… animals starve
2. poisonous gases form in atmosphere
3. Other ancient 'mass extinctions' show an impact cause

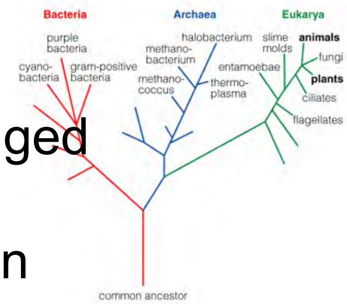


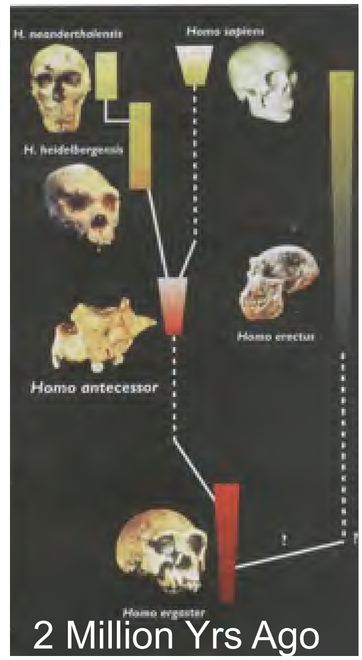


Chicxulub impact - 65 M years ago

When Did Humans Come Along?

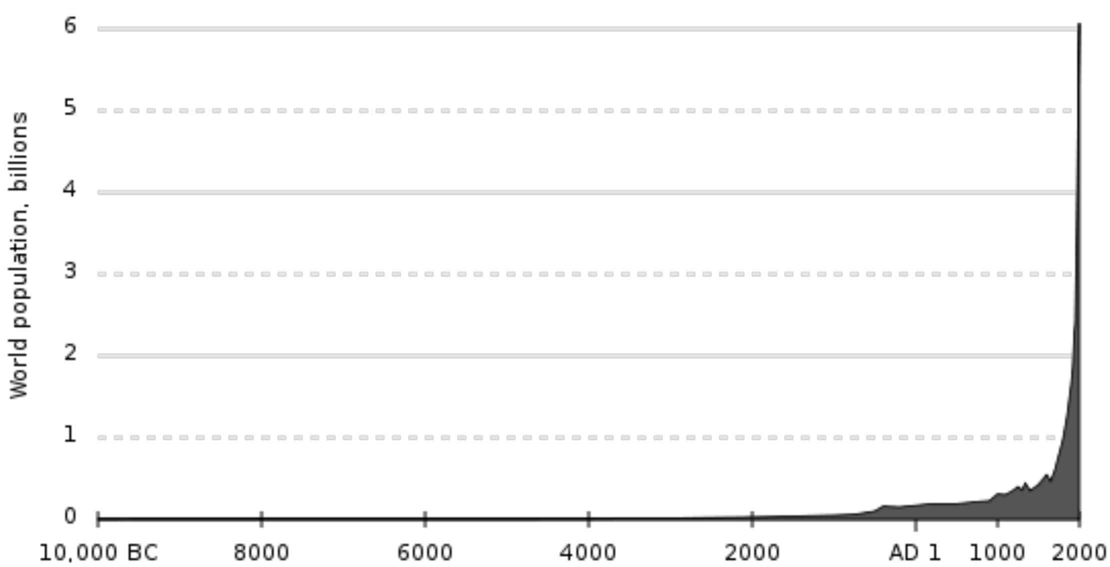
- Life formed ~3.5 Billion yr ago
- Atmosphere changed ~2 bya)
- Diversity explosion (0.54 bya)
- Humans ~few million yr ago)





"Humans are but an insignificant twig on a vast arborescent bush, which, if planted again from seed, would unlikely reproduce us, or anything like us" - Steven Jay Gould

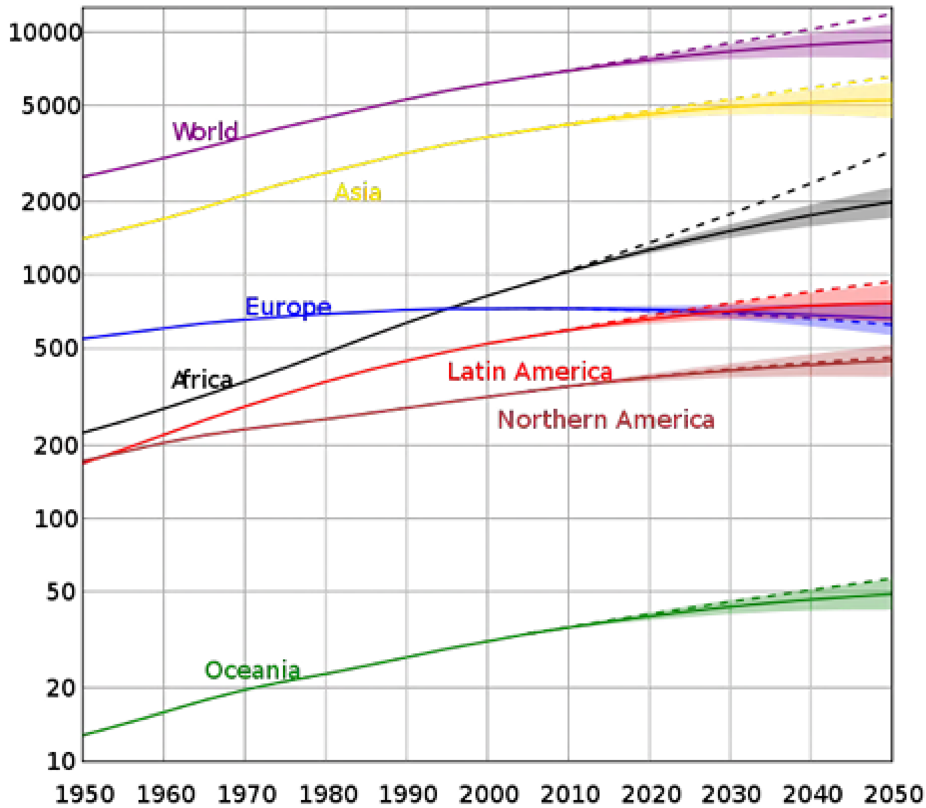
Why does it feel so crowded all of a sudden?



Consider also 'the rate of change' of society, technology

Population

Millions of People



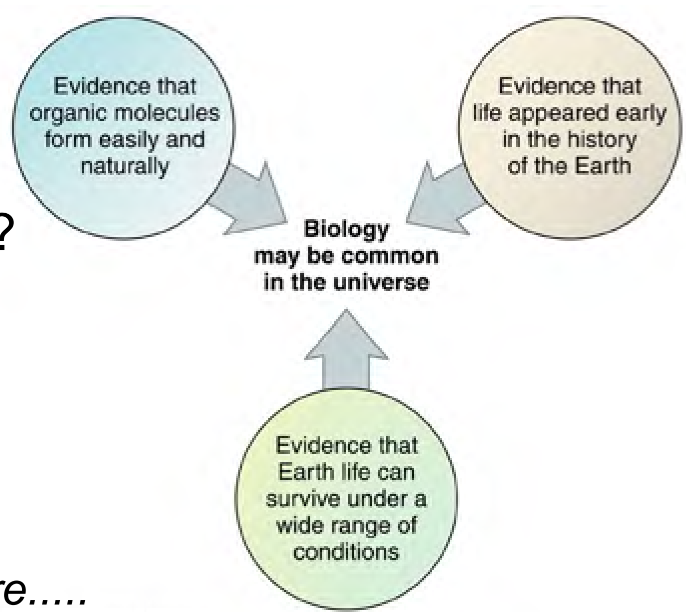
Life elsewhere in our solar system?

- *Chemicals*
- *Water*
- *Energy*

Hardest to find on other planets

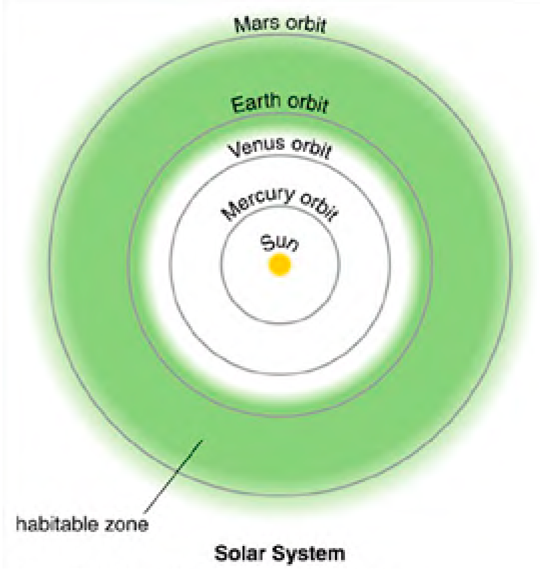
Where might these things be available?

- Mars?
- Europa??
- Enceladus??
- Titan???



We could discuss more.....

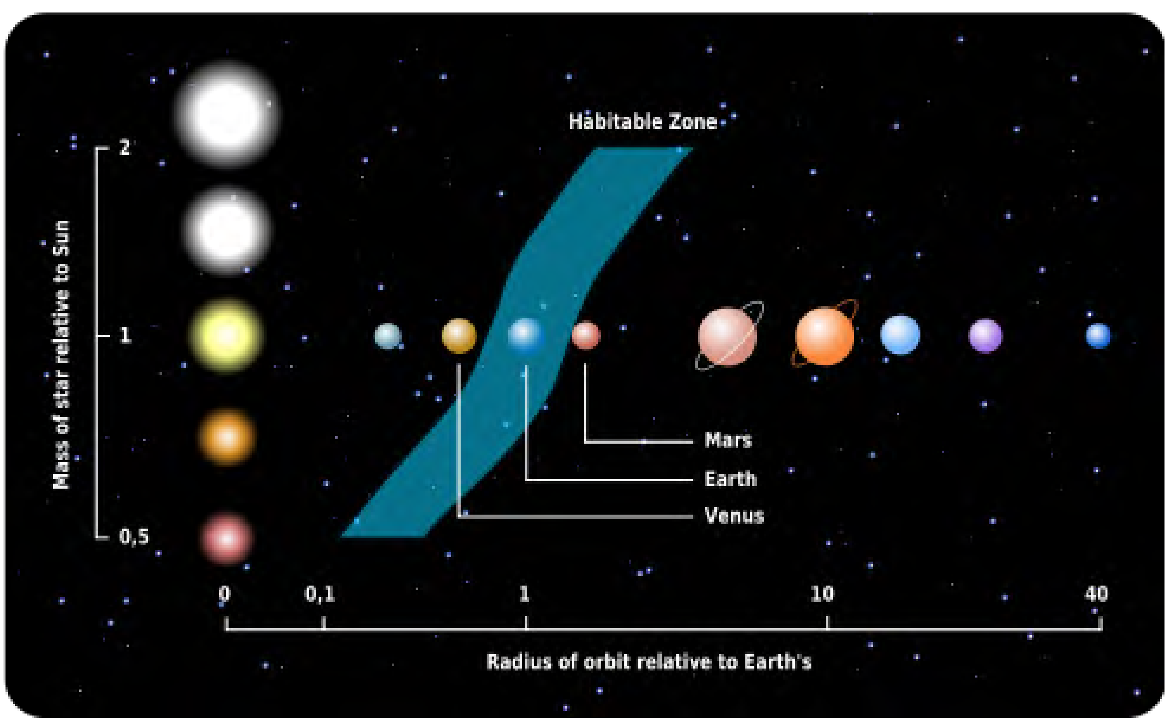
Habitable Zones around stars

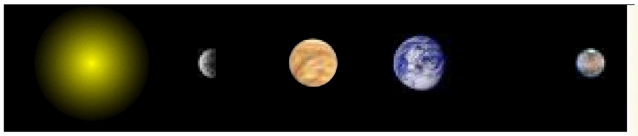


Smaller, cooler the star, the closer in the habitable zone

… the range in "distance from a star" at which liquid water can exist on the planet's surface for billions of years

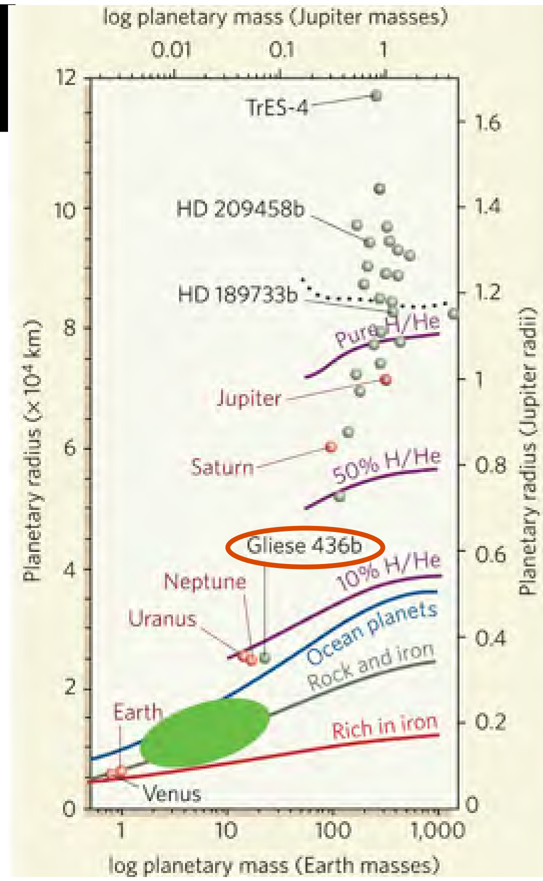
Odds seem good for planets within habitable zones…





So far…..

- >400 planets found orbiting other stars
- only one in Habitable Zone (almost?)



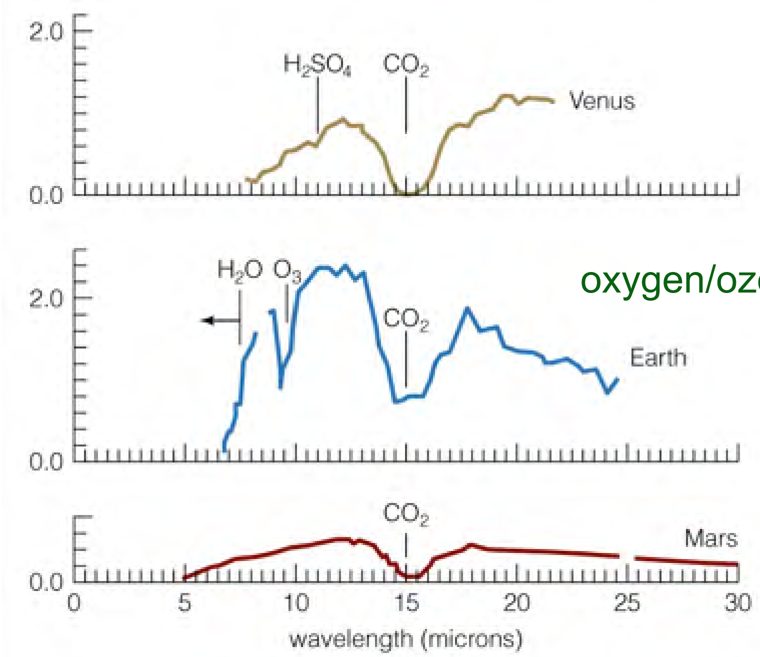
Spectral Signatures of Life

Look for chemical disequilibrium

Venus

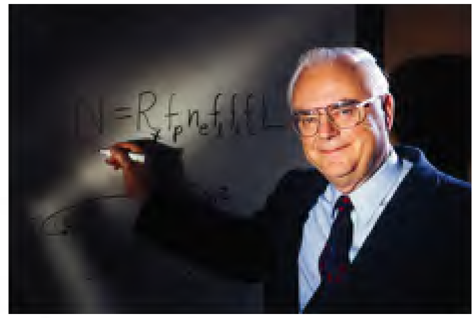
Earth

Mars



The Drake Equation

Number of civilizations with which communication might be possible



The Drake equation states that:

$$N = R^{*} \times f_p \times n_e \times f_\ell \times f_i \times f_c \times L$$

where:

N = the number of civilizations in our galaxy with which communication might be possible;

and

R^{*} = the average rate of star formation per year in our galaxy
f_p = the fraction of those stars that have planets
n_e = the average number of planets that can potentially support life per star that has planets
f_ℓ = the fraction of the above that actually go on to develop life at some point
f_i = the fraction of the above that actually go on to develop intelligent life
f_c = the fraction of civilizations that develop a technology that releases detectable signs of their existence into space
L = the length of time such civilizations release detectable signals into space.[3]

- Numbers we could put in this equation are very, very poorly known - basically, wild guesses
- Biggest unknown is probably how long civilizations last

http://www.youtube.com/watch?v=0Ztl8CG3Sys&feature=related Carl Sagan on Drake Eqn.