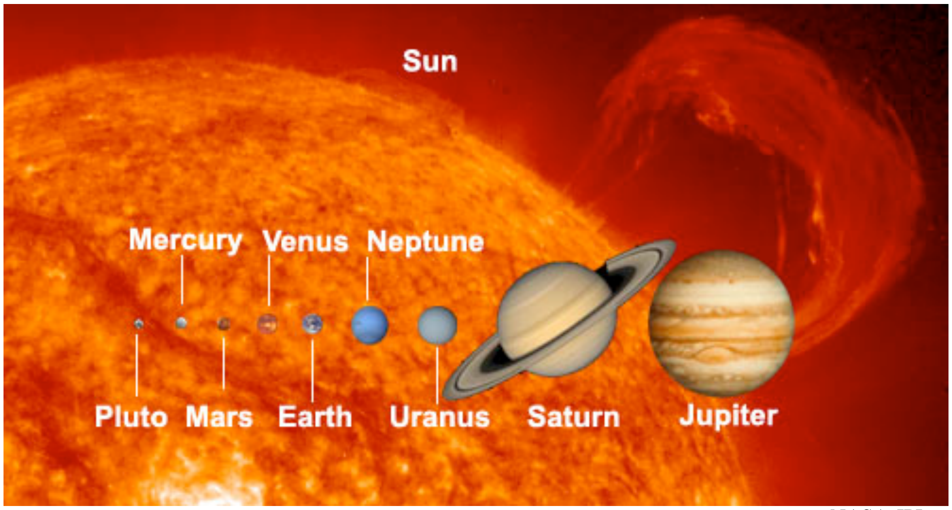
Formation of the Solar System & the Structure of Earth

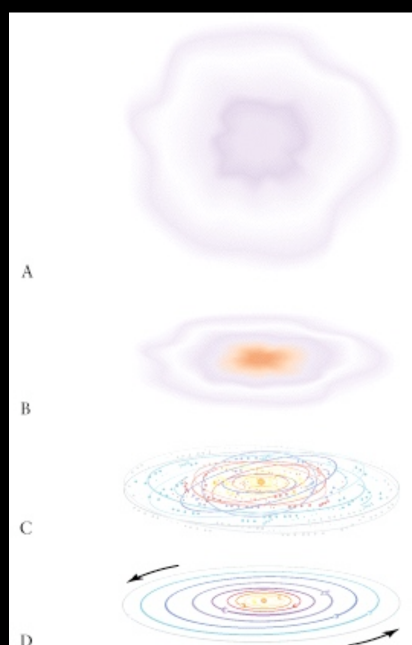
OCEAN 355 Lecture Notes #2



NASA-JPL

Origin of Solar System from nebula

- Slowly rotating cloud of gas & dust
- Gravitational contraction
- High P=High T (PV=nRT)
- Rotation rate increases (conserve angular momentum)
- Rings of material condense to form planets (Accretion)



Stanley (1999)

Observational Clues to the Origin of the Planets

·Inner planets are small and dense

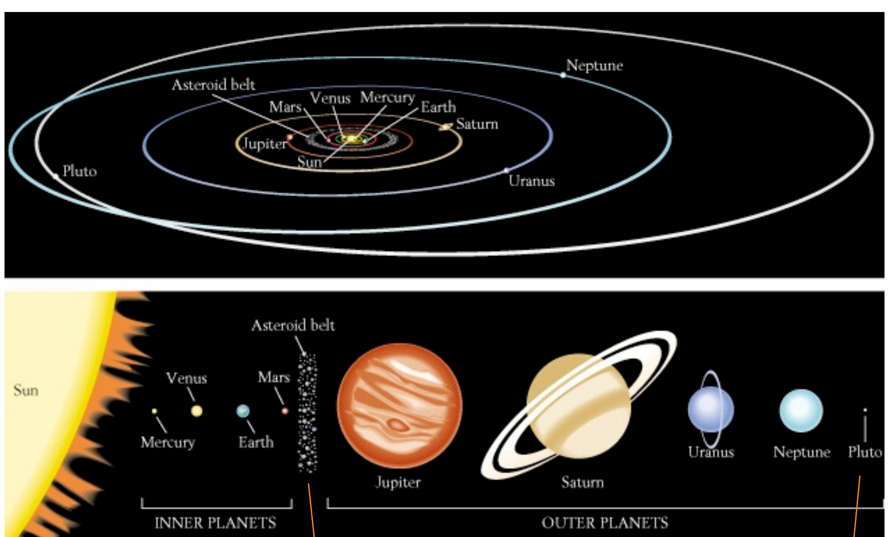
·Outer planets are large and have low density

·Satellites of the outer planets are made mostly of ices

•Cratered surfaces are everywhere in the Solar System

•Saturn has such a low density that it can't be solid anywhere

The Solar System



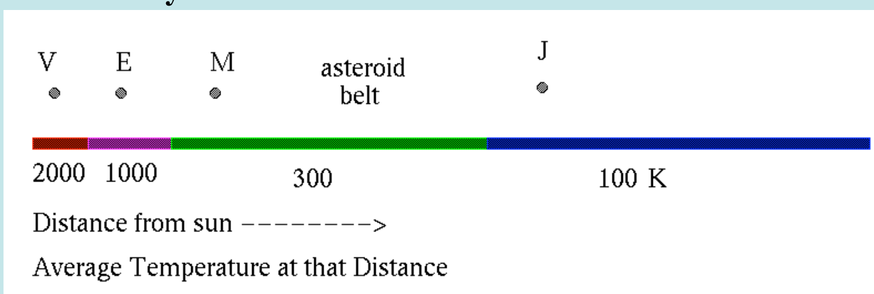
“Failed Planet”

Anomalous Planet

Stanley (1999)

Formation of the Earth by Accretion: 1

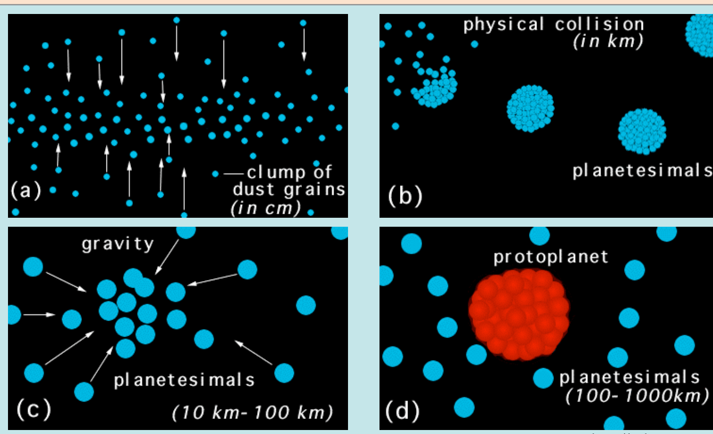
•**Initial solar nebula consisted of cosmic dust & ice with least volatile material condensing closest to the Sun and most volatile material condensing in outer solar system.**



http://zebu.uoregon.edu/ph121/l7.html

Formation of the Earth by Accretion: 2

- Step 1: **accretion of cm sized particles**
- Step 2: **Physical Collision on km scale**
- Step 3: **Gravitational accretion on 10-100 km scale**
- Step 4: **Molten protoplanet from the heat of accretion**



http://zebu.uoregon.edu/ph121/l7.html

Formation of the Earth by Accretion: 3

•Tremendous heat generated in the final accretion process resulted in initially molten objects.

•Any molten object of size greater than about 500 km has sufficient gravity to cause gravitational separation of light and heavy elements thus producing a *differentiated* body.

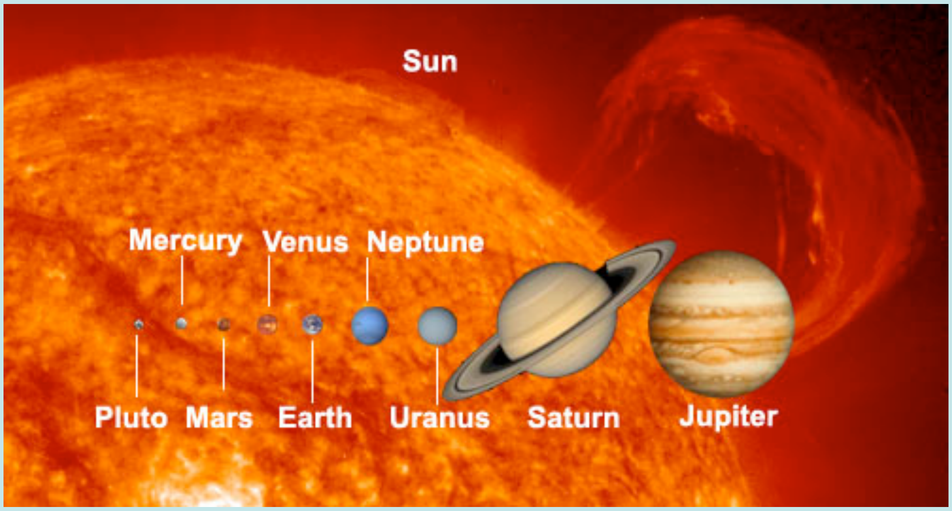
•The accretion process is inefficient, there is lots of left over debris.

•In the inner part of the solar system, leftover rocky debris cratered the surfaces of the newly formed planets *(Heavy Bombardment*, 4.6-3.8 Ga).

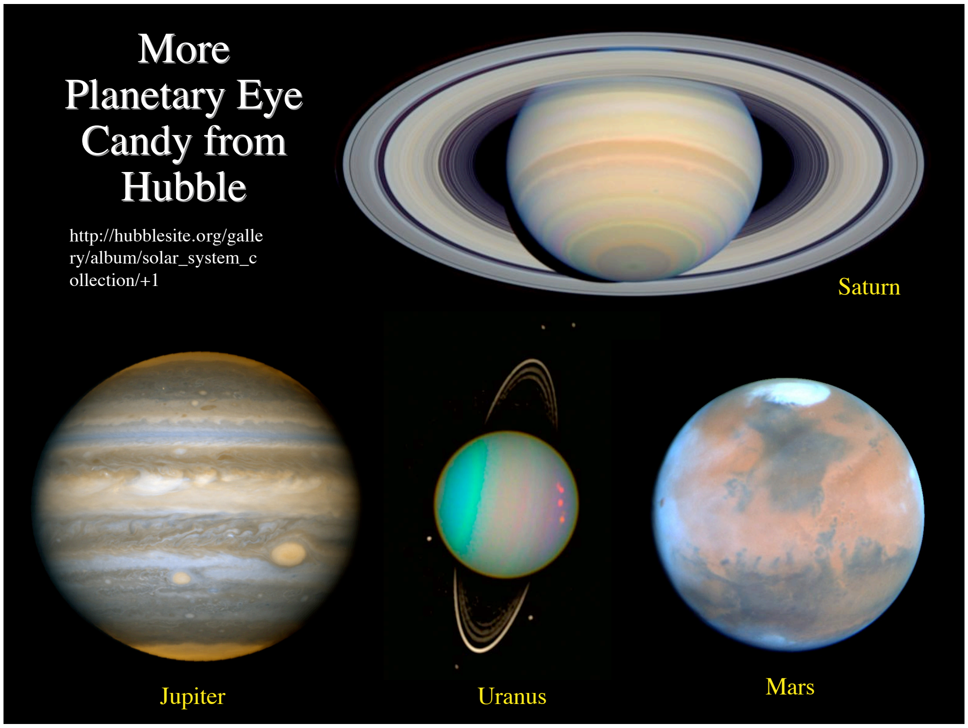
•In the outer part of the solar system, the same 4 step process of accretion occurred but it was accretion of ices (cometisemals) instead of grains.

http://zebu.uoregon.edu/ph121/l7.html

The Sun & Planets to Scale



NASA-JPL



After much outcry, NASA plans a final space shuttle servicing mission to HST in Aug. '08 to extend capabilities through 2013

In 2004, NASA administrators canceled a final servicing mission to the telescope that had been scheduled for 2006. The officials based the decision on concern for the safety of astronauts after the loss of the space shuttle Columbia in 2003. Scientists, politicians, and astronomy enthusiasts protested that the decision would bring an early end to the telescope's observations. NASA officials then agreed to study the possibility of sending a robotic craft to perform needed repairs.

STS-125: Final Shuttle Mission to Hubble Space Telescope

Image above: The astronauts selected for the final shuttle mission to perform work on the Hubble Space Telescope pose for a group photo. From left to right are astronauts Megan McArthur, Michael Good, Gregory C. Johnson, Scott Altman, John Grunsfeld, Michael Massimino and Andrew Feustel. Image credit: NASA

HOUSTON - NASA managers officially are targeting August 7, 2008, for the launch of the fifth and final space shuttle servicing mission to the Hubble Space Telescope. During the 11-day flight, Atlantis' seven astronauts will repair and improve the observatory's capabilities through 2013.

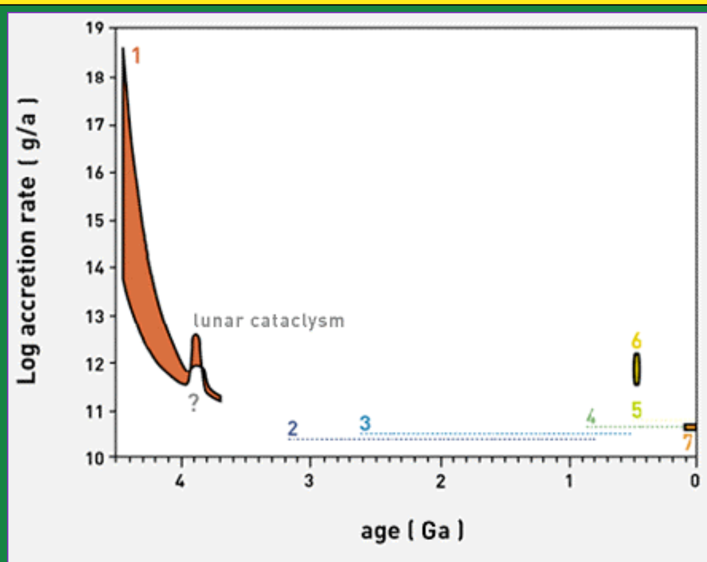
Mission planners have been working since last fall, when the flight was announced, to determine the best time in the shuttle manifest to support the needs of Hubble while minimizing the impact to International Space Station assembly. NASA also will support a "launch on need" flight during the Hubble mission. In the unlikely event a rescue flight becomes necessary, shuttle Endeavour currently is planned to lift off from Launch Pad 39-B at NASA's Kennedy Space Center, Fla. However, managers constantly are evaluating the manifest to determine the best mission options.

Shuttle missions beyond the Hubble flight, designated STS-125, still are being assessed. Shuttle and station program officials will continue to consider options for the remainder of the shuttle flights to complete construction of the space station by 2010, when the fleet will be retired. Those target launch dates are subject to change.

http://www.nasa.gov/mission_pages/hubble/servicing/index.html

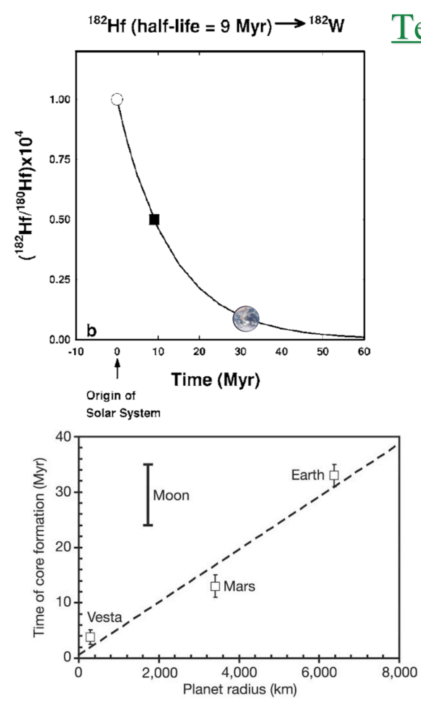
http://spaceflight.nasa.gov/gallery/images/shuttle/sts-109/hires/sts109-331-010.jpg

Earth Accretion Rate Through Time



Schmitz et al.. (1997) *Science*, Vol. 278: 88-90, and references therein.
http://www.whoi.edu/science/MCG/pge/project4.html

Terrestrial Planets Formed Rapidly

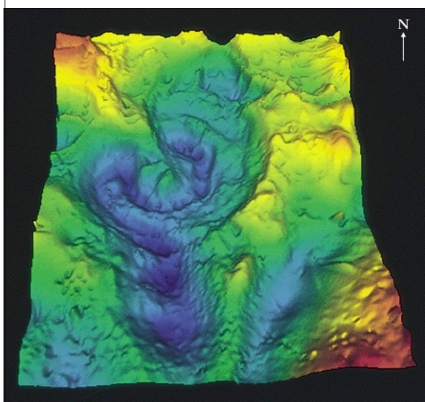


- Hafnium-182 decays to Tungsten-182 with a half-life of 9 Myr
- ~60 Myr after the beginning of the Solar System all ^{182}Hf would have decayed
- Hf is retained entirely in the mantle during core-mantle segregation while W is preferentially partitioned into the core.
- If core formation occurred during the lifetime of ^{182}Hf, an excess of ^{182}W should develop in the mantle as a consequence of its enhanced Hf/W ratio
- This excess of ^{182}W has been measured & indicates that core formation on Earth occurred ~30 Myr after the beginning of the Solar System
- So inner planets formed very rapidly (<30 Myr) with smaller bodies forming faster
- Moon must have formed by another mechanism…

Jacobsen (2005) *Ann. Rev. Earth & Planetary Sci.*, 33: 531-570
Kleine et al. (2002) *Nature* 418: 952-955
Yin et al. (2002) *Nature* 418: 949-952

Accretion continues…

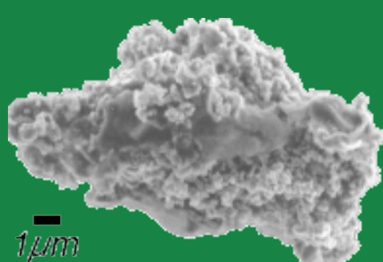
Chicxulub Crater, Gulf of Mexico
•200 km crater
•10-km impactor
•65 Myr BP
•Extinction of 75% of all species!



Meteor (Barringer) Crater, Arizona
•1 km diam. Crater
•40-m diam Fe-meteorite
•50 kyr BP
•300,000 Mton
•15 km/s

http://www.gi.alaska.edu/remsense/features/impactcrater/imagexplain.htm

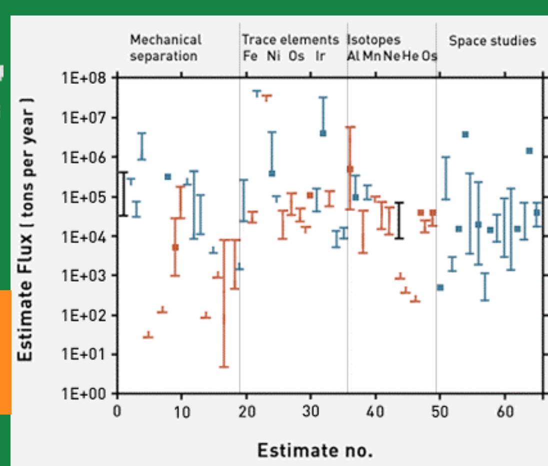
Interplanetary Dust Accumulation



http://presolar.wustl.edu/work/idp.html

40±20 x10^4 metric tons/ yr (40 x10^{10} g) interplanetary dust accretes every yr!

(or 524.1 Ford Explorers/day)
2090 kg / 2007 Sport Trac Explorer



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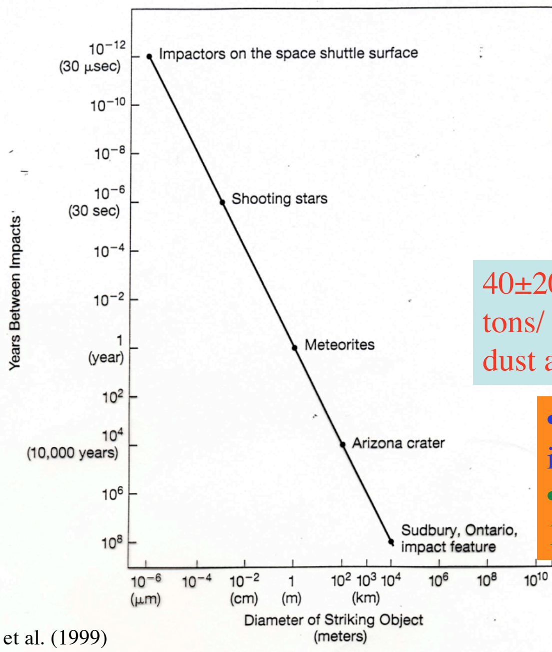
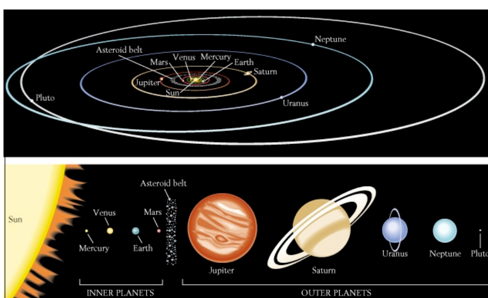


Kump et al. (1999)

Size & Frequency of Impacts

$40 \pm 20 \times 10^4$ metric tons/ yr interplanetary dust accretes every yr!

- 100 m object impacts every 10 kyr
- 10 km object every 100 Myr

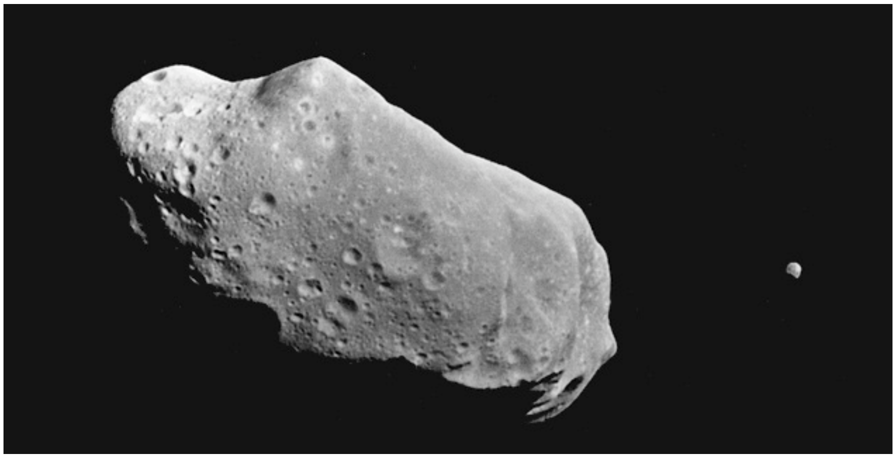


The Asteroid Belt

- A relic of the accretion process. A failed planet.
- Gravitational influence of Jupiter accelerates material in that location to high velocity.
- High-velocity collisions between chunks of rock shatter them.
- The sizes of the largest asteroids are decreasing with time.

Total mass (Earth = 1)	0.001
Number of objects > 1 km	~100,000
Number of objects > 250 km	~12
Distance from Sun	2-4 AU
Width of asteroid belt (million km)	180

Asteroid 243 IDA

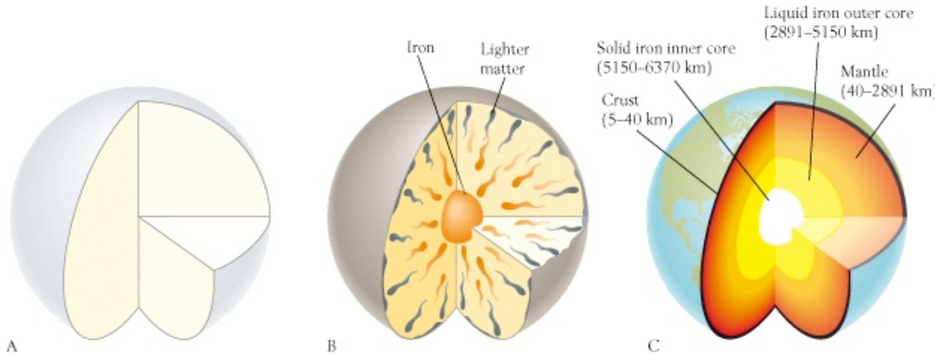


•Meteorite = asteroid that has landed on earth
•All chondrites (meteorites) date to ~4.5 B.y.
•Cratering indicates early origin

Differentiation of the Earth: 1

- VM Goldschmidt (1922) published landmark paper "Differentiation of the Earth":
  1. Earth has a chondritic (meteoritic) elemental composition.
  2. Surface rocks are not chemically representative of solar abundances, therefore must be differentiated.
- Proto-planet differentiated early into a dense iron-rich core surrounded by a metal sulfide-rich shell above which floated a low-density silicate-rich magma ocean.
- Cooling of the magma caused segregation of dense silicate minerals (pyroxenes & olivines) from less dense minerals (feldspars & quartz) which floated to surface to form crust.
- In molten phase, elements segregate according to affinities for: Fe = siderophile, sulfide = chalcophile & silicate = lithophile.

Differentiation of Earth: 2



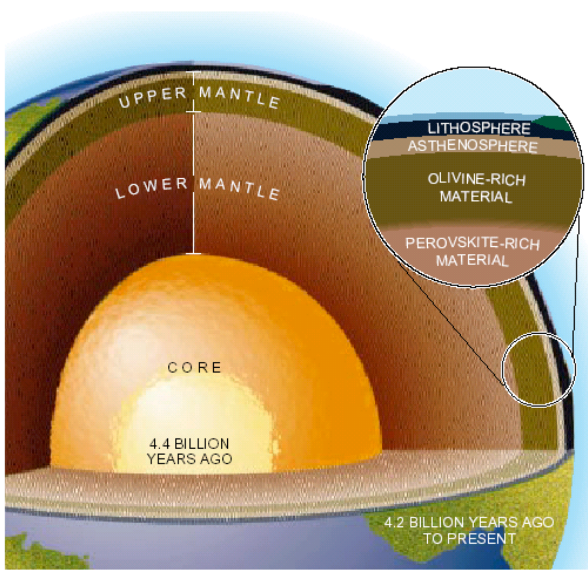
Undifferentiated protoplanet (chondritic composition)

Early differentiation; magma ocean

Fully differentiated Earth

- Driven by density differences
- Occurred within ~100 Myr

Differentiation of the Earth: 3



Allegre & Schneider, *Sci. Am.*(1994)

•Differentiation of Earth

Homogenous planetesimal

Earth heats up

- Accretion and *compression* (T~1000°C)
- *Radioactive decay* (T~2000°C)

Iron melts--migrates to center, forming ***core***

- *Frictional heating* as iron migrates

Light materials float--***crust***

Intermediate materials remain--***mantle***

Differentiation of Earth, Continents, Ocean & Atmosphere

•Differentiation of Continents, Oceans, and Atmosphere

Continental crust forms from differentiation of primal crust

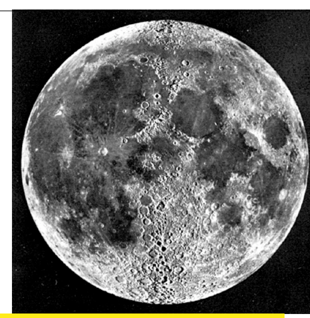
Oceans and atmosphere

Two hypotheses

- ***internal***: degassing of Earth's interior (volcanic gases)
- ***external***: comet impacts add H_2O CO_2, and other gases

Early atmosphere rich in H_2, H_2O, N_2, CO_2; deficient in O_2

Earth's Crustal Evolution: 1. 3 Types of Planetary Crust



1° = original crystalline material to solidify from magma oceans of newly accreted bodies. None of this survives on Earth, but the white highlands of the moon are a good example. Impact that created moon produced 1° crust.

2° = slow heating by radioactive decay melts small quantities of rock in planetary interiors. Results in eruption of basaltic lavas. E.g., Earth's ocean floor, surfaces of Mars & Venus, lunar maria.

Taylor & McLennan (1996); NASA-JPL

Origin of the Moon (Artist's Rendition!)

Stanley (1999)

Moon-Forming Impact

Canup R & AspaugE:Eos Trans. AGU, 82(47), Fall Meet. Suppl., Abstract U51A-02, 2001
http://www.swri.edu/9what/releases/canupmoon.htm

Hypothesis for lunar origin - Moon forms from debris ejected as a result of the collision of a roughly Mars-sized impactor with early Earth

•Geophysical simulations use a method known as smooth particle hydrodynamics, or SPH and can achieve resolutions sufficient to study the production of orbit-bound debris necessary to yield the Moon.

•Off-center, low-velocity collisions yield material in bound orbit from which a satellite may then accumulate.

•Simulations must account for mass, angular momentum and compositions of the earth-Moon system.

•Must yield an Earth that retains an iron-rich core and a moon that is appropriately iron-depleted and the right density.

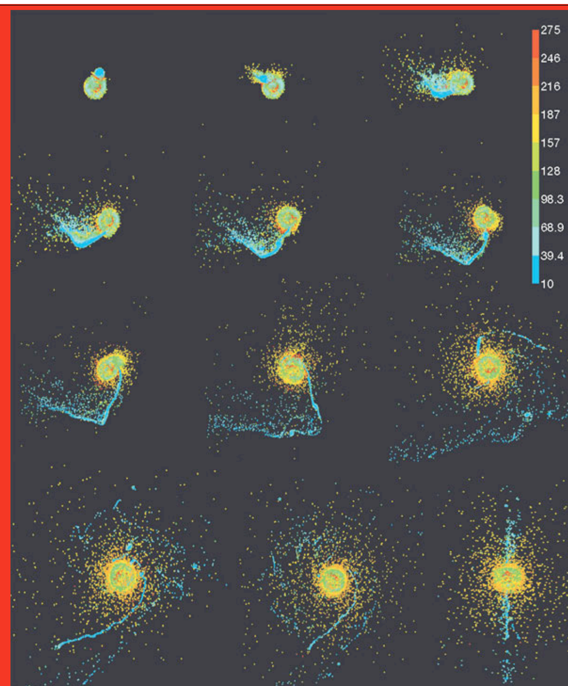
SPH results suggest:

- -The object had 10-12% of Earth's mass (Mars-size!)
- -Produces a satellite with <3% Fe by mass. Unable to be subsequently captured.
- -Happened near end of Earth's accretional history.
- -Resulted in melting of Earth crust.

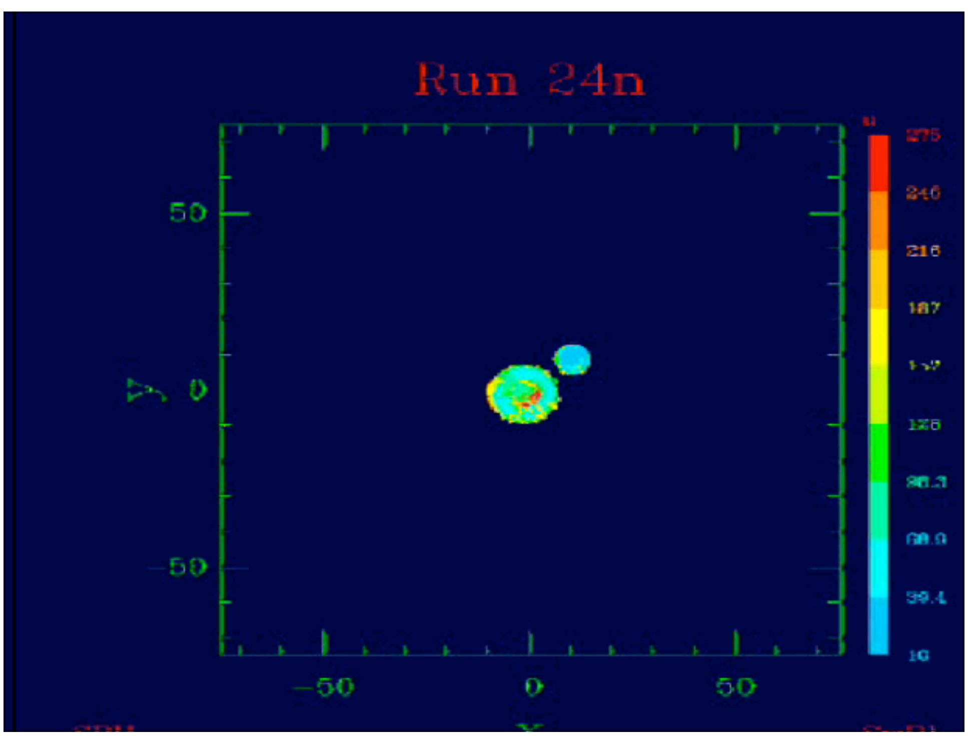
Numerical Simulation of Moon-Formation Event

-Mars-size object (10% M_E) struck Earth
-core merged with Earth
-Moon coalesced from ejected debris of impactor's mantle

-Explains high rotation rate of Earth
-Heat of impact melted crust
-magma ocean #2

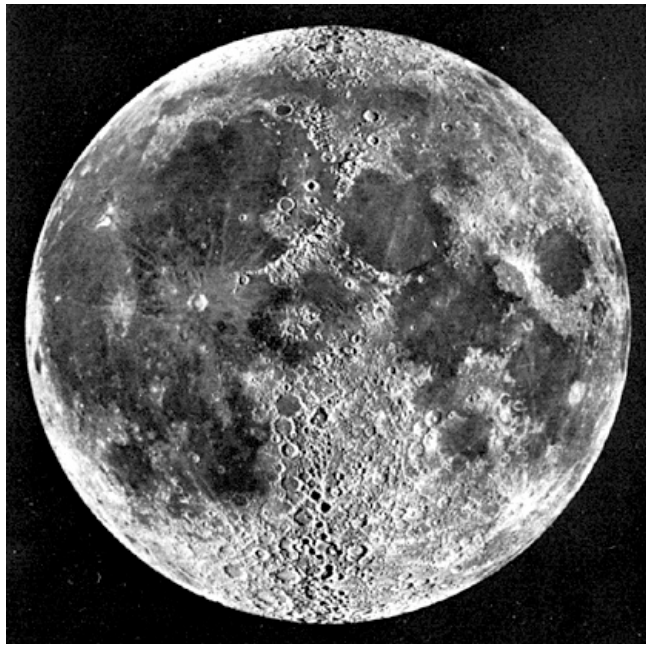


Canup & Asphaug (2001), *Nature*, Vol. 412.



The Moon

- Critical to life (stabilizes tilt)
- Rocks from crater rims are 4.0-4.6 Ba (heavy bombardment)
- Jupiter's gravity shielded Earth and Moon from 1,000x more impacts!



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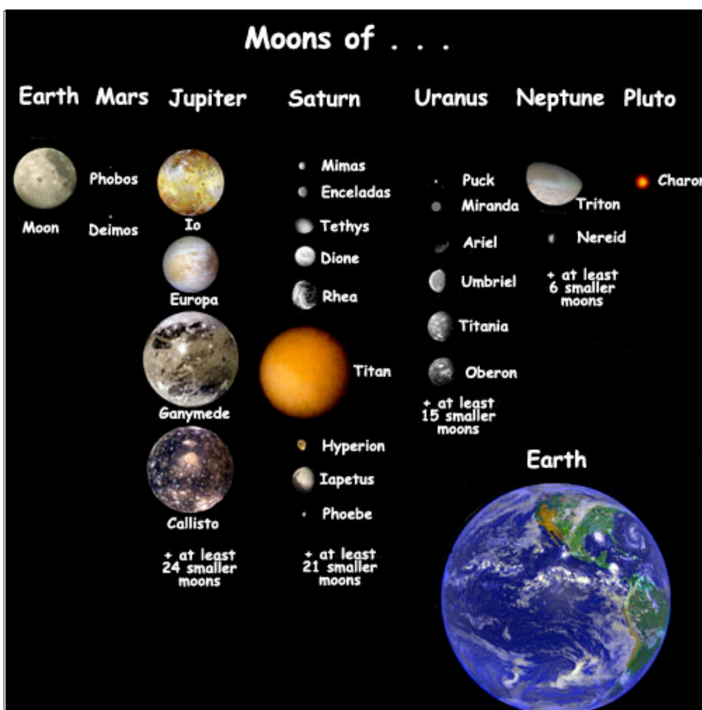
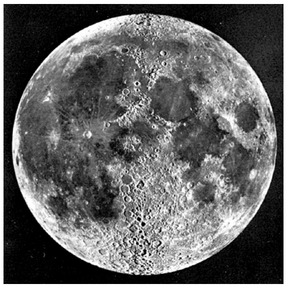


Moons of the Solar System to Scale

NASA-JPL

Earth's Crustal Evolution: 1. 3 Types of Planetary Crust



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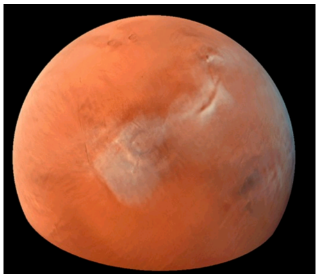
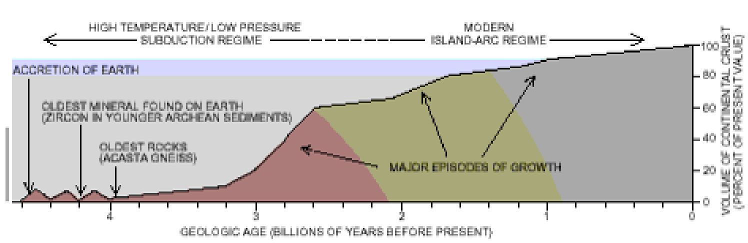
Taylor & McLennan (1996); NASA-JPL



Earth's Crustal Evolution: 2

<u>3°Crust</u> = Formed from slow, continuous distillation by volcanism on a geologically active planet (I.e., plate tectonics).

- Results in highly differentiated magma distinct from basalt. I.e., the low-density, light-colored granite we see in rocks on the continents.
- Earth may be the only planet where this type of crust exists.
- Unlike 1° & 2° crusts, which form in < 200 M.y., 3° crusts evolve over billions of years.



CRUSTAL GROWTH has proceeded in episodic fashion for billions of years. An important growth spurt lasted from about 3.0 to 2.5 billion years ago, the transition between the Archean and Proterozoic eons. Widespread melting at this time formed the granite bodies that now constitute much of the upper layer of the continental crust.

Taylor & McLennan (1996)

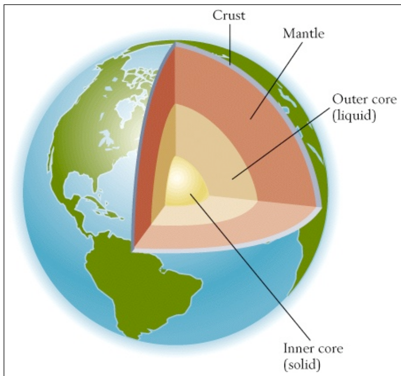
Igneous Rocks

Stanley (1999)

The Crust & Mantle

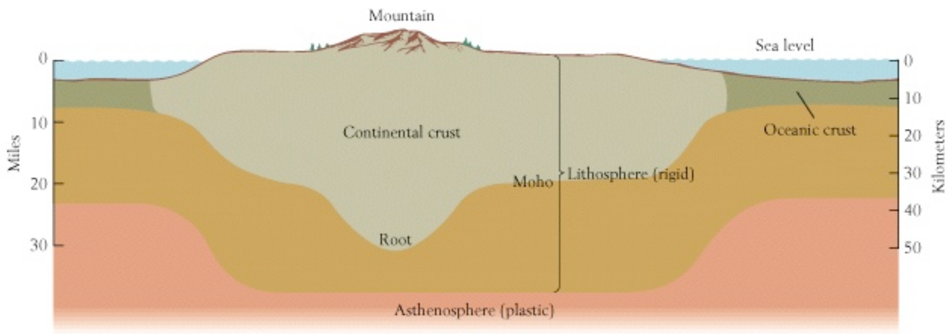
The Crust
- Ocean Crust
  - 3-15 km thick
  - Basaltic rock
  - Young (<180 Ma)
  - Density ~ 3.0 g/cm3
- Continental Crust
  - 35 km average thickness
  - Granitic rock
  - Old (up to 3.8 Ga)
  - Density ~ 2.7 g/cm3
- Crust "floating" on "weak" mantle

The Mantle
- ~2900 km thick
- Comprises >82% of Earth's volume
- Mg-Fe silicates (rock)
- Two main subdivisions:
  - Upper mantle (upper 660 km)
  - Lower mantle (660 to ~2900 km; "Mesosphere")

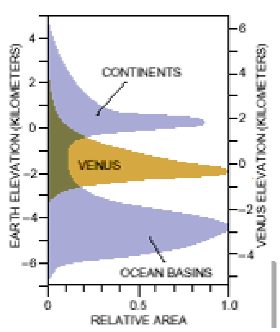


Structure of Earth

From Stanley (1999)



Why is Continental Crust “Elevated Relative to Oceanic Crust?



SURFACE ELEVATIONS are distributed quite differently on the earth (*blue*) and on Venus (*gold*). Most places on the earth stand near one of two prevailing levels. In contrast, a single height characterizes most of the surface of Venus. (Elevation on Venus is given with respect to the planet's mean radius.)

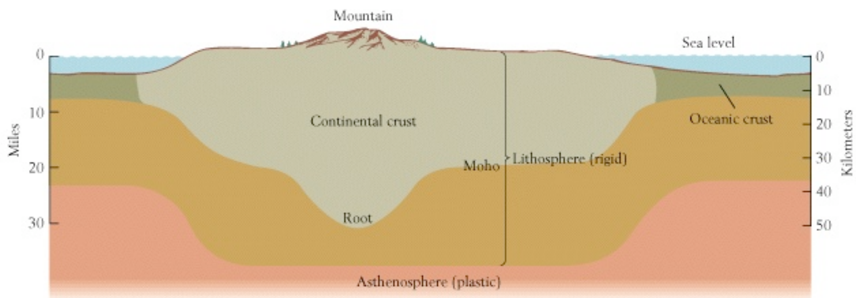
- •High-density Basalt sinks into mantle more than low-density Granite.
- •Volcanism continually produces highly differentiated continental crust on Earth.
- •Venus surface appears to be all basalt.
- •Plate tectonics & volcanism do not appear to be happening on Venus (or Mars, Moon).
- •So Earth may be unique in Solar System. And plate tectonics & volcanism may be critical in determining habitability.

Taylor & McLennan *Sci. Am.* (1996)

Lithosphere & Asthenosphere

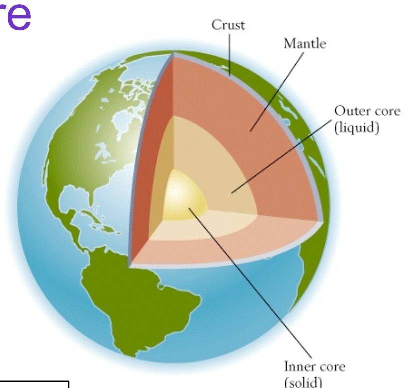
Lithosphere/Asthenosphere: Outer 660 km divided into 2 layers based on mechanical properties. Includes the Mantle + Crust

- ***Lithosphere***
  - Rigid outer layer including crust & upper mantle
  - Averages 100 km thick; thicker under continents
- ***Asthenosphere***
  - Weak, ductile layer under lithosphere
  - Lower boundary ~660 km (entirely within mantle)



The Core

- **Outer Core**
  - ~2300 km thick
  - *Liquid* Fe with Ni, S, O, and/or Si
  - Magnetic field is evidence of flow
  - Density ~ 11 g/cm3
- Inner Core
  - ~1200 km thick
  - *Solid* Fe with Ni, S, O, and/or Si
  - Density ~13.5 g/cm3



- Earth's Interior: How do we know its structure?
  - Avg density of Earth (5.5 g/cm^3)
  - Denser than crust & mantle
  - Composition of meteorites
  - Seismic wave velocities
  - Laboratory experiments
  - Chemical stability
  - Earth's magnetic field

From Stanley (1999)

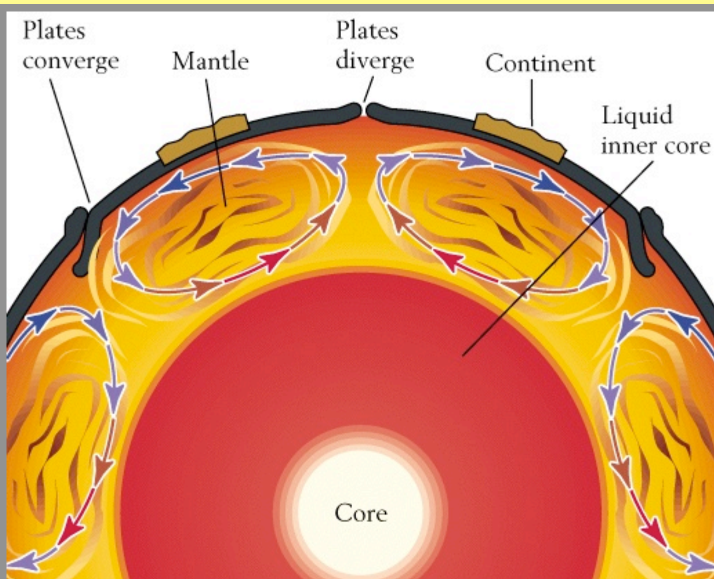
Basics of Geology

Lithospheric Plates

From Stanley (1999)

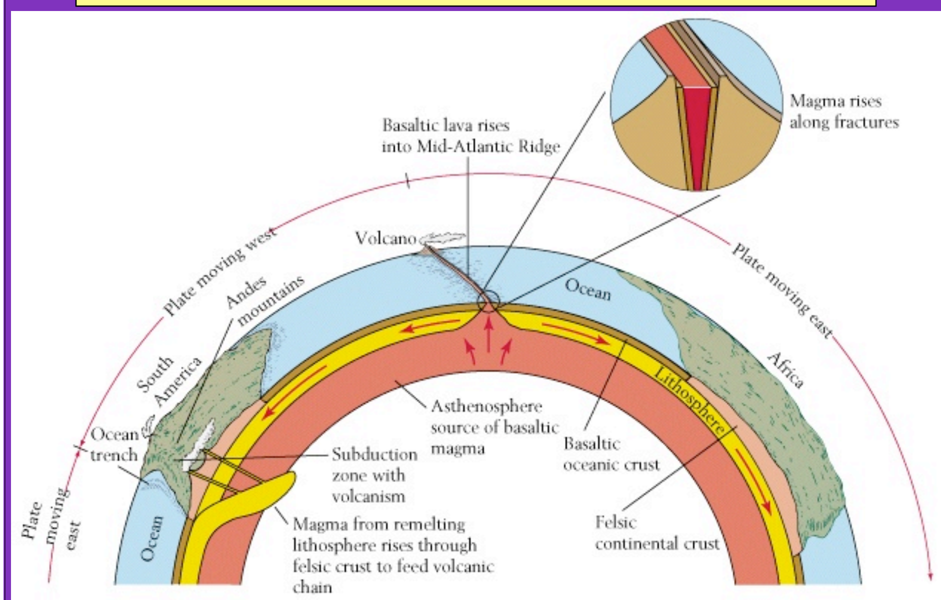
- 8 large plates (+ add'l. small ones)
- Average speed: 5 cm/yr
- 3 types of motion result in 3 types of boundaries: sliding toward (subduction zones), sliding away (ridge axes), sliding along (transform faults)

Convection Drives Plate Movements

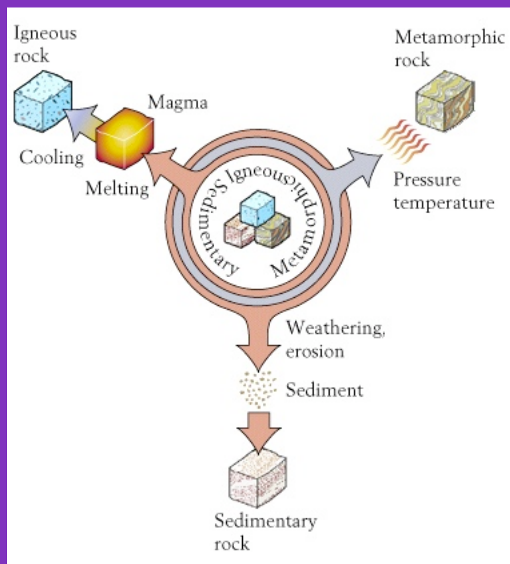


From Stanley (1999)

Tectonic Activity in the South Atlantic



From Stanley (1999)

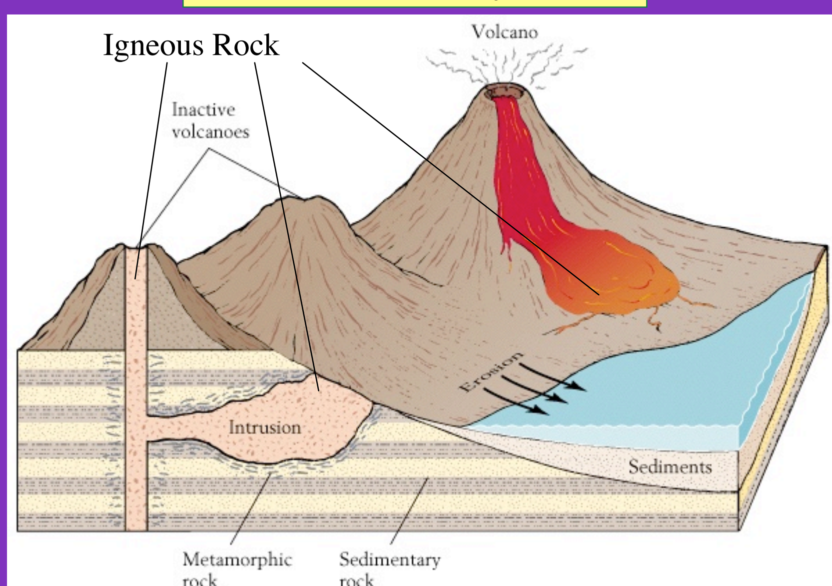


From Stanley (1999)

Rock Basics

Igneous + metamorphic = Crystalline Rocks

The Rock Cycle



From Stanley (1999)

Igneous Rocks 101

•Felsic: Si-,Al-rich. Light-colored, low-density. Feldspar (pink) & quartz (SiO_2)-rich. Most continental crust. Granite most abundant.
•Mafic: Mg-, Fe-rich. Dark-colored, high-density. Most oceanic crust. Ultramafic rock (more dense) forms mantle below crust.
•Extrusive: cools rapidly; small crystals
•Intrusive: cools slowly; large crystals

Basalt (Oceanic Crust)

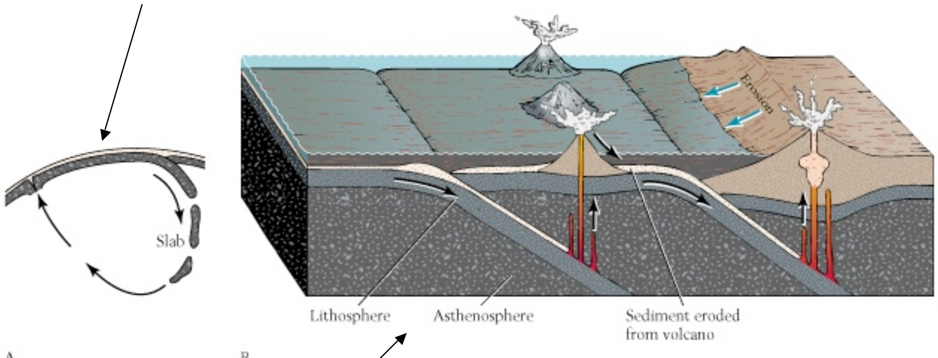
Granite (Continental Crust)

Stanley (1999)

ME MI
FE FI

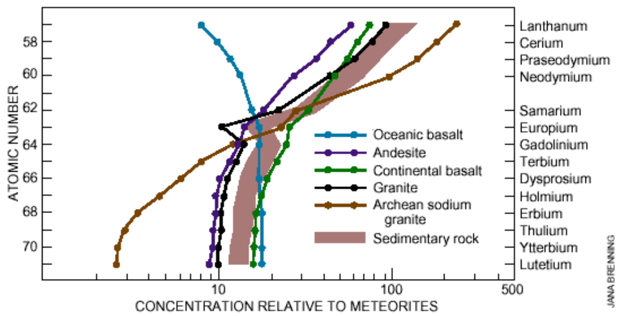
Plate Tectonics & the Rock Cycle

- Slab of lithosphere is subducted, melted & incorporated into asthenosphere
- Convection carries molten material upward where it emerges along a spreading zone as new lithosphere.



•Subducted sediment melts at a shallower depth where it contributes to magma emitted from an island arc volcano and a mountain chain volcano
•Erosion of volcanic rock provides sediment sediment to complete cycle

From Stanley (1999)



RARE-EARTH ELEMENT abundance patterns provide characteristic chemical markers for the types of rock that have formed the earth's crust. Although igneous rocks (those that solidify from magma) can have highly variable rare-earth element signatures (*dotted lines*), the pattern for most sedimentary rocks falls within a narrow range (*gray band*). That uniformity arises because sediments effectively record the average composition of the upper continental crust.

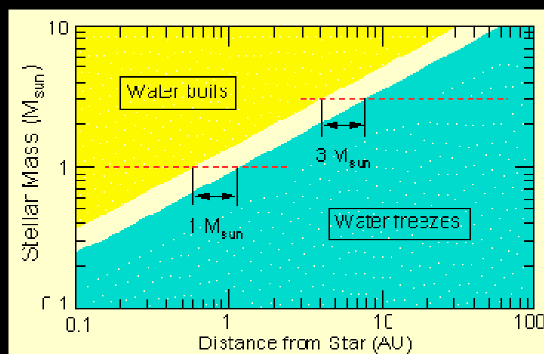
Sedimentary Rocks Represent Homogenous Mixture of Continental Crust

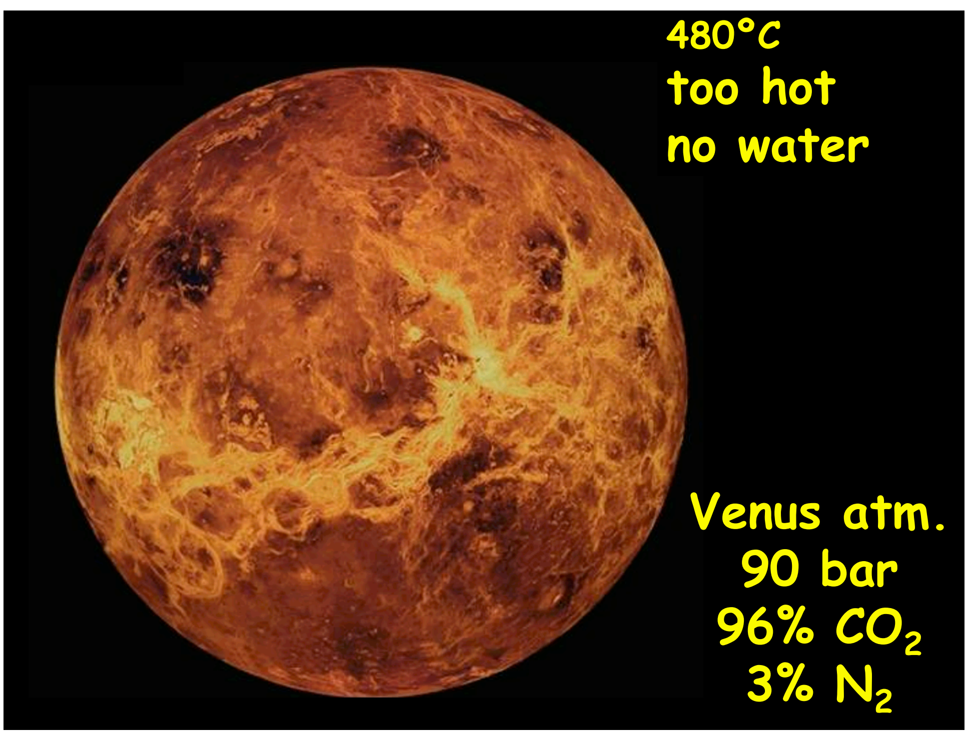
Taylor & McLennan *Sci*. *Am*. (1996)

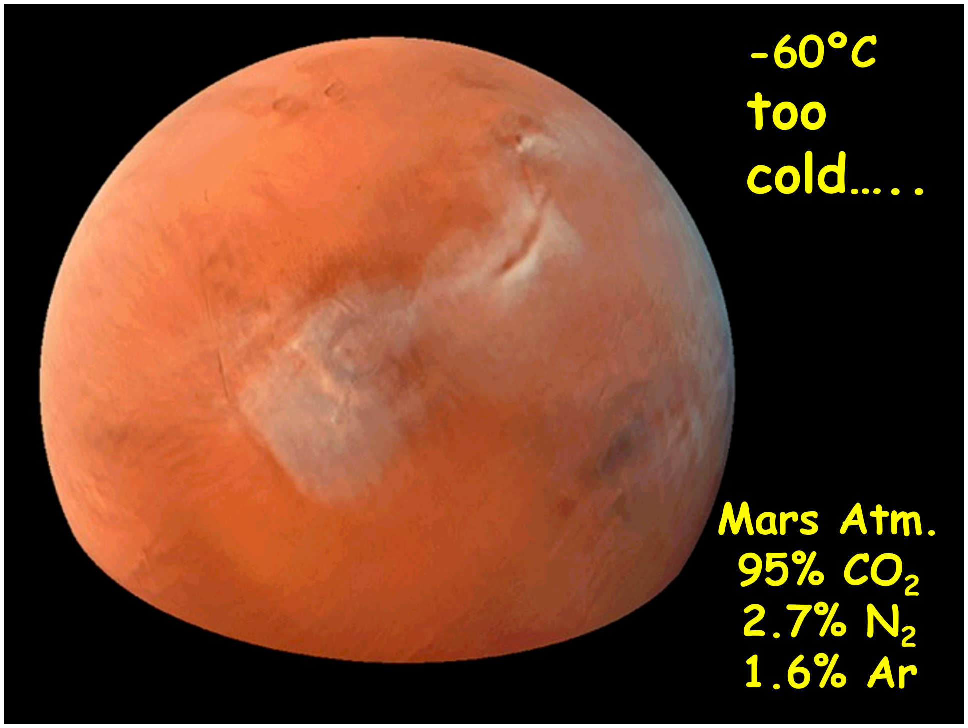
The Habitable Zone of the Solar System

Habitable Zone (Ecosphere)

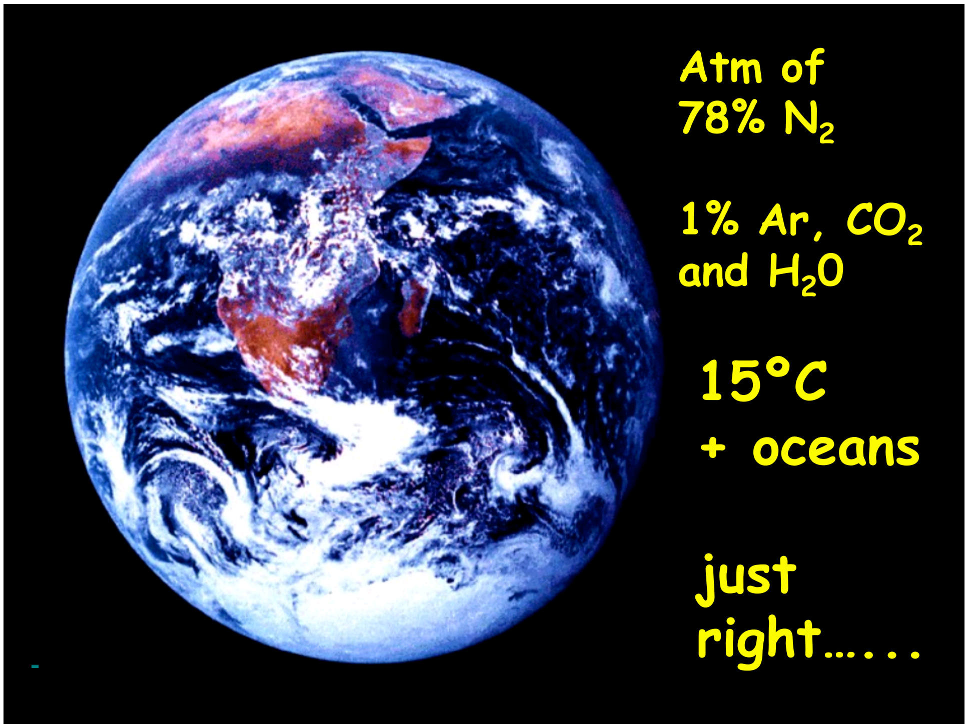
- Region around a star where planet temperature allows liquid water to exist
- $273 < T_p < 373$ K
- distance of the habitable zone from the star will vary depending on the type of star

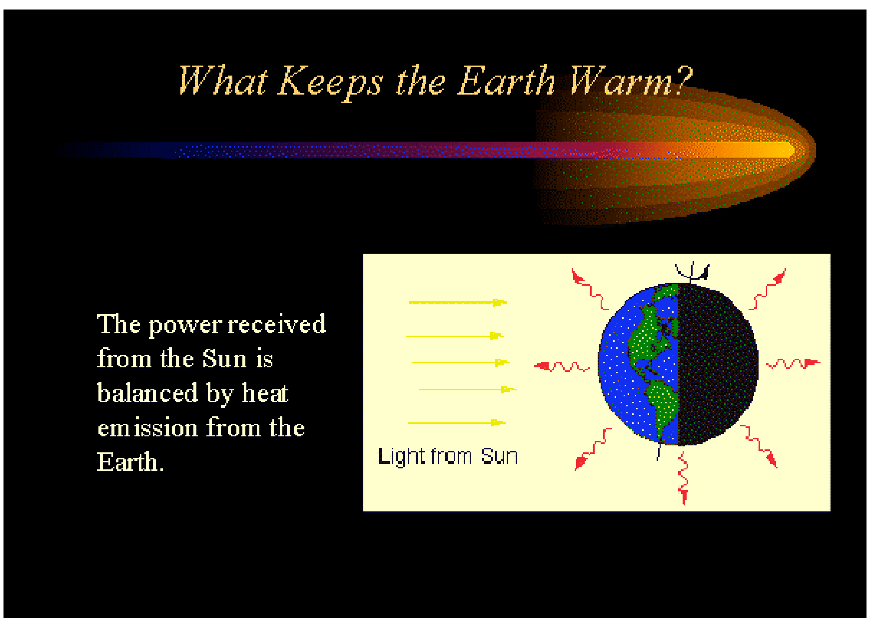





-60°C
too
cold…..
Mars Atm.
95% CO_2
2.7% N_2
1.6% Ar


no atmosphere
…..and no life


Atm of
78% N_2
1% Ar, CO_2
and H_2O
15°C
+ oceans
just
right…...


What Keeps the Earth Warm?
The power received from the Sun is balanced by heat emission from the Earth.
Light from Sun

Equilibrium Temperature

Power absorbed by the planet is: $P_{in} = (1-A)\dfrac{\pi R_p^2}{4\pi a_p^2} L_*$

where R_p is radius of planet, a_p the radius of its orbit and A is the albedo (reflectivity). If star and planet emit like black bodies:

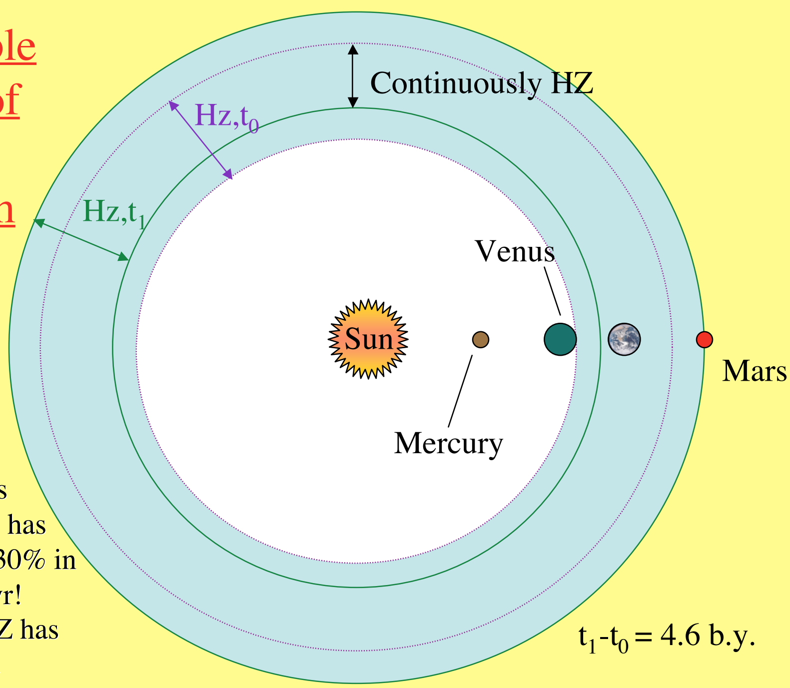
$P_{out} = 4\pi R_p^2 \sigma T_p^4$ and $L_* = 4\pi R_*^2 \sigma T_*^4$

where σ is Stefan's Constant. Equating $P_{in}=P_{out}$, we find

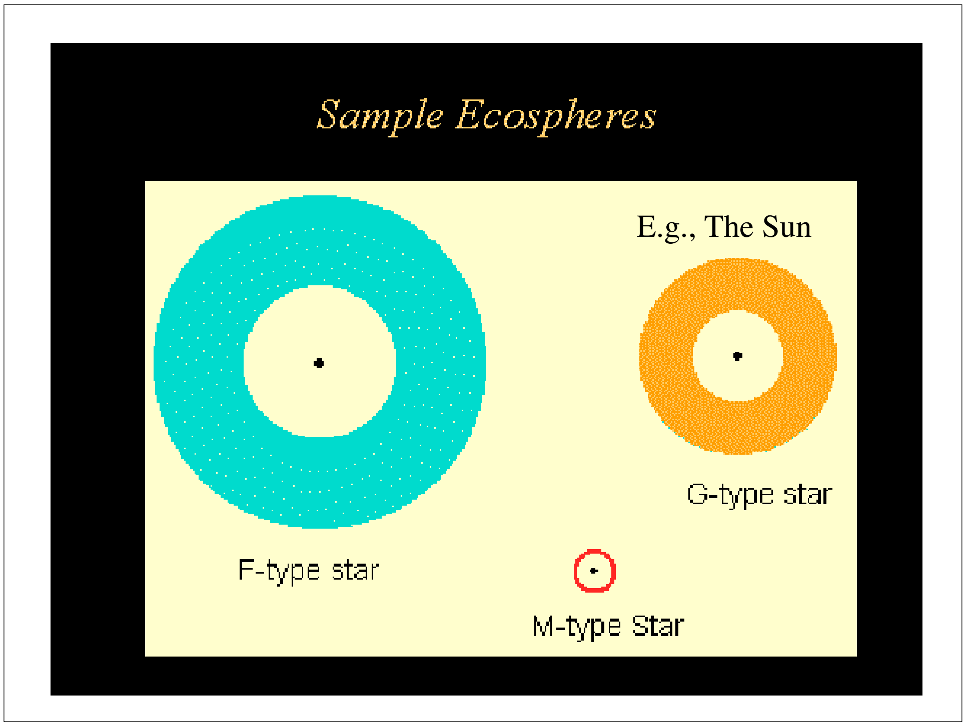
$$T_p = T_* \sqrt{\frac{R_*}{2a_p}}[1-A]^{1/4}$$

Must allow liquid water to exist!

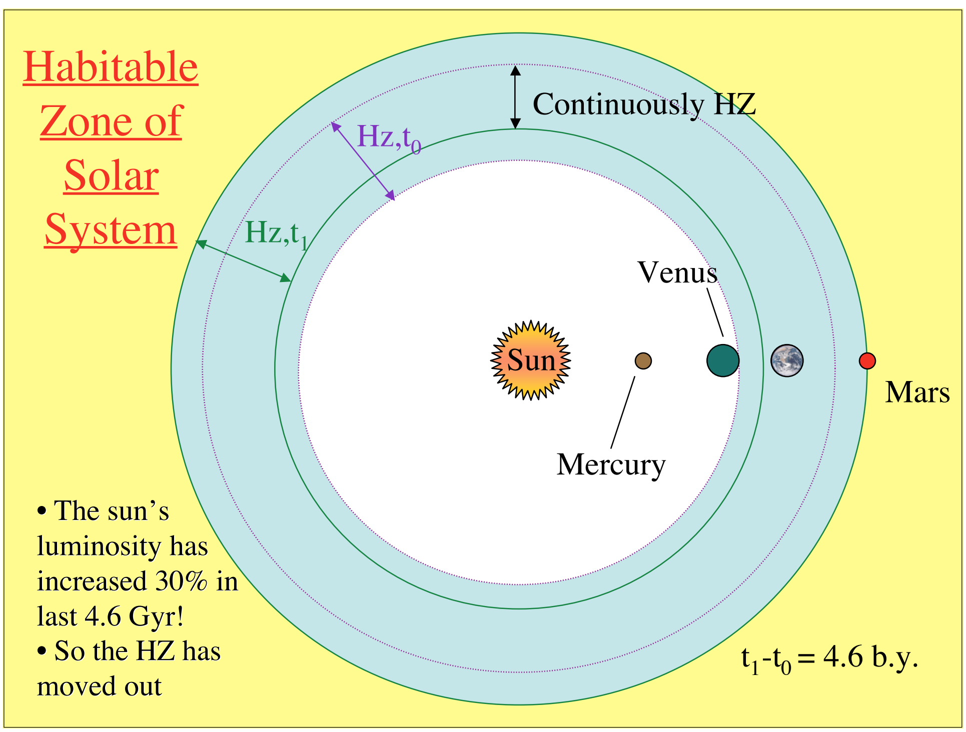
Habitable Zone of Solar System



- The sun's luminosity has increased 30% in last 4.6 Gyr!
- So the HZ has moved out



Sample Ecospheres
E.g., The Sun
G-type star
F-type star
M-type Star



Habitable Zone of Solar System
Continuously HZ
Hz,t_0
Hz,t_1
Venus
Sun
Mercury
Mars
• The sun's luminosity has increased 30% in last 4.6 Gyr!
• So the HZ has moved out
t_1-t_0 = 4.6 b.y.

Other Considerations Influencing HZ

Caveat: We are relegated to only considering life as we know it & to considering physical conditions similar to Earth

- Greenhouse effect: Increases surface T
  (e.g., Venus, at 0.72 AU, is within HZ, but T_s~745 K!)
- Lifetime of star: larger mass = shorter lifetime
  (must be long enough for evolution)
- UV radiation emission: larger mass = more UV
  (deleterious to life… as we know it)
- Habitable zone moves outward with time
  (star luminosity increases with age)

Further Characteristics of the Habitable Zone

- Liquid water
- Sources of carbon and energy
  - CO_2, organic matter
  - energy from chemistry of rocks + water
  - energy from the sun
- Mechanisms of renewal and recycling
  - Nutrients limited
  - Space = habitat limited (continents…)
  - **Mechanism = Tectonism. Is it that simple?**

The Galactic Habitable Zone

"The Galactic habitable zone (GHZ), analogous to the concept of the circumstellar habitable zone, is an annular region lying in the plane of the Galactic disk possessing the heavy elements necessary to form terrestrial planets and a sufficiently clement environment over several billion years to allow the biological evolution of complex multicellular life."

Lineweaver et al. (2004) *Science* Vol. 303: 59-62.

Habitable Zone of the Milky Way Galaxy

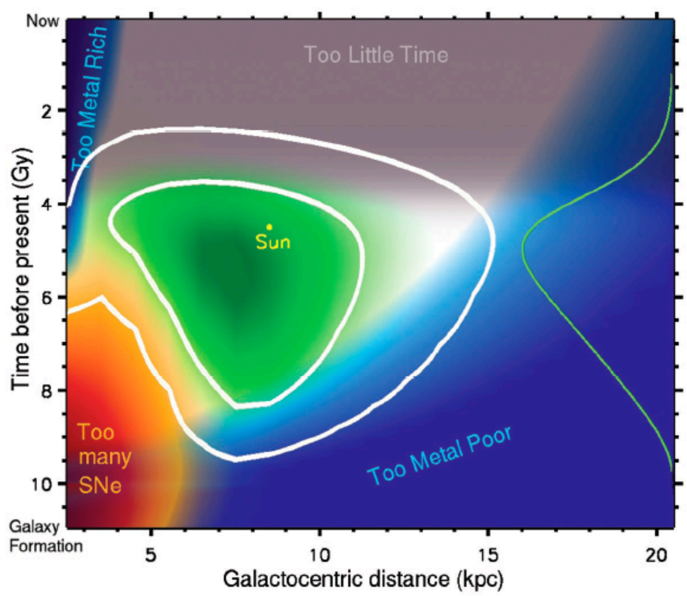
Requirements

•Metals (Fe)

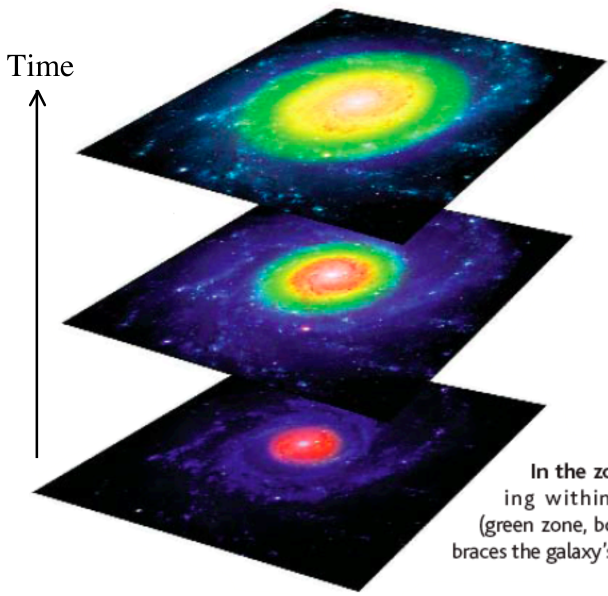
•Protection from supernovae

•Time for evolution

1 Parsec = 3.26



Lineweaver et al. (2004) *Science* Vol. 303: 59-62.

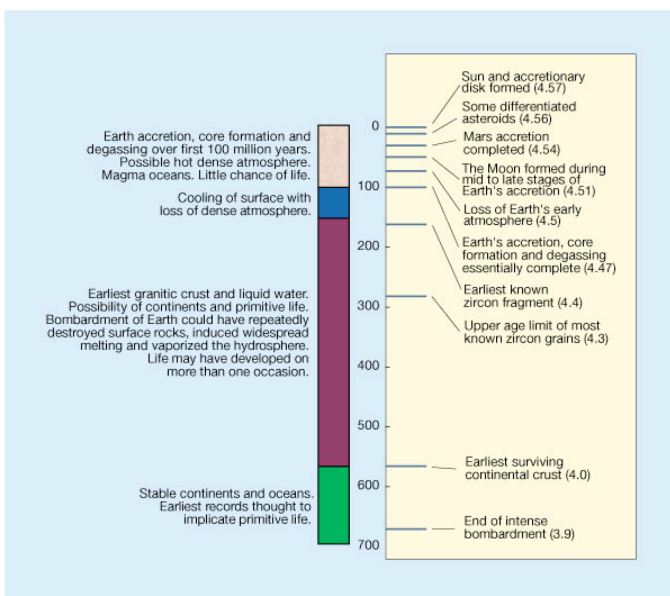


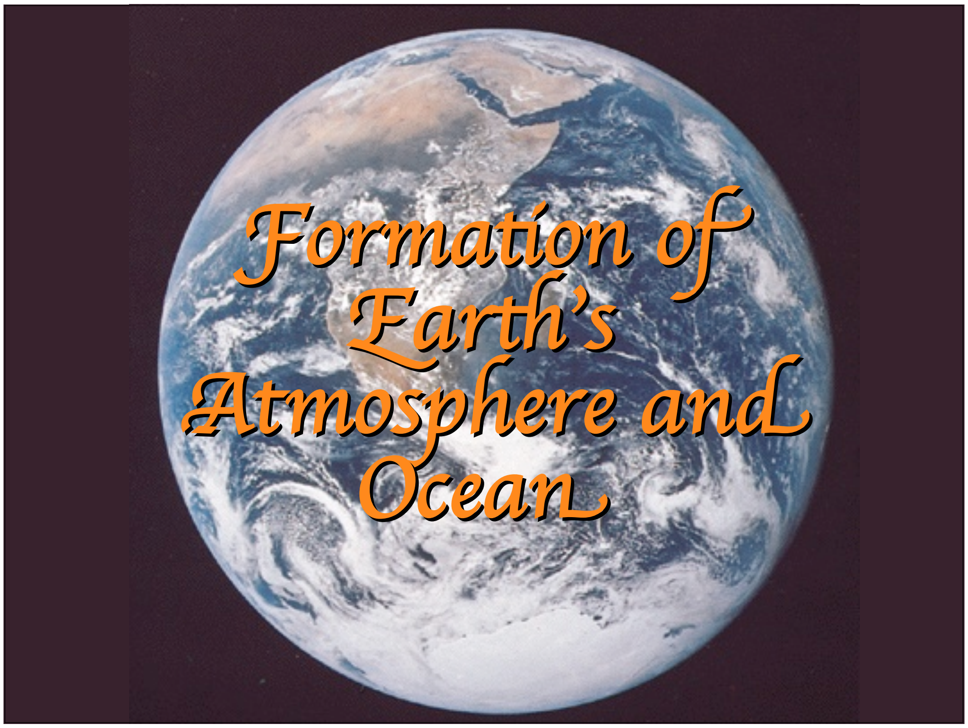
Milky Way HZ

In the zone. A ring spreading within the Milky Way (green zone, bottom to top) embraces the galaxy's life-friendly stars.

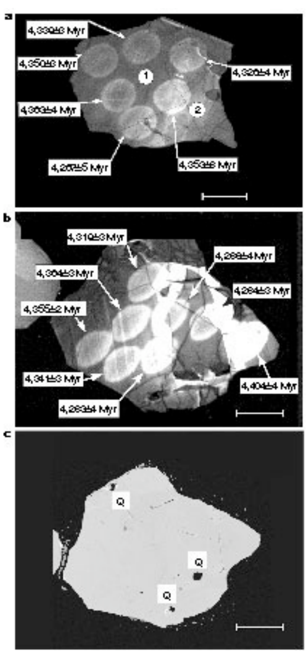
Irion (2004) *Science* Vol. 303: 26-27.

Early Earth History

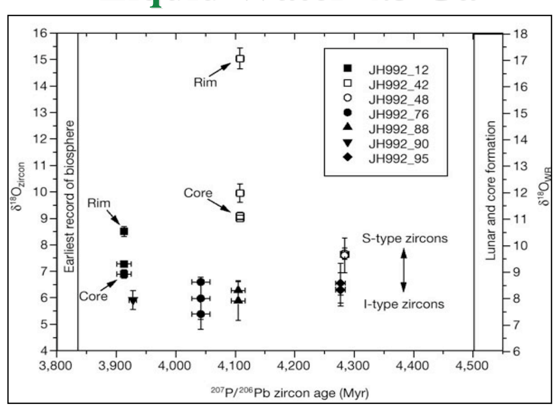




Evidence from Zircons for Liquid Water 4.3 Ga



Wilde et al., *Nature* (2001)



•Heavy oxygen isotope ratios ($^{18}O/^{16}O$) are produced by low-temperature interactions between rock & *liquid* water.

•4.3 Ga zircons have high $^{18}O/^{16}O$, implying the rocks that were melted to form the magma from which the zircons crystallized included material that had been at the surface in the presence of liquid water.

Theories for Origin of Earth's Volatile Components: Atmosphere & Oceans

•Arrived with the planetesimals, partly survived the accretion process and outgassed during volcanic activity (Hogbom 1894, Rubey 1951-5). Volcanic gases vary in composition; not primordial and may have been recycled many times. No record of the time and conclusive answers about this scenario (Turekian, 1972; Delsemme, 1997).

•Arrived with comets during the late bombardment - late veneer hypothesis (Delsemme, 1997)

•Arrived with one or more hydrated planetesimals from the outer asteroid belt (Morbidelli, 2001)

•Arrived with comets and mixed with accreted water

Formation of Atmosphere and Ocean

- Impact Degassing

  Planetesimals rich in volatiles (H_2O, N_2, CH_4, NH_3) bombard Earth

  Volatiles accumulate in atmosphere

  Energy of impact + Greenhouse effect = Hot surface

  (>450 km impactor would evaporate ocean)

- Steam Atmosphere?

  Or alternating condensed ocean / steam atmosphere

- Heavy Bombardment (4.6-3.8 Byr BP)

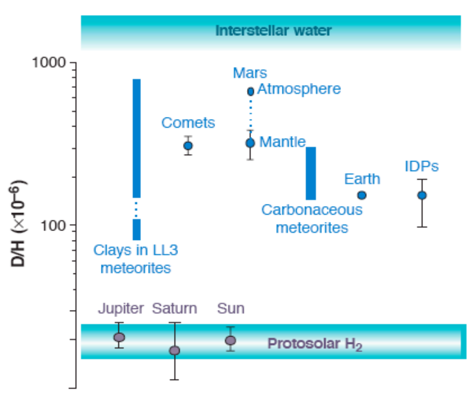
  1st 100 Myr main period of accretion

  Evidence from crater density and dated rocks on Moon, Mars and Mercury

Composition of Comet Halley Volatiles (modeled)

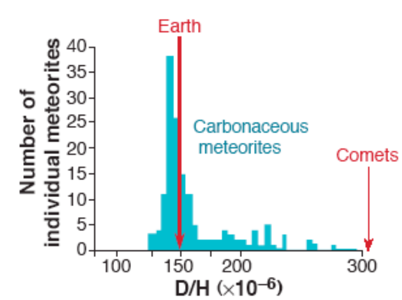
78.5 % H_2O	2.6% N_2	1.5% C_2H_4	0.1% H_2S
4.0% H_2CO	0.8% NH3	0.5% CH_4	0.05% S2
4.5% HCO-OH	1.0% HCN	0.2% C_3H_2	0.05% CS_2
1.5% CO	0.8% N_2H_4		
	0.4% $C_4H_4N_2$		
92% with O	5.6% with N	2.6% H/C	0.2% S

D/H Evidence for Origin of Earth's Water from Meteorites



An isotopic enigma. Distribution of the hydrogen isotopic composition in solar system bodies. Blue, water; purple, molecular hydrogen.

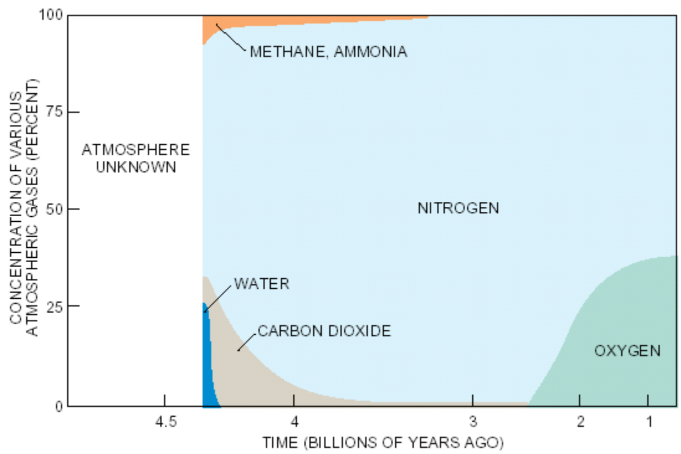
•Planets formed from collisional accretion of many primitive planets (10-1000 km diam) w/ unstable orbits around Sun
•Addition of water-rich bodies during accretion contributed small fraction of water but most added by a few late giant impactors.
•Late impactors had D/H ratios similar to carbonaceous meteorites because they originated from the same cold region of the asteroid belt.



Water from meteors. Distribution of the hydrogen isotopic ratio in carbonaceous meteorites compared with Earth and comets. According to this distribution, water on Earth seems mostly derived from a meteoritic source.

Robert (2001) *Science* Vol. 293: 1056-1058

Composition of Earth's Early Atmosphere



ATMOSPHERIC COMPOSITION, shown by the relative concentration of various gases, has been greatly influenced by life on the earth. The early atmosphere had fairly high concentrations of water and carbon dioxide and, some experts believe, methane, ammonia and nitrogen. After the emergence of living organisms, the oxygen that is so vital to our survival became more plentiful. Today carbon dioxide, methane and water exist only in trace amounts in the atmosphere.

Allegre & Schneider (1994)

Earth's Early Atmosphere

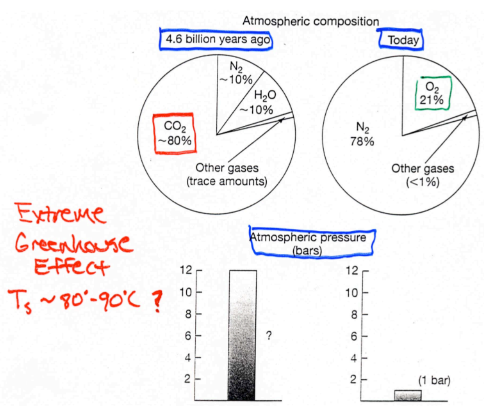


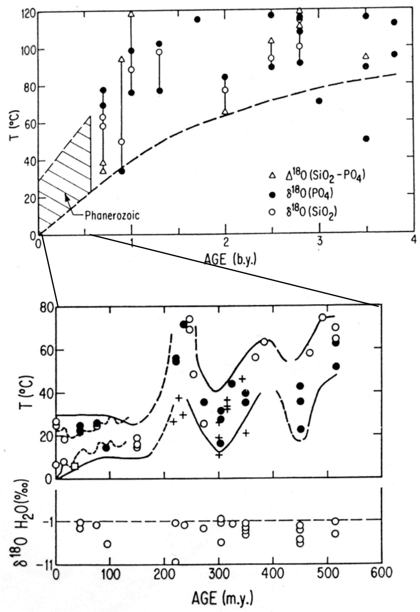
FIGURE 8-7
Possible atmospheric composition and pressure during the heavy bombardment period, compared with today.

Changes in Atmospheric Composition over Time

	Prebiotic Atmosphere	*Archean Atmosphere*	*Modern Atmosphere*
Surface pressure	1–10 bars	1–2 bars	1 bar
Constant → N_2	10–80%	50–80%	78%
O_2	about 0	about 0	21%
CO_2	30–90%	10–20%	0.036%
CH_4	10–100 ppm	1000–10,000 ppm	1.6 ppm
CO	100–1000 ppm		0.1–0.2 ppm
H_2	100–1000 ppm		0.5 ppm

Kump et al. (1999) The Earth System, Prentice Hall, New Jersey, 351 p.

Evidence for High Surface T on early Earth



• Oxygen isotope ratios in cherts & phosphates indicate surface temperatures may have exceeded 60°C for most of the period 4-1 Gyr ago

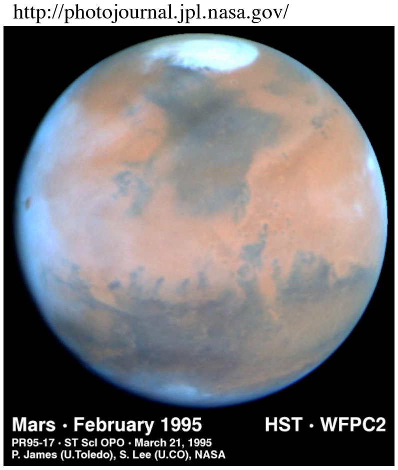
USGS image

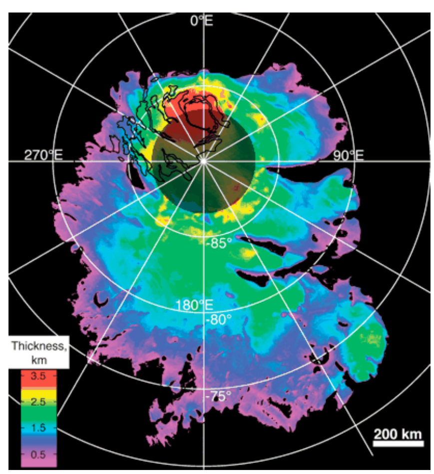
Karhu & Epstein (1986) *Geochimica et Cosmochimica Acta* Vol. 50: 1745-1756

Water Elsewhere in Solar System:

Water Ice on Mars

http://photojournal.jpl.nasa.gov/

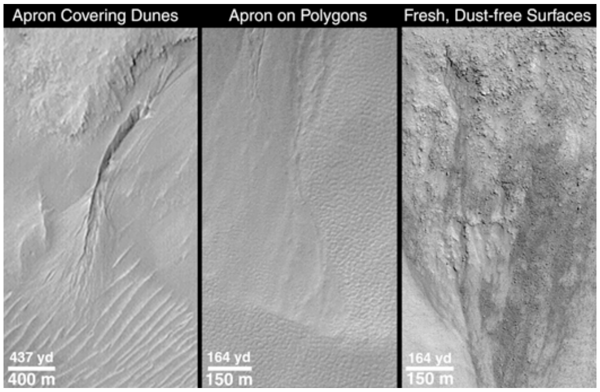




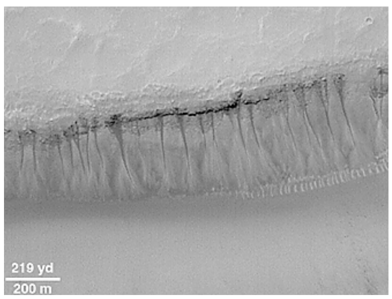
Plaut et al. (2007) *Science* Vol. 316: 92-95.

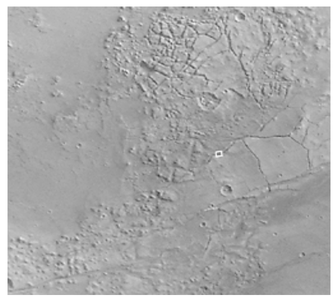
• South Pole water ice thickness: The total volume is estimated to be 1.6 x 10^6 cubic kilometers, which is equivalent to a global water layer approximately 11 meters thick.

Evidence of Recent Water flow on Mars



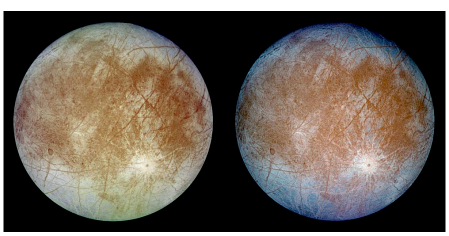
- Martian gullies proposed to have formed by seepage & runoff of liquid water in recent martian times





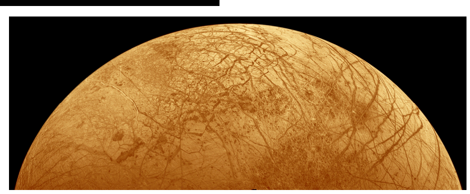
http://www.msss.com/mars_images/moc/june2000/age/index.html

Water on Europa

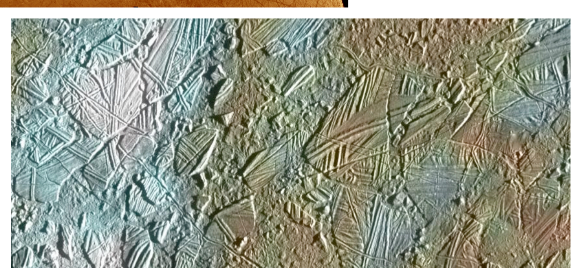


- One of Jupiter's 4 large (Galilean) satellites
- 25% of Earth's radius

- Crust composed of water & ice



- Fragmented chunks of water ice on Europa's surface



http://science.nasa.gov/newhome/headlines/ast09sep99_1.htm; http://www.solarviews.com/eng/europa.htm