12.842 / 12.301 Past and Present Climate
Fall 2008

12.842 Climate Physics and Chemistry

Fall 2008

Ed Boyle, Kerry Emanuel, Carl Wunsch

Paleoclimate Lectures

Sept. 8, 10, 12, 15, 17, 19, 26, 29

Ocean & Atmospheric Chemistry Lectures

Oct. 20, 22, 24 27, 29, 31

Climate Physics and Chemistry Fall 2008 **Paleoclimate Outline**

I. The Origin of the Elements, Galaxies, Solar System, and Earth

A. Big bang: H and He
B. Early Stars: 100-1000 solar masses
C. Fusion nucleosynthesis
D. Supervovae and neutron-capture nucleosynthesis
E. Galaxies
F. Solar nebula and planetary formation
G. Accretion and planetary differentiation; formation of the moon
H. Plate tectonics

II. The Origin and Co-Evolution of the Atmosphere, Life, and the Earth Surface

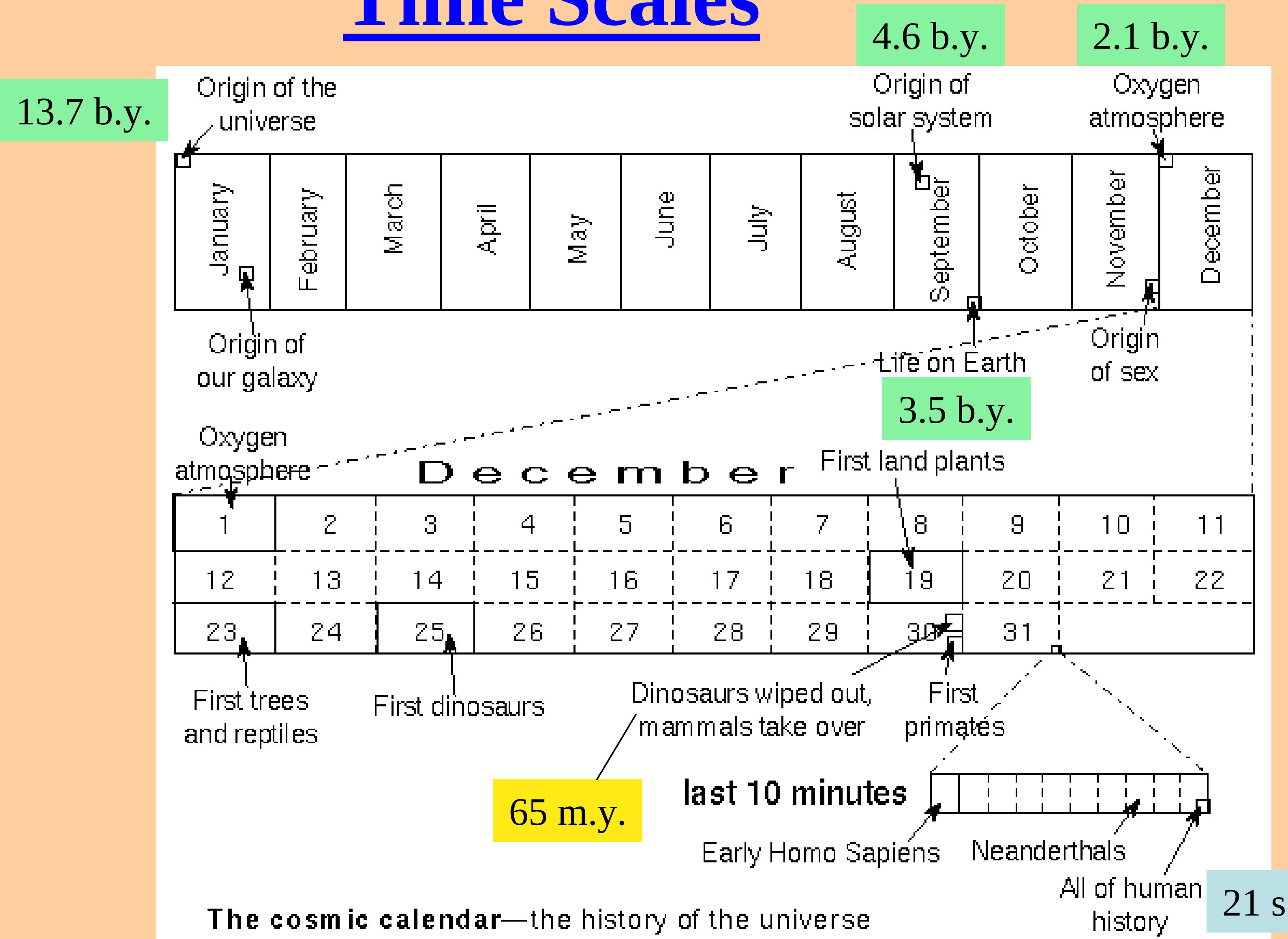
A. Evidence on the origin of microbial life
B. Evolution of atmospheric composition and the rise of oxygen
C. The Proterozoic: evolution of complex multicellular organisms

III. Evolution of the Earth's Climate

A. Planetary radiation balance and the faint young sun paradox
B. The greenhouse effect and radiatively active gases
C. The CO_2-climate connection: global carbon cycle (tectonics, volcanism, rainfall and weathering, and buffering effect on surface temperature)
D. Snowball earth?
E. Proterozoic climate evolution: sunny with a chance of snow
F. Biotic crises: global mass extinctions
G. The Cenozoic slide towards glaciation
H. Pleistocene ice ages
I. Abrupt climate change

The Origin of the Earth, Atmosphere & Life

Time Scales



The cosmic calendar—the history of the universe compressed to one year. All of recorded history (human civilization) occurs in last 21 seconds!

Avg. human life span=0.15 s

Outline:

I. The first three minutes of the big bang (beginning at the point where experimentally verified physics applies).

II. Formation of stars and galaxies

III. Stellar nucleosynthesis

IV. Supernova nucleosynthesis

V. Formation and differentiation of planets

Time	T(K)	E	Density	What's Happening?

The standard cosmological model of the formation of the universe:

"The Big Bang"

Table removed due to copyright restrictions.

- From Steven Weinberg, ***The First Three Minutes***

- Also see: http://superstringtheory.com/cosmo/cosmo3.html for a terrific tour of the Big Bang!

Outline:

I. The first three minutes of the big bang (beginning at the point where experimentally verified physics applies

A. When we begin, the universe is about the size of a baseball. Quarks and antiquarks existed in almost equal numbers. There was a slight excess of quarks over antiquarks (1 in 10^9). Most of the rest of the quarks and antiquarks annihilated each other and are converted to photons, with a few surviving as protons and neutrons.

B. At t=0.02 seconds, the universe is the size of a baseball and consists mainly of photons (10^9 for every proton or neutron).

C. Electrons and positrons are being created from photons ("pair production"). Protons and neutrons created from quarks interconvert (proton<->neutron). Approximately equal numbers of protons and neutrons.

D. Free neutrons are not stable (they decay in about 10 minutes). As interconversion slows with decreasing temperature, the universe develops an excess of protons over neutrons.

E. Thirteen seconds after the beginning, the universe has cooled sufficiently that pair production ceases.

F. Three minutes after the beginning, electrons and positrons are nearly all gone. The universe has coole sufficiently to allow protons and neutrons to bind together to form deuterium nuclei, and then helium nuclei. Neutrons are stable in the nucleus, so proton:neutron ratio stabilizes at 86:14). Hydrogen (74% and helium (26%) nuclei comprise the mass of the universe. Nothing heavier is formed.

G. 35 minutes: Nuclear processes stop. Excess of 1 electron in 10^9 survives from primeval fireball. Universe is opaque to radiation because of strong interactions between nuclei and photons.

H. ~100,000 years: Universe has cooled to ~3000°K. During a 30,000 year period, temperature of univer cools from 3000°K to 2700°K. Probability of black-body photons having an energy of >13.7 electron volts (the binding energy of a hydrogen atom) becomes infinitesimal, and atoms become stable. Universe becomes transparent to radiation. Cosmic background radiation fills the universe and cools a universe expands.

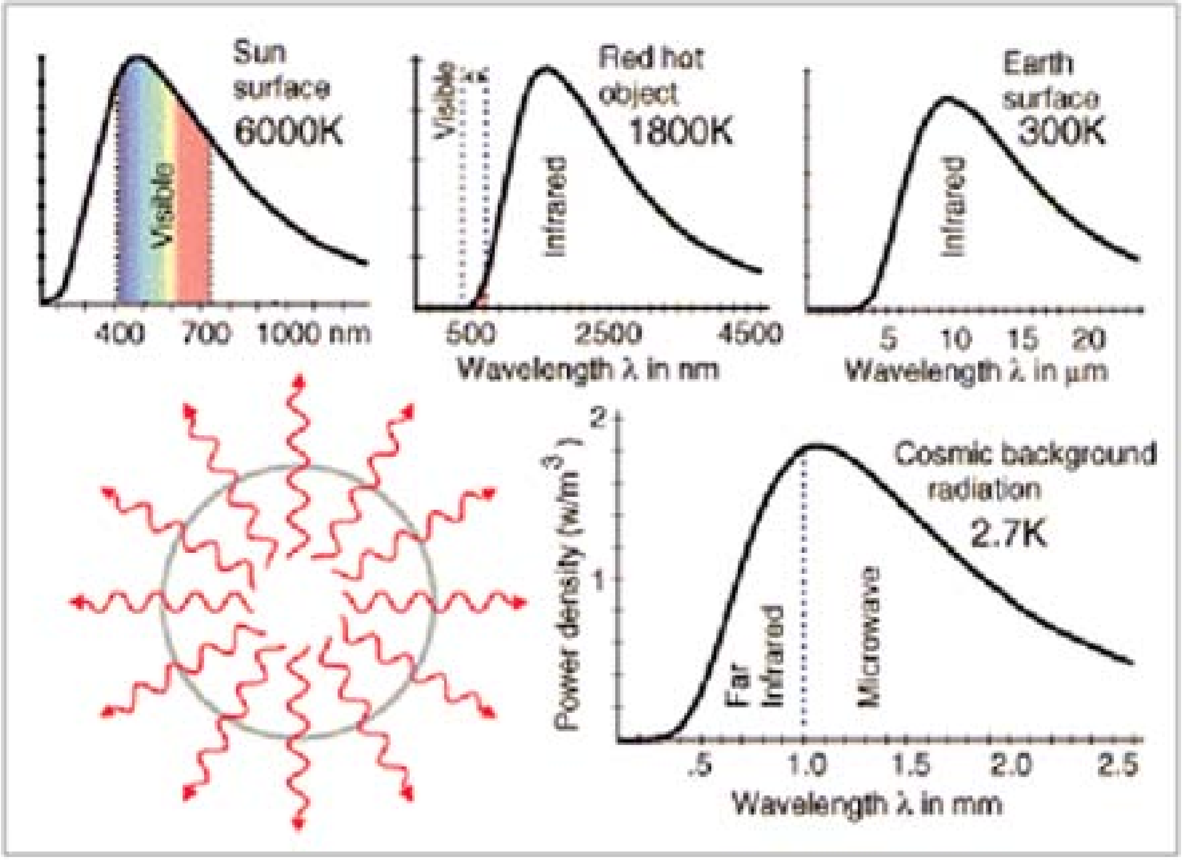
Also note that the total charge is nearly neutral.

Evidence for the Big Bang #1: An Expanding Universe

- The galaxies we see in all directions are moving away from the Earth, as evidenced by their red shifts.
- The fact that we see all stars moving away from us does not imply that we are the center of the universe!
- All stars will see all other stars moving away from them in an expanding universe.
- A rising loaf of raisin bread is a good visual model: each raisin will see all other raisins moving away from it as the loaf expands.

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html & http://map.gsfc.nasa.gov/m_uni/uni_101bbtest1.html & http://en.wikipedia.org/wiki/Metric_expansion_of_space

Evidence for the Big Bang #2: The 3K Cosmic Microwave Background



- Uniform background radiation in the microwave region of the spectrum is observed in all directions in the sky.
- Has the wavelength dependence of a Blackbody radiator at ~3K.
- Considered to be the remnant of the radiation emitted at the time the expanding universe became transparent (to radiation) at ~3000 K. (Above that T matter exists as a plasma (ionized atoms) & is opaque to most radiation.)

The Cosmic Microwave Background in Exquisite Detail: Results from the Microwave Anisotropy Probe (MAP)-Feb. 2003

- Age of universe: 13.7 +/- 0.14 Ga

Image removed due to copyright restrictions.

Results from the Cosmic Microwave Anisotropy Probe (CMAP), Seife (2003) *Science*, Vol. 299:992-993.

utline:

The first three minutes of the big bang (beginning at the point where experimentally verified physics applies).

A. When we begin, the universe is about the size of a baseball. Quarks and antiquarks existed in almost equal numbers. There was a slight excess of quarks over antiquarks (1 in 10^9). Most of the rest of the quarks and antiquarks annihilated each other and are converted to photons, with a few surviving as protons and neutrons.

B. At t=0.02 seconds, the universe is the size of a baseball and consists mainly of photons (10^9 for every proton or neutron).

C. Electrons and positrons are being created from photons ("pair production"). Protons and neutrons created from quarks interconvert (proton<->neutron). Approximately equal numbers of protons and neutrons.

D. Free neutrons are not stable (they decay in about 10 minutes). As interconversion slows with decreasing temperature, the universe develops an excess of protons over neutrons.

E. Thirteen seconds after the beginning, the universe has cooled sufficiently that pair production ceases.

F. Three minutes after the beginning, electrons and positrons are nearly all gone. The universe has cooled sufficiently to allow protons and neutrons to bind together to form deuterium nuclei, and then helium nuclei. Neutrons are stable in the nucleus, so proton:neutron ratio stabilizes at 86:14). Hydrogen (74%) and helium (26%) nuclei comprise the mass of the universe. Nothing heavier is formed.

G. 35 minutes: Nuclear processes stop. Excess of 1 electron in 10^9 survives from primeval fireball. Universe is opaque to radiation because of strong interactions between nuclei and photons.

H. ~100,000 years: Universe has cooled to ~3000°K. During a 30,000 year period, temperature of universe cools from 3000°K to 2700°K. Probability of black-body photons having an energy of >13.7 electron volts (the binding energy of a hydrogen atom) becomes infinitesimal, and atoms become stable. Universe becomes transparent to radiation. Cosmic background radiation fills the universe and cools as universe expands.

Also note that the total charge is nearly neutral.

Time T(K) E Density What's Happening?

The standard cosmological model of the formation of the universe:

"The Big Bang"

Table removed due to copyright restrictions.

- From Steven Weinberg, ***The First Three Minutes***

- Also see: http://superstringtheory.com/cosmo/cosmo3.html for a terrific tour of the Big Bang!

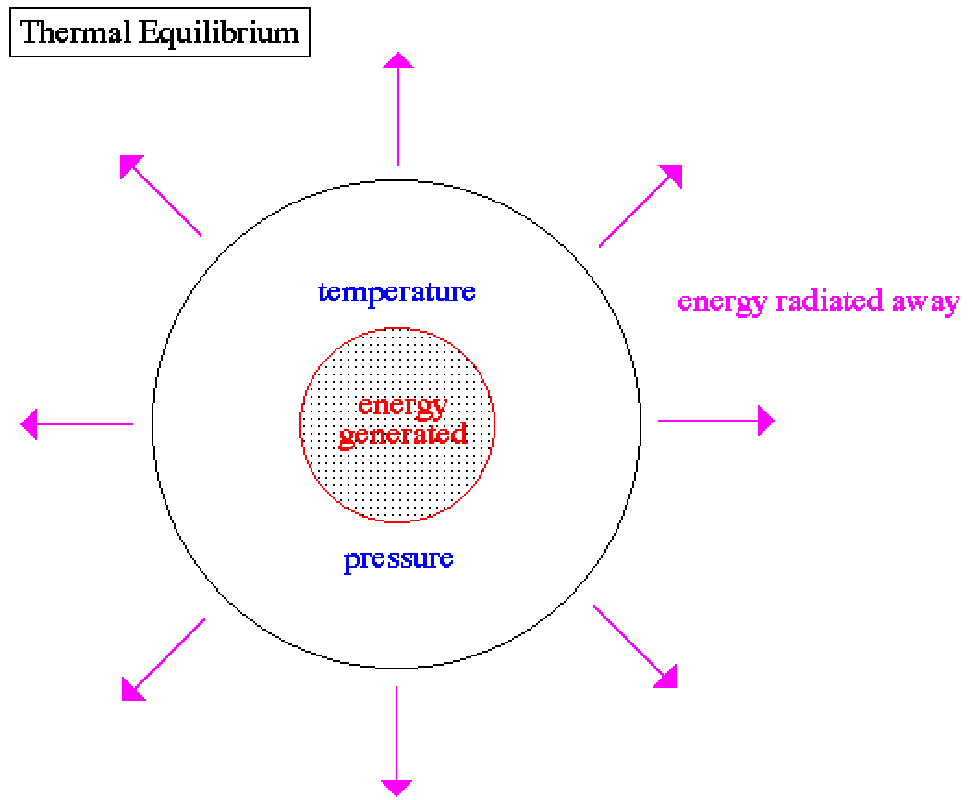
First stars:
100-250 million years after the big bang

- 100-1000 solar masses
- 4-14 solar radii
- 1-30,000,000 solar luminosity units
- 100,000-110,000°K
- 3,000,000 year lifetime

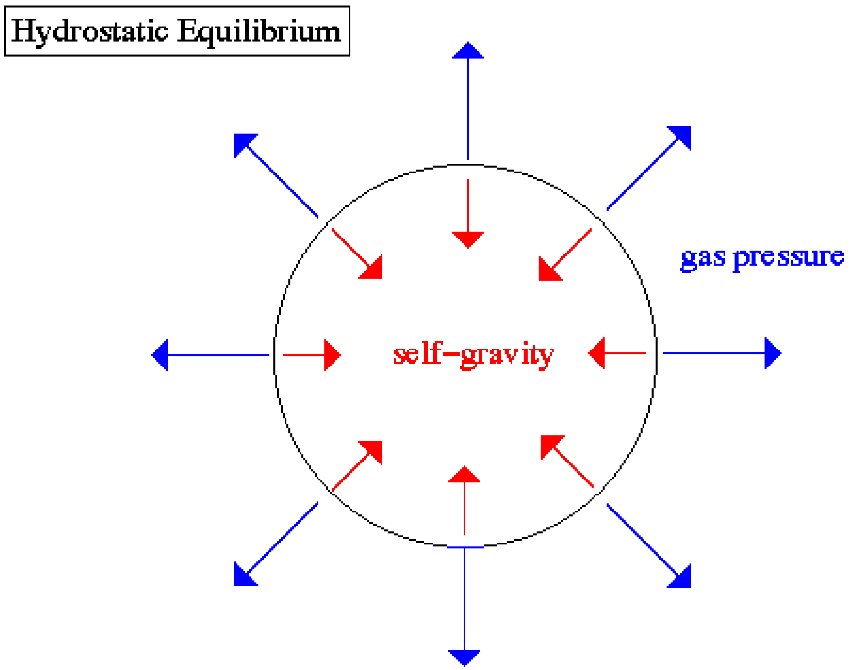
Star Maintenance

•Gravity balances pressure (Hydrostatic Equilibrium)

•Energy generated is radiated away (Thermal Equilibrium)



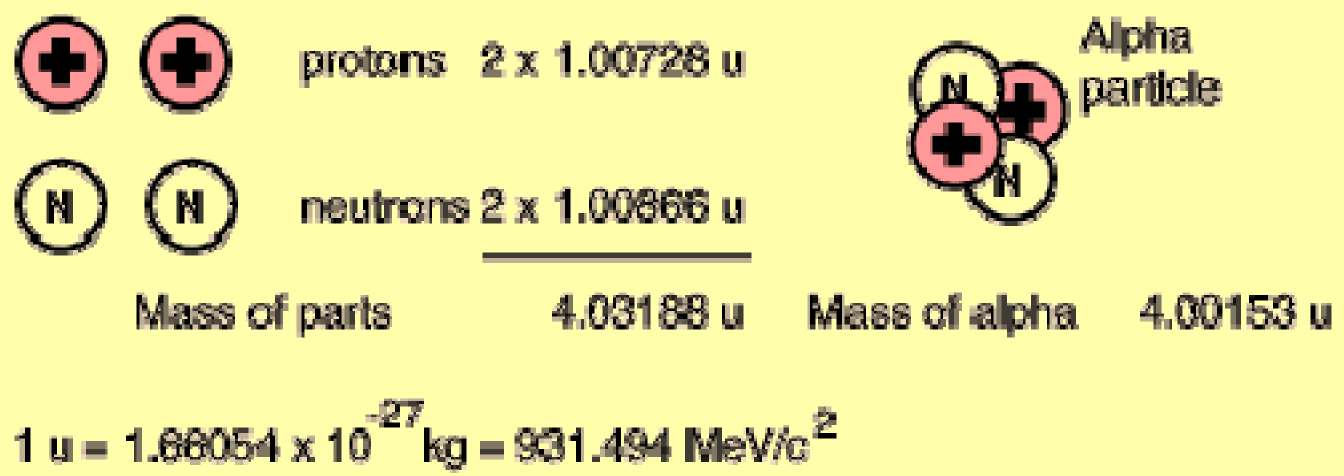
the energy generated must be radiated away, if the energy production is increased, the temperature goes up, therefore the pressure goes up and the star expands – the surface area increases and more energy is radiated to space to balance the increased production



the Sun is not expanding or contracting, therefore it is in equilibrium, the downward force of gravity is balanced by the higher force of pressure

Nuclear Binding Energy

- Nuclei are made up of protons and neutrons, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.
- The difference is a measure of the nuclear binding energy which holds the nucleus together.
- This energy is released during fusion.



- BE can be calculated from the relationship: BE = Δmc^2
- For α particle, Δm= 0.0304 u, yielding BE=28.3 MeV

The mass of nuclei heavier than Fe is *greater* than the mass of the nuclei merged to form it.

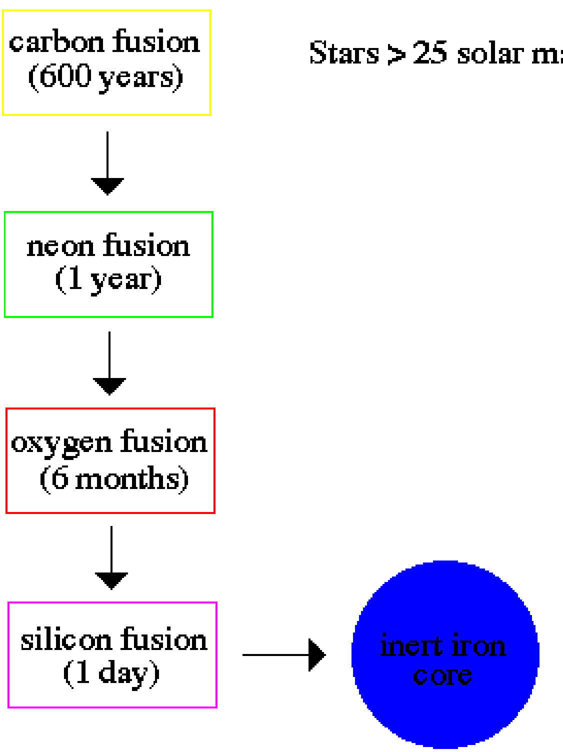
Hydrogen to Iron

- Elements above iron in the periodic table cannot be formed in the normal nuclear fusion processes in stars.
- Up to iron, fusion yields energy and thus can proceed.
- But since the "iron group" is at the peak of the binding energy curve, fusion of elements above iron dramatically absorbs energy.

Image removed due to copyright restrictions.

Supernovae: Death of massive stars

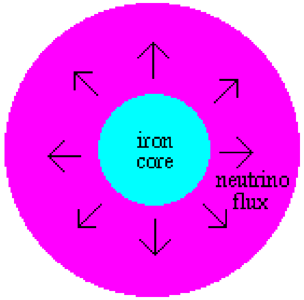
Stars > 25 solar masses



Supernova Explosion

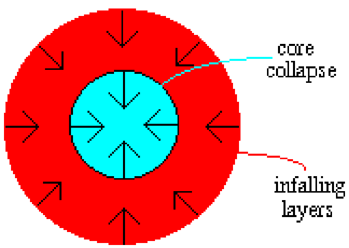
Inert iron core stops producing energy, but continues to produce neutrinos which release energy from core

Densities climb, protons and electrons combine to produce neutrons and more neutrinos



Sudden lost of energy causes core to collapse from lack of pressure support

Regions around core are unsupported and plunge onto core at speeds up to 15% the speed of light

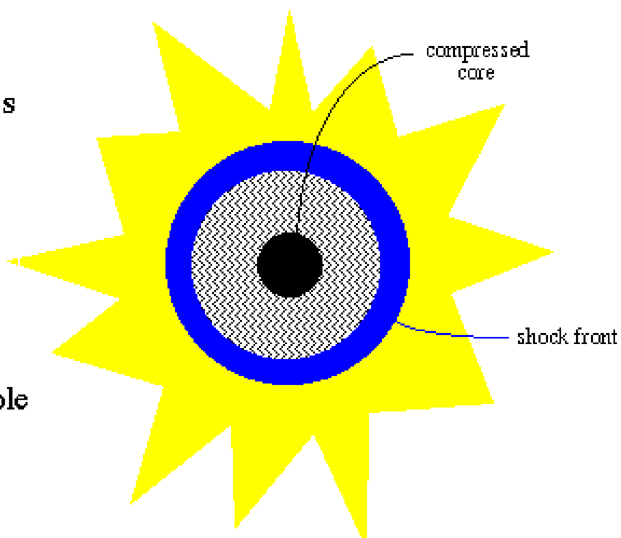


Neutron densities are so high in core that it is incompressible and rigid. Infalling layers strike core and rebound.

In a fraction of a second, a wave of matter forms a shock front and moves outward towards stellar surface.

Shock wave hits surface of star and explodes

Inward shock compresses remaining stellar core into neutron star or black hole



Supernovae

- E release so immense that star outshines an entire galaxy for a few days.

Images removed due to copyright restrictions.

Supernova 1991T in galaxy M51

- Supernova can be seen in nearby galaxies, ~ one every 100 years (at least one supernova should be observed if 100 galaxies are surveyed/yr).

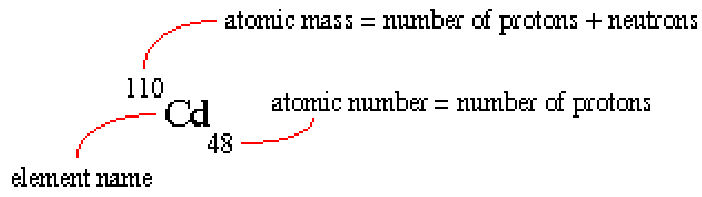
Neutron Capture & Radioactive Decay

- Neutron capture in supernova explosions produces some unstable nuclei.

- These nuclei radioactively decay until a stable isotope is reached.

Nucleosynthesis by Neutron Capture

construction of elements beyond iron involves the capture of a neutron to produce isophotes. Unstable isotopes decay into new elements



$^{110}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{111}_{48}Cd$ neutron capture

$^{111}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{112}_{48}Cd$ stable isotope

$^{112}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{113}_{48}Cd$ stable isotope

$^{113}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{114}_{48}Cd$ stable isotope

$^{114}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{115}_{48}Cd$ unstable isotope

$^{115}_{48}Cd \longrightarrow {}^{115}_{49}In + e^{-} + \nu$ radioactive decay

Nucleosynthesis I: Fusion Reactions in Stars

Fusion Process	**Reaction**	**Ignition T (10^6 K)**
Hydrogen Burning	H-->He,Li,Be,B	50-100
Helium Burning	He-->C,O	200-300
Carbon Burning	C->O,Ne,Na,Mg	800-1000
Neon, Oxygen Burning	Ne,O-->Mg-S	2000
Silicon Burning	Si-->**Fe**	3000

Produced in early universe

3 He = C, 4 He = O

Fe is the end of the line for E-producing fusion reactions...

Elements Heavier than Iron

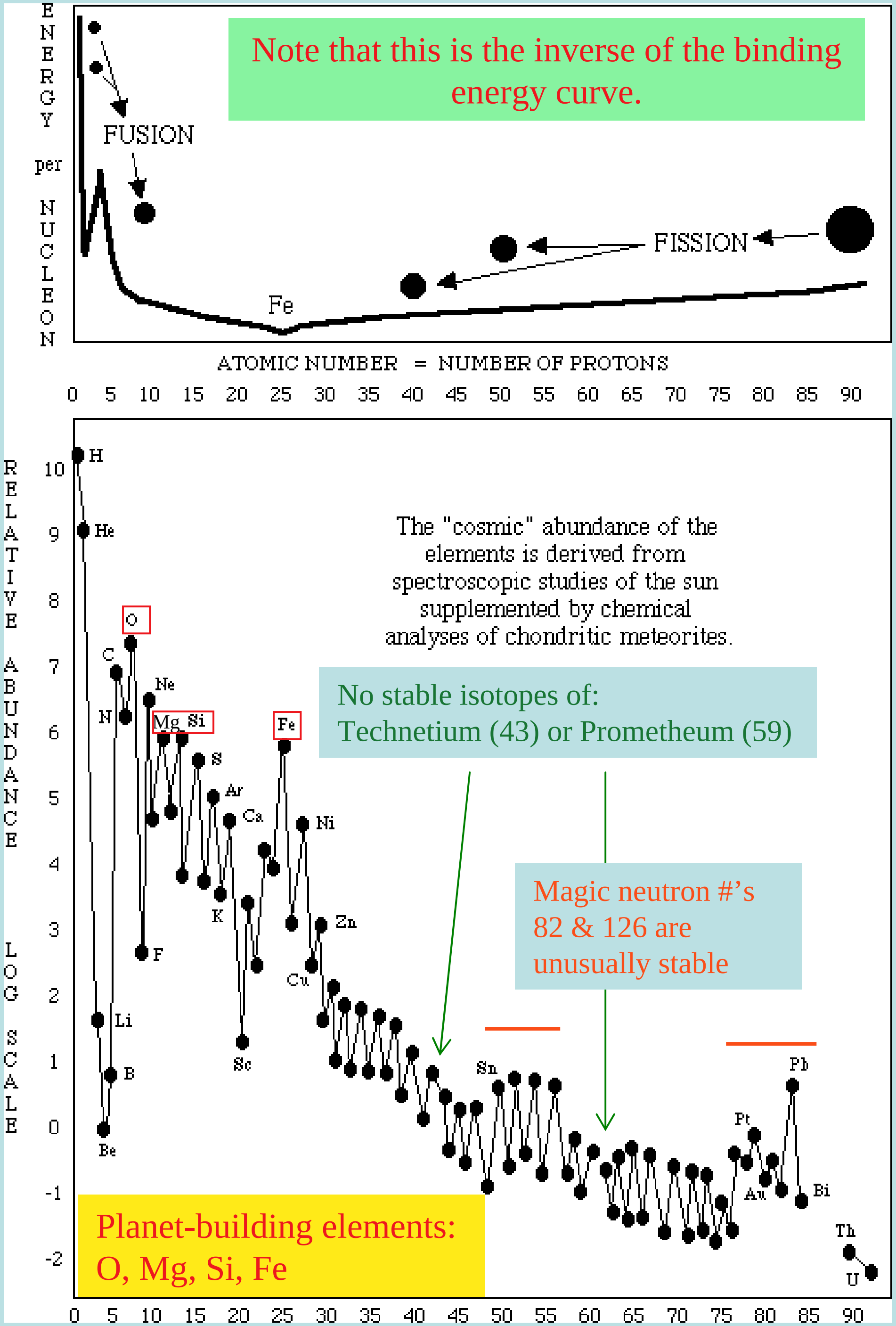
•To produce elements heavier than Fe, enormous amounts of energy are needed which is thought to derive solely from the cataclysmic explosions of supernovae.

•In the supernova explosion, a large flux of energetic neutrons is produced and nuclei bombarded by these neutrons build up mass one unit at a time (neutron capture) producing heavy nuclei.

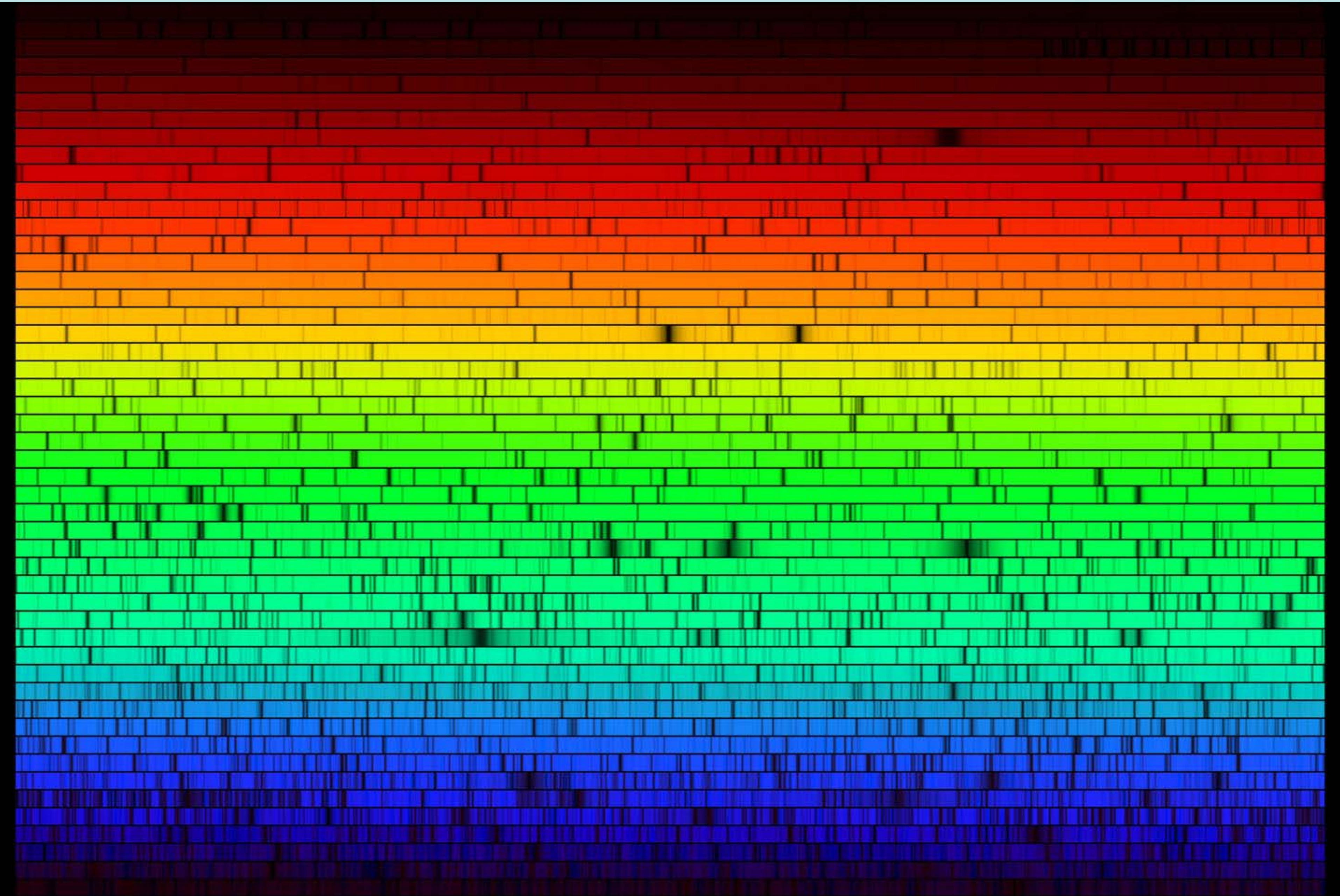
•The layers containing the heavy elements can then be blown off be the explosion to provide the raw material of heavy elements in distant hydrogen clouds where new stars form.

Cosmic Abundance of the Elements

- H (73%) & He (25%) account for 98% of all nuclear matter in the universe.
- Low abundances of Li, Be, B due to high combustibility in stars.
- High abundance of nuclei w/ mass divisible by ^{4}He: C,O,Ne,Mg,Si,S,Ar,Ca
- High Fe abundance due to max binding energy.
- Even heavy nuclides favored over odd due to lower “neutron-capture cross-section” (smaller target = higher abundance).
- All nuclei with >208 particles are radioactive (^{209}Bi was recently shown to be extremely weakly radioactive).



Solar spectrum



Galaxies!

- A remarkable deep space photograph made by the Hubble Space Telescope
- Every visible object (except the one foreground star) is thought to be a galaxy.

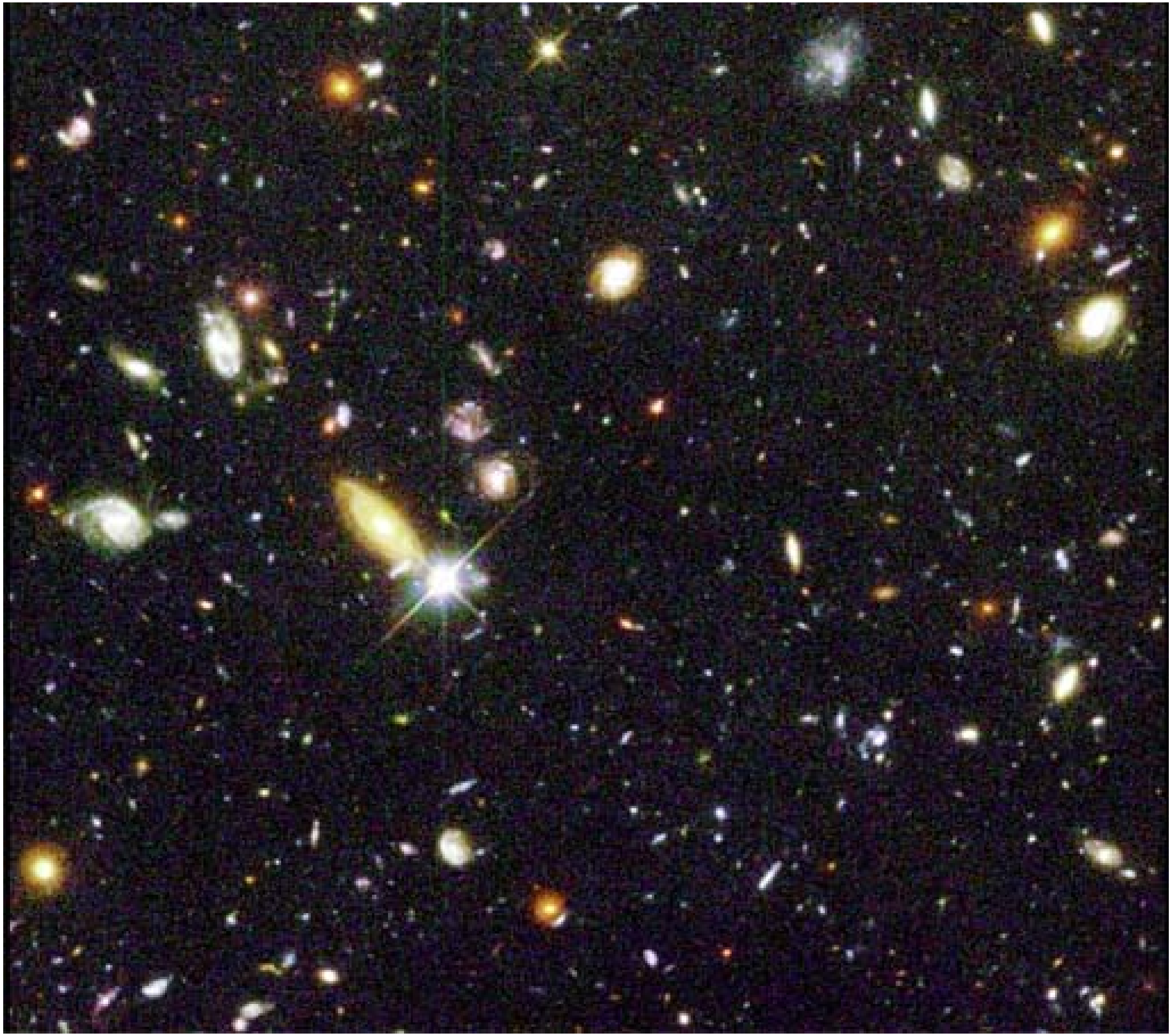


Image courtesy of NASA.

Galaxy Geometries & The Milky Way

- There are many geometries of galaxies including the spiral galaxy characteristic of our own Milky Way.

Image removed due to copyright restrictions.

Image removed due to copyright restrictions.

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

- Several hundred billion stars make up our galaxy
- The sun is ~26 lt.y. from the center

Protostar Formation from Dark Nebulae

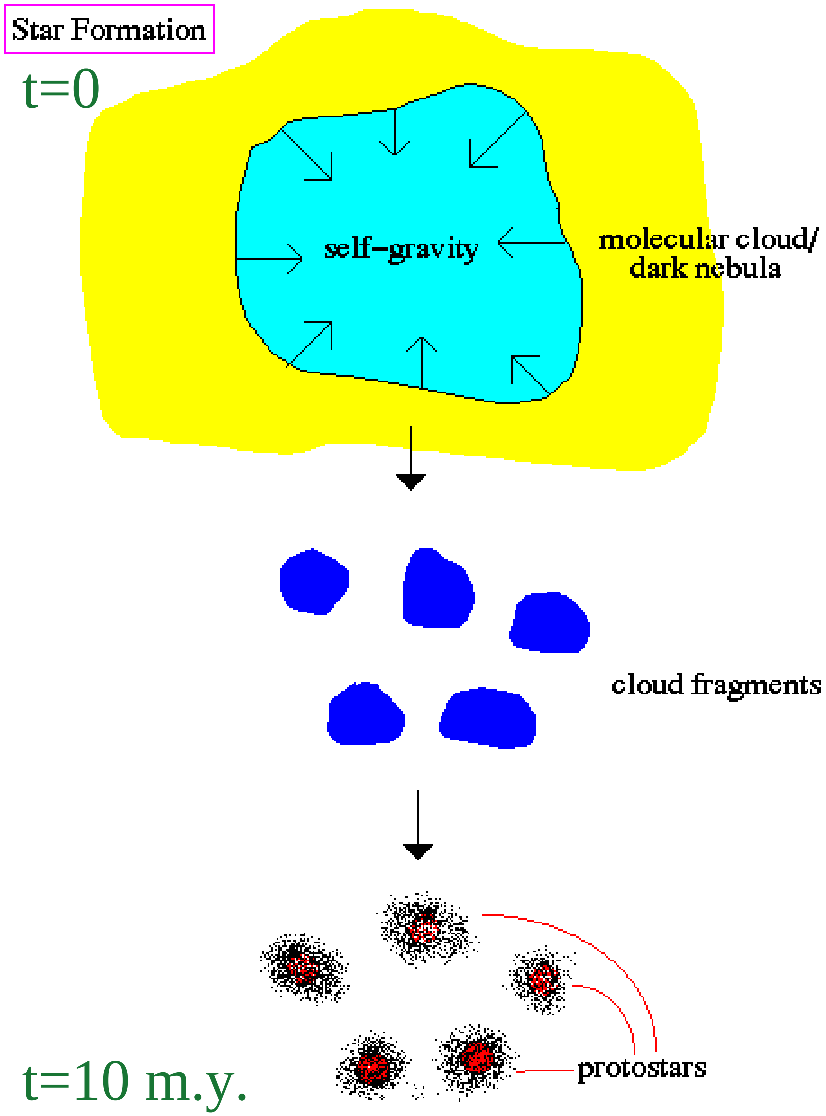
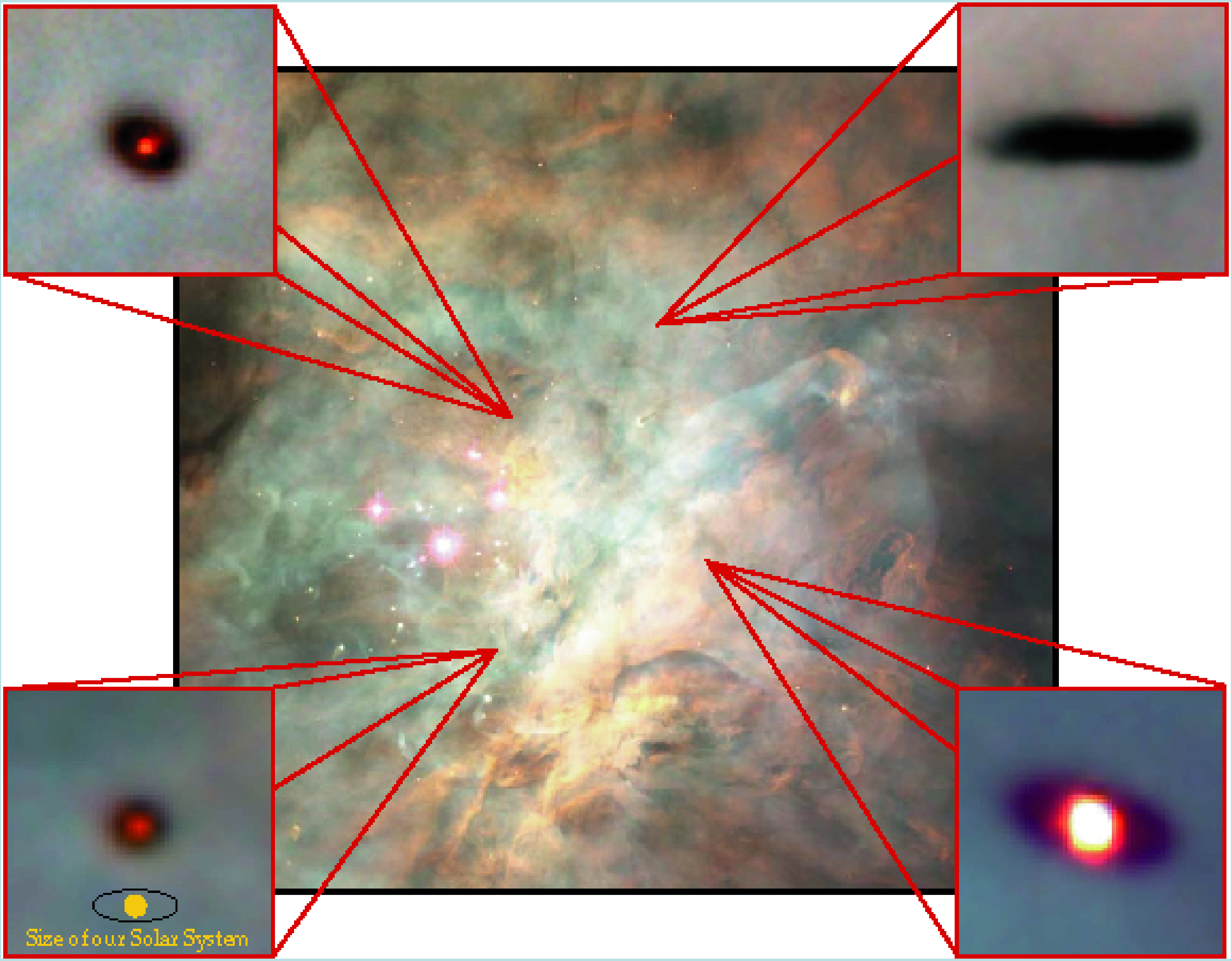


Image removed due to copyright restrictions.

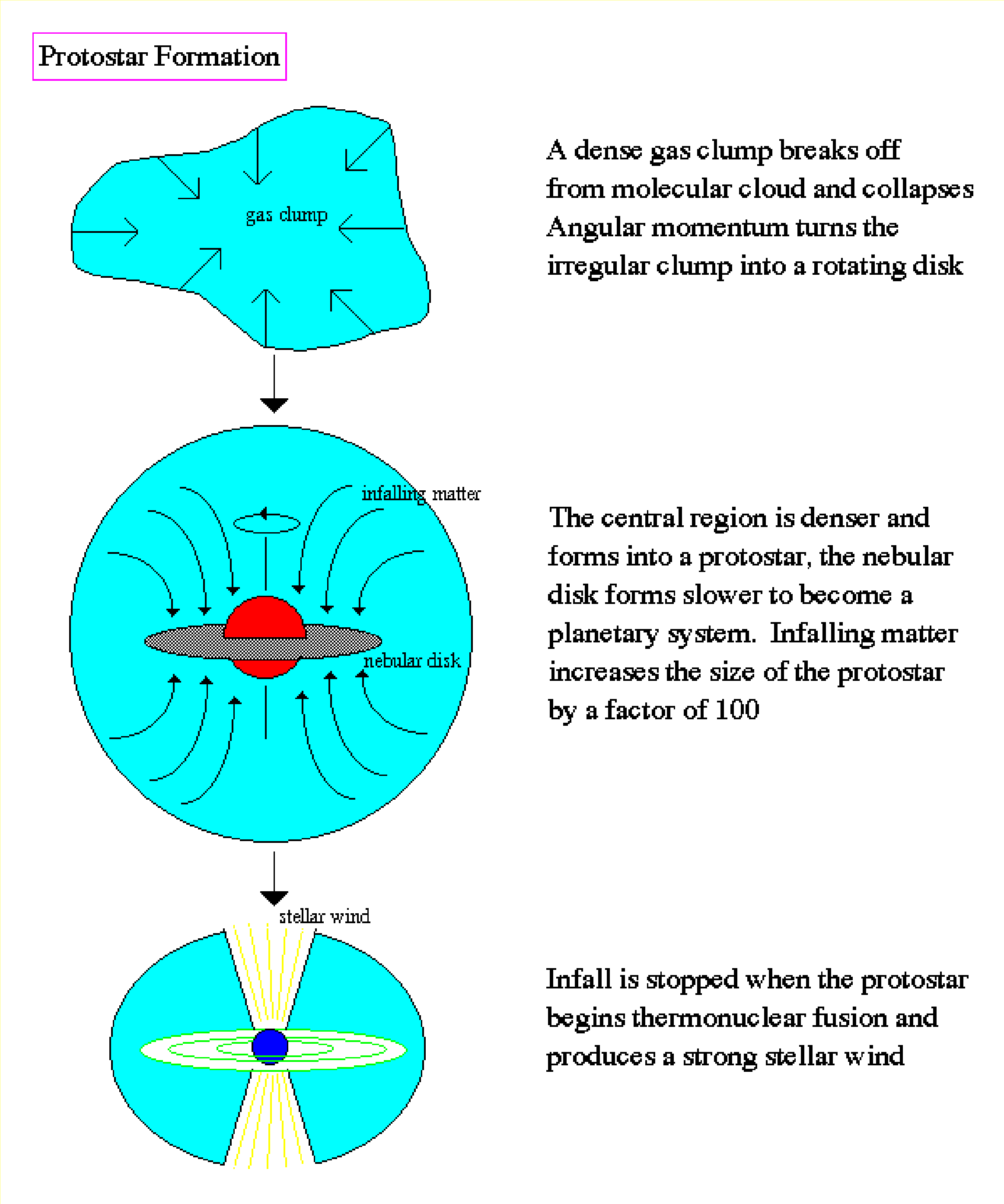
Dark Nebulae: Opaque clumps or clouds of gas and dust. Poorly defined outer boundaries (e.g., serpentine shapes). Large DN visible to naked eye as dark patches against the brighter background of the Milky Way.

Candidate Protostars in the Orion Nebula



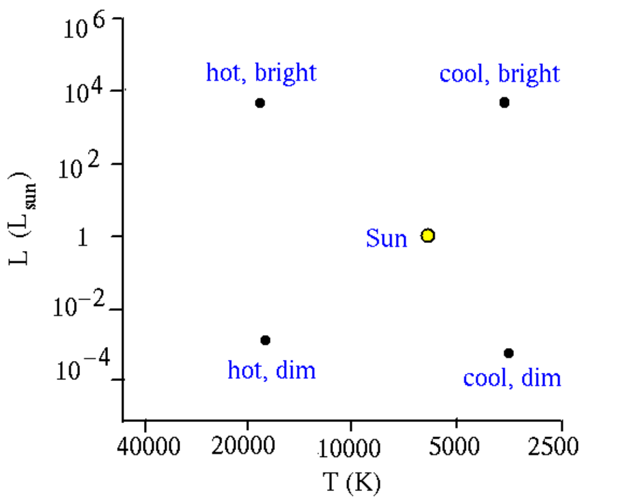
NASA/Hubble Telescope

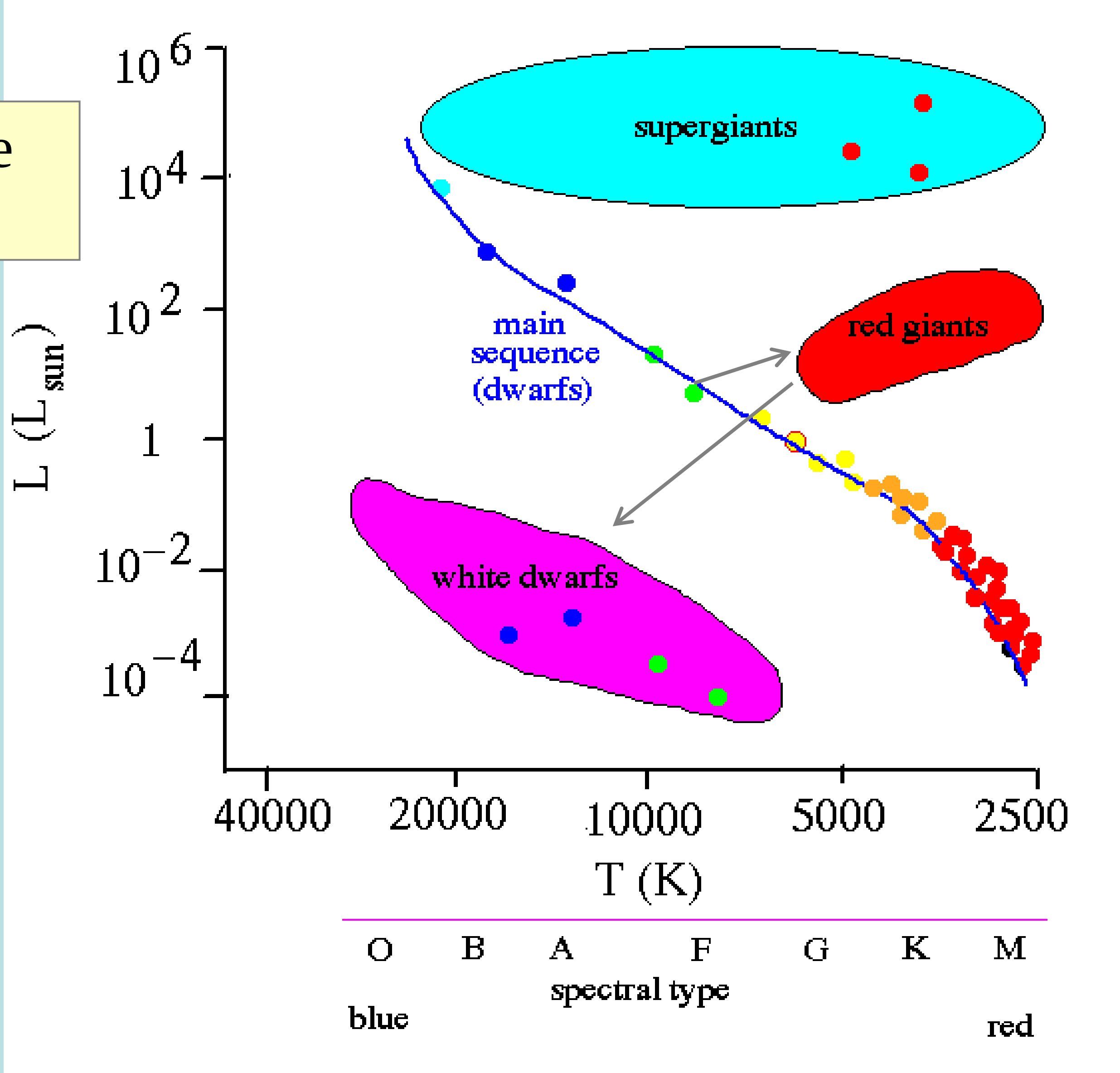
Star Formation from Protostar



Stellar Evolution

- 90% of all stars lie on main sequence





- Hertzsprung-Russell Diagram

- Above Stars are from solar Neighborhood

End of a Star's Life

- Stars < ~25 M_{sun} evolve to white dwarfs after substantial mass loss.
- Due to atomic structure limits, all white dwarfs must have mass less than the Chandrasekhar limit (1.4 M_s).
- If initial mass is > 1.4 M_s it is reduced to that value catastrophically during the planetary nebula phase when the envelope is blown off.
- This can be seen occurring in the Cat's Eye Nebula:

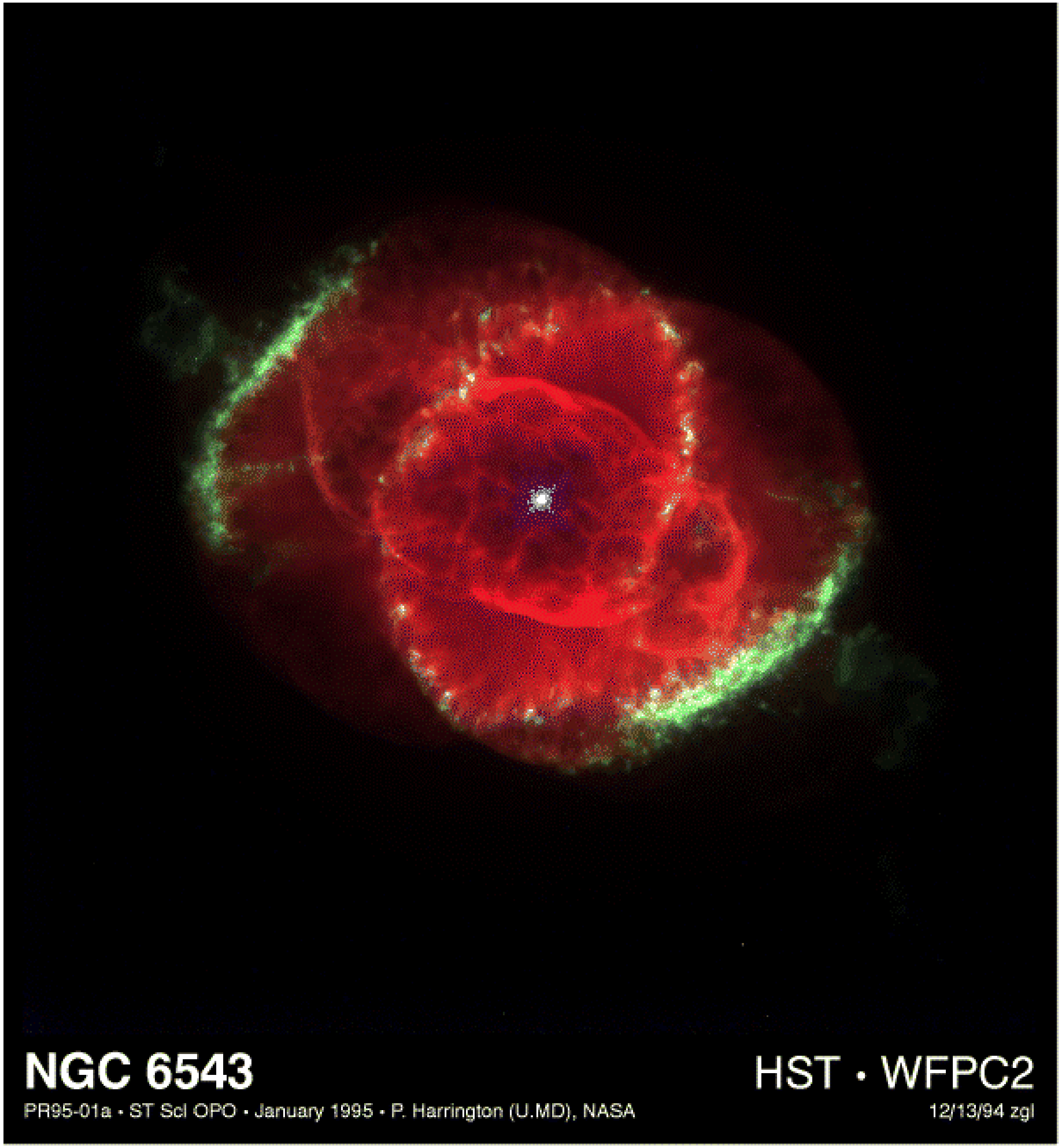
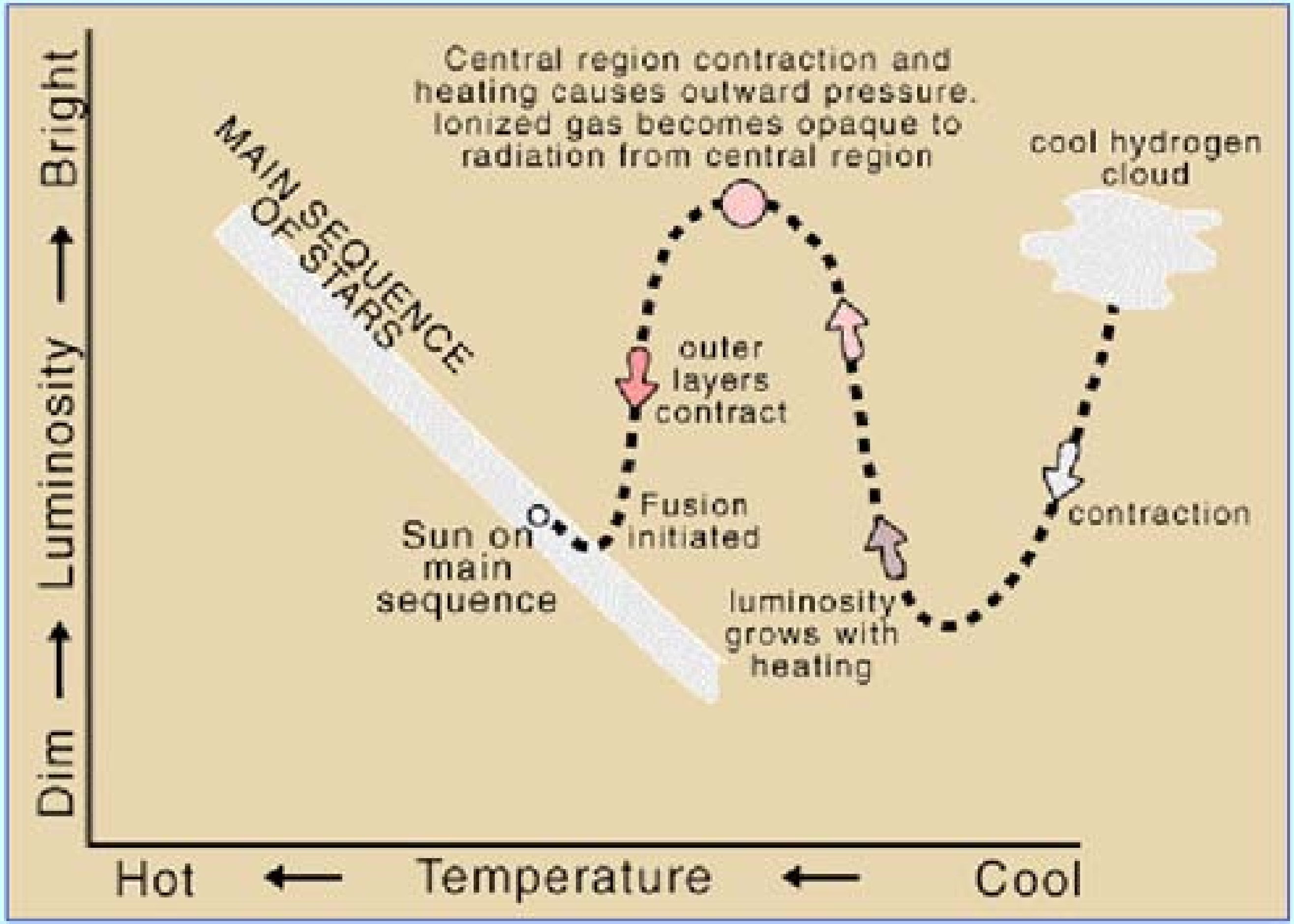


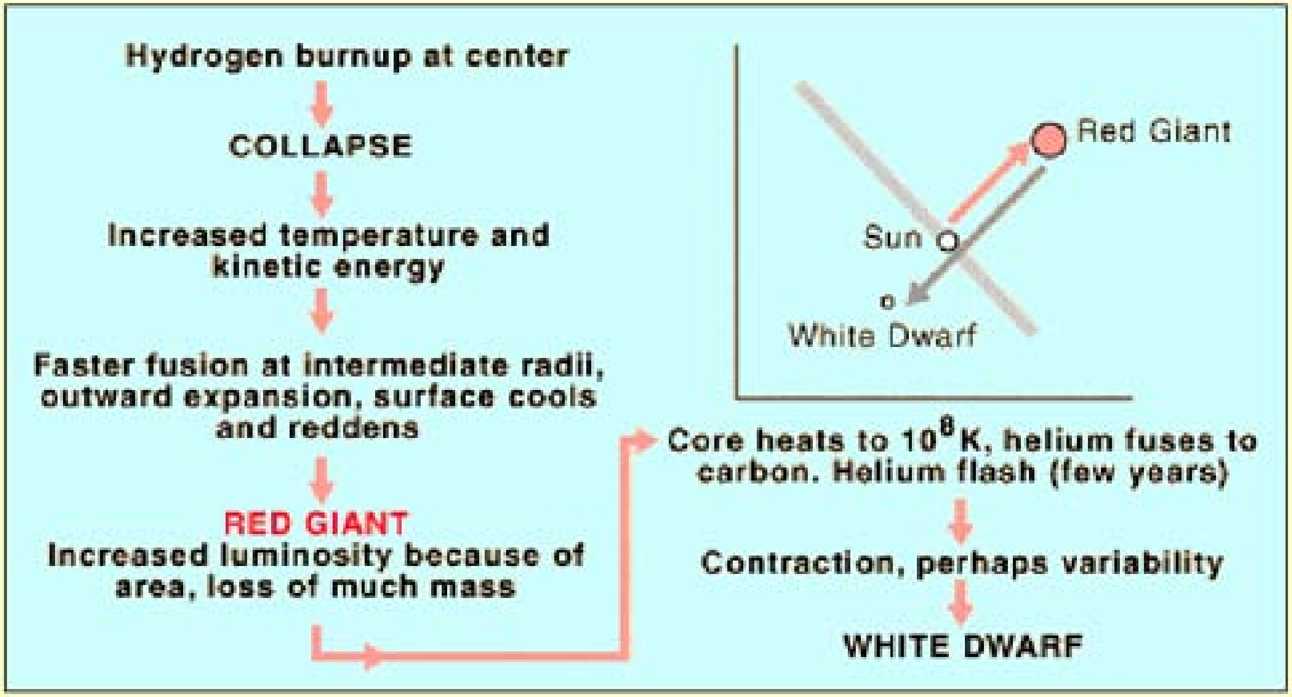
Image courtesy of NASA.

Sun's Evolution Onto the Main Sequence



•Where it will stay for ~10 b.y. (4.6 of which are past) until all hydrogen is exhausted…

Sun's Future Evolution Off the Main Sequence



- In another ~5 b.y. the Sun will run out of hydrogen to burn
- The subsequent collapse will generate sufficiently high T to allow fusion of heavier nuclei
- Outward expansion of a cooler surface, sun becomes a Red Giant
- After He exhausted and core fused to carbon, helium flash occurs.
- Rapid contraction to White Dwarf, then ultimately, Black Dwarf.

White Dwarf Phase of Sun

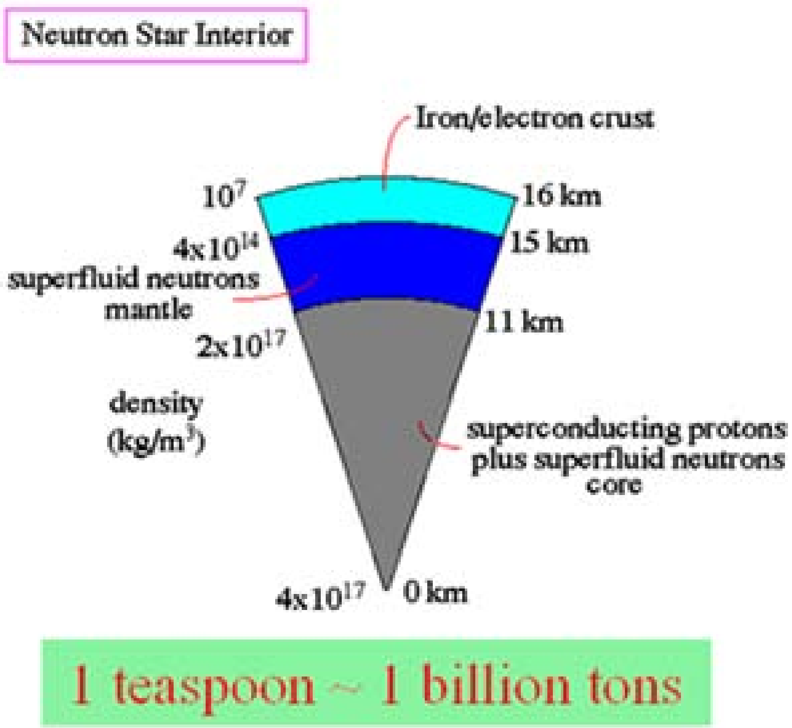
- When the triple-alpha process (fusion of He to Be, then C) in a red giant star is complete, those evolving from stars < 4 M_{sun} do not have enough energy to ignite the carbon fusion process.
- They collapse, moving down & left of the main sequence, to become white dwarfs.
- Collapse is halted by the pressure arising from electron degeneracy (electrons forced into increasingly higher E levels as star contracts).

Image removed due to copyright restrictions.

(1 teaspoon of a white dwarf would weigh 5 tons. A white dwarf with solar mass would be about the size of the Earth.)

Neutron Stars & Black Holes

Supernovae yield neutron stars & black holes



- The visual image of a black hole is one of a dark spot in space with no radiation emitted.
- Its mass can be detected by the deflection of starlight.
- A black hole can also have electric charge and angular momentum.

Image removed due to copyright restrictions.

Formation of the Solar System & the Structure of Earth

Images & links: Maria Zuber Website, 12.004 Introduction to Planetary Science, http://web.mit.edu/12.004/www/sites.html

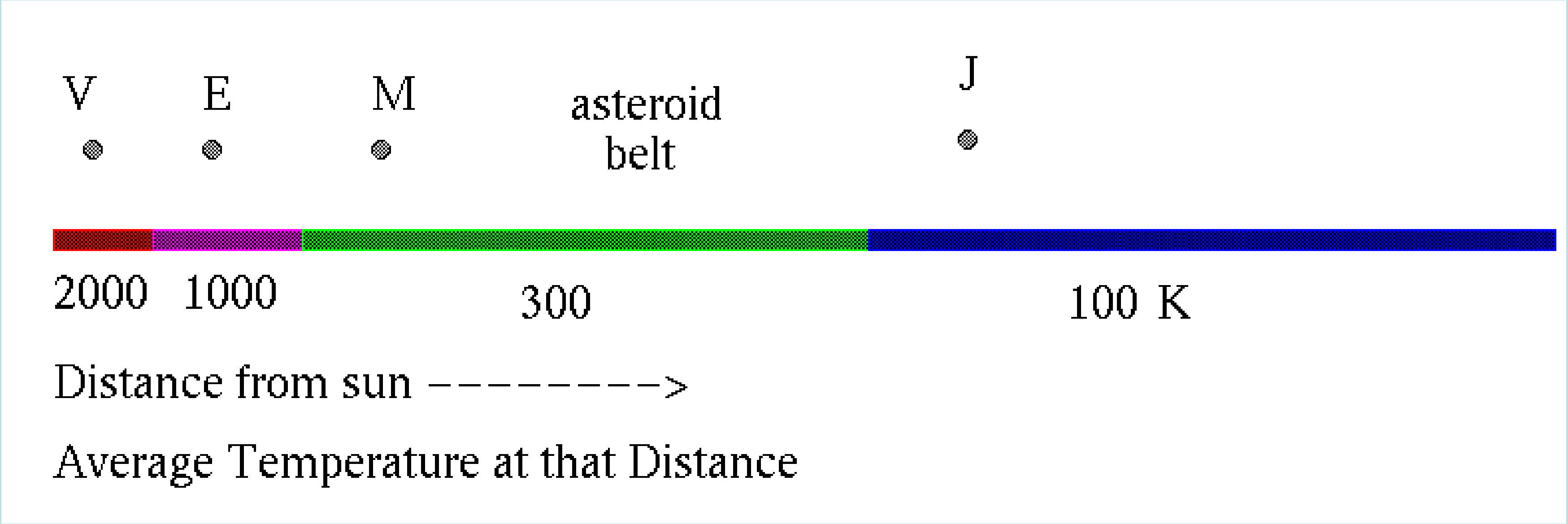
Origin of Solar System from nebula

- 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)

Image removed due to copyright restrictions.

Formation of the Earth by Accretion: 1

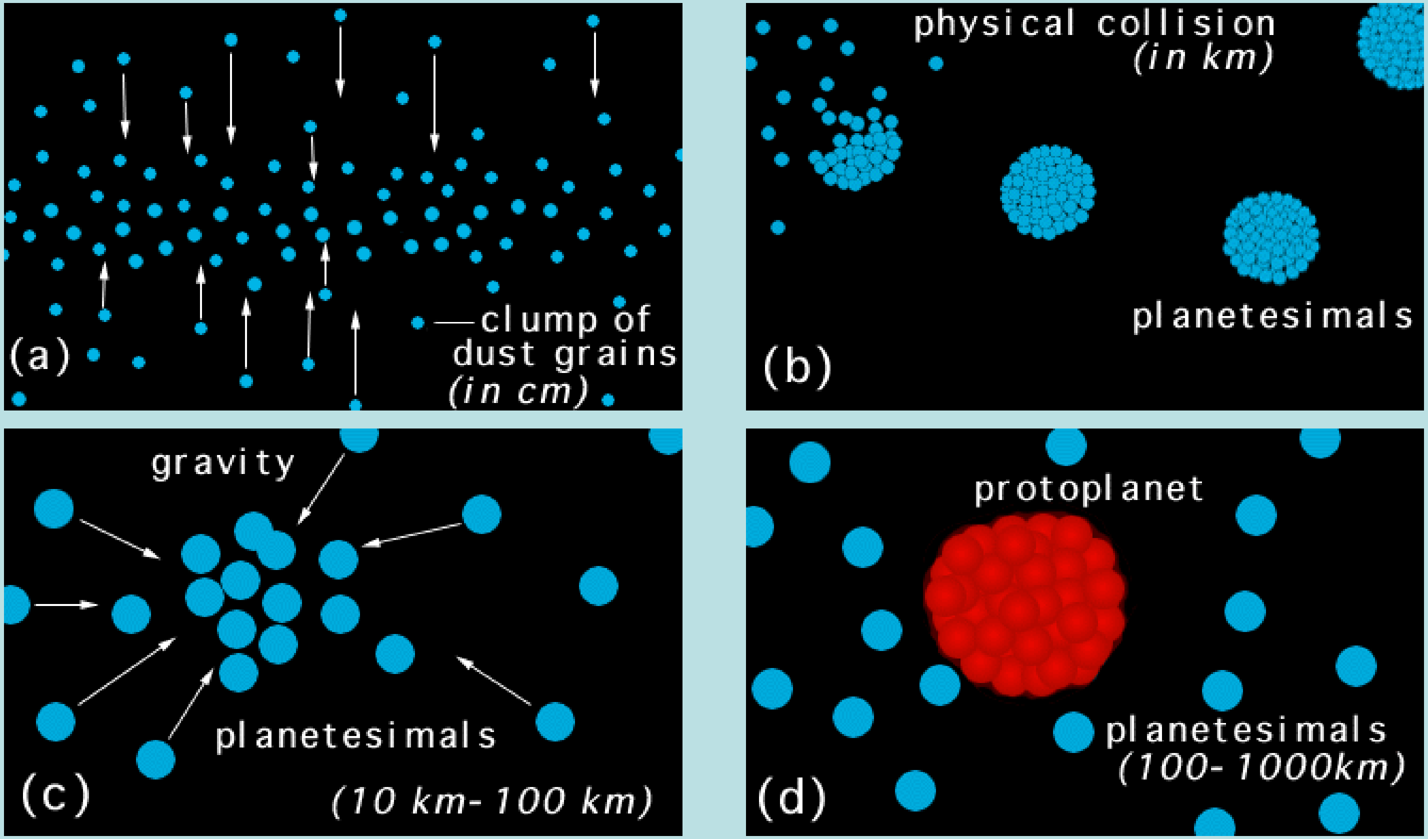
- **Initial solar nebula consisted of cosmic dust & ice with least volatile material condensing closest to the Sun and most volatile material condensing in outer solar system.**



Courtesy of the Electronic Universe. Used with permission. 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**



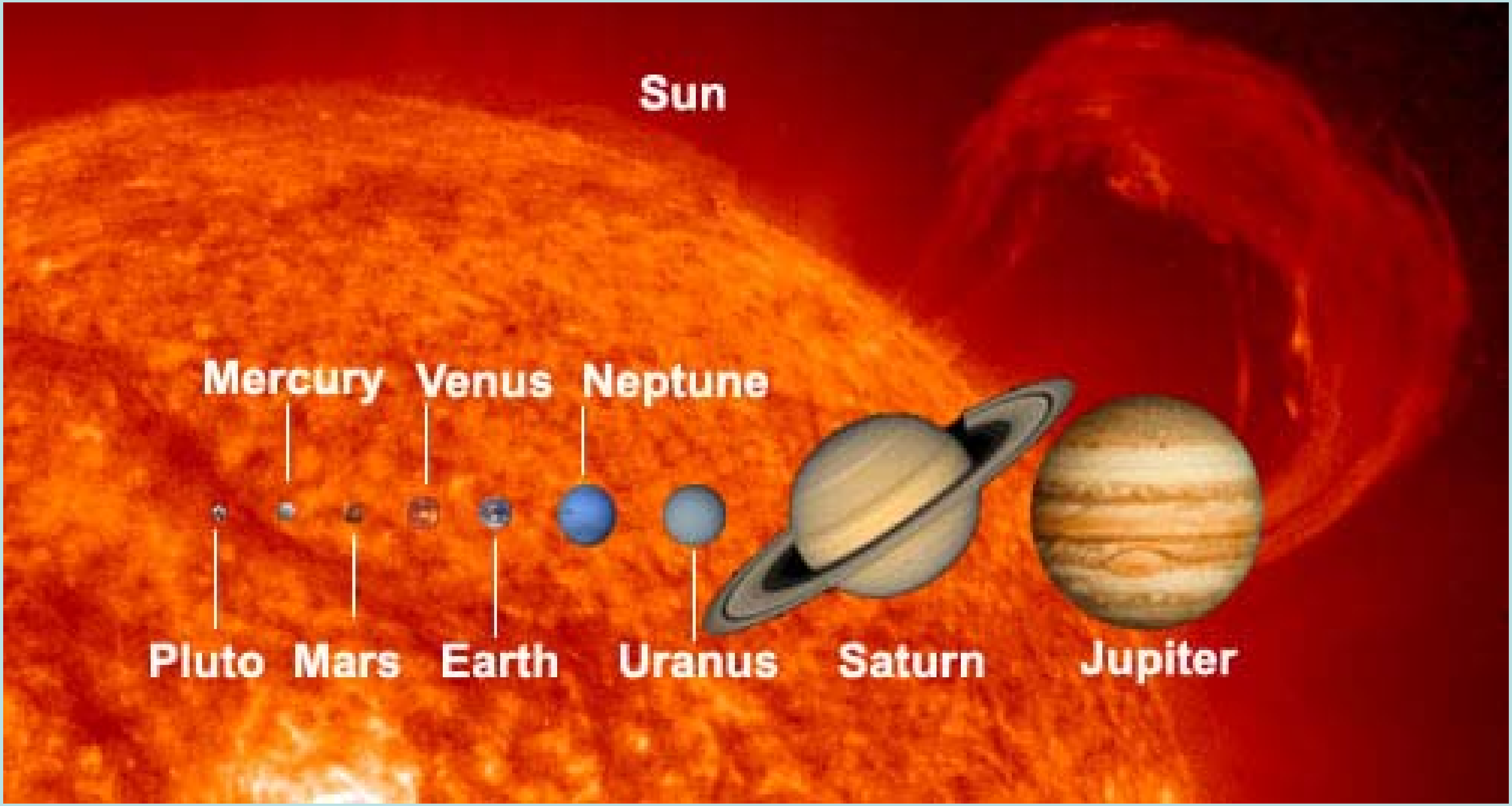
 http://zebu.uoregon.edu/ph121/l7.html

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 phases 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 (cometesimals) instead of grains.

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

The Sun & Planets to Scale



NASA-JPL

Age of the earth and meteorites

Assume that the solar system was well-mixed with respect to their initial uranium (U) and lead (Pb) isotope compositions, and that meteorites and the earth have behaved as closed systems since then.

$$\frac{\left(\frac{207}{204}\right)_{now} - \left(\frac{207}{204}\right)_{initial}}{\left(\frac{206}{204}\right)_{now} - \left(\frac{206}{204}\right)_{initial}} = \left(\frac{235}{238}\right)_{now} \left[\frac{e^{\lambda_{U235}T} - 1}{e^{\lambda_{U238}T} - 1}\right]$$

Image removed due to copyright restrictions.

Lead isochron for meteorites and modern ocean sediment. The slope of this isochron (Equation 19.9) indicates an age of $T = 4.54 \pm 0.07 \times 10^9$ y for meteorites, based on the decay constants in Table 18.2 (Patterson, 1956).

from Faure, 1986, Principles of Isotope Geology

Earth Accretion Rate Through Time

Image removed due to copyright restrictions.

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

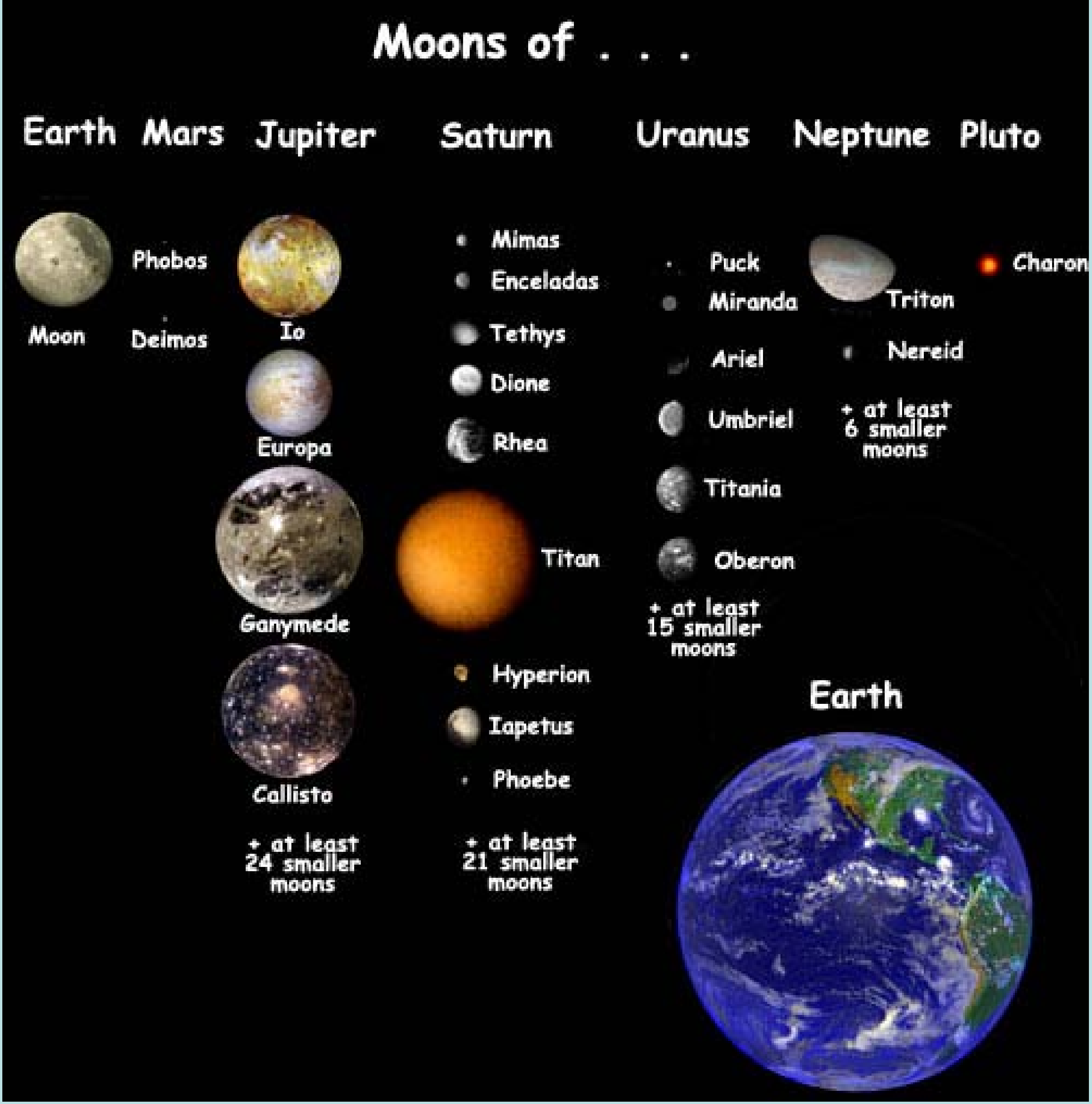
1: Pre-Nectarian lunar craters (e.g., Ryder, 1989; Taylor, 1992)
2: Erathosthenian craters (e.g., McEwen et al., 1997)
3: Proterozoic impacts, Australia (Shoemaker & Shoemaker, 1996)
4: Lunar farside rayed craters (McEwen et al., 1997)
5: US Mississippi lowland craters (Shoemaker, 1977)
6: Early Ordovician meteorite flux estimate (Schmitz et al., 1996, 1997)
7: Cenozoic ET matter flux, Os isotope model (Peucker-Ehrenbrink, 1996)

Moon Forming Simulation

- Mars-size object (10% M_E) struck Earth
- core merged with Earth
- melted crust (magma ocean #2)
- Moon coalesced from ejected Mantle debris
-Caused high Earth rotation rate, stabilized obliquity

Images removed due to copyright restrictions.

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



Moons of the Solar System to Scale

NASA-JPL

The moon and the earth's rotation rate

- When the moon formed, it was much closer to earth than it is today.
- Over geological time, tidal interactions between the moon and earth have dissipated energy and increased the radius of the moon's orbit to where it is today (this outward motion continues).
- The earth's rotation is slowing down for the same reason. Shortly after the formation of the moon, the day length may have been ~2x shorter than it is today.

The moon stabilizes the earth’s orbital parameters…

- The gravitational interaction between the moon and earth stabilizes the tilt angle of the earth’s rotation (obliquity). Compare Earth’s ~2° obliquity variations to Mars, which has much higher variability. This has significant implications for climate variability.

Image removed due to copyright restrictions.

Calculated obliquity of Mars (Edvardsson and Karlsson (2008)

Differentiation of the Earth:1

- V.M. 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

Image removed due to copyright restrictions.

Undifferentiated protoplanet (chondritic composition)

Early differentiation; magma ocean

Fully differentiated Earth

- Driven by density differences
- Occurred on Earth within ~30 Myr

Stanley (1999)

Extinct Radionuclides

An 'extinct radionuclide' formed during stellar or supernovae nucleosynthesis prior to coalescence of our solar-system, and subsequently decayed away completely.

Some important extinct radionuclides:

Parent	Daughter	Decay mode	Half-life Myr
^{146}Sm	^{144}Nd	α	103
^{244}Pu	various	fission	82
^{129}I	^{129}Xe	β	16
^{247}Cm	^{235}U	3α, 2β	15.6
^{182}Hf	^{182}W	2β	9.0
^{107}Pd	^{107}Ag	β	6.5
^{53}Mn	^{53}Cr	β	3.7
^{60}Fe	^{60}Ni	2β	1.5
^{26}Al	^{26}Mg	β	0.7
^{41}Ca	^{41}K	β	0.1

Image removed due to copyright restrictions.

Nature 418:952

Terrestrial Planets Accreted Rapidly

- Carbonaceous chondrites (meteorites) are believed to be most primitive material in solar system.
- Abundance of daughter (^{182}W) of extinct isotope (^{182}Hf) supports this (W moves with metals, Hf with silicates).
- Argues for very rapid (<30 M.y.) accretion of inner planets.

Accretion continues…

Chicxulub Crater, Gulf of Mexico

- 200 km crater
- 10-km impactor
- 65 Myr BP
- Extinction of 75% of all species!

Image removed due to copyright restrictions.

Image removed due to copyright restrictions.

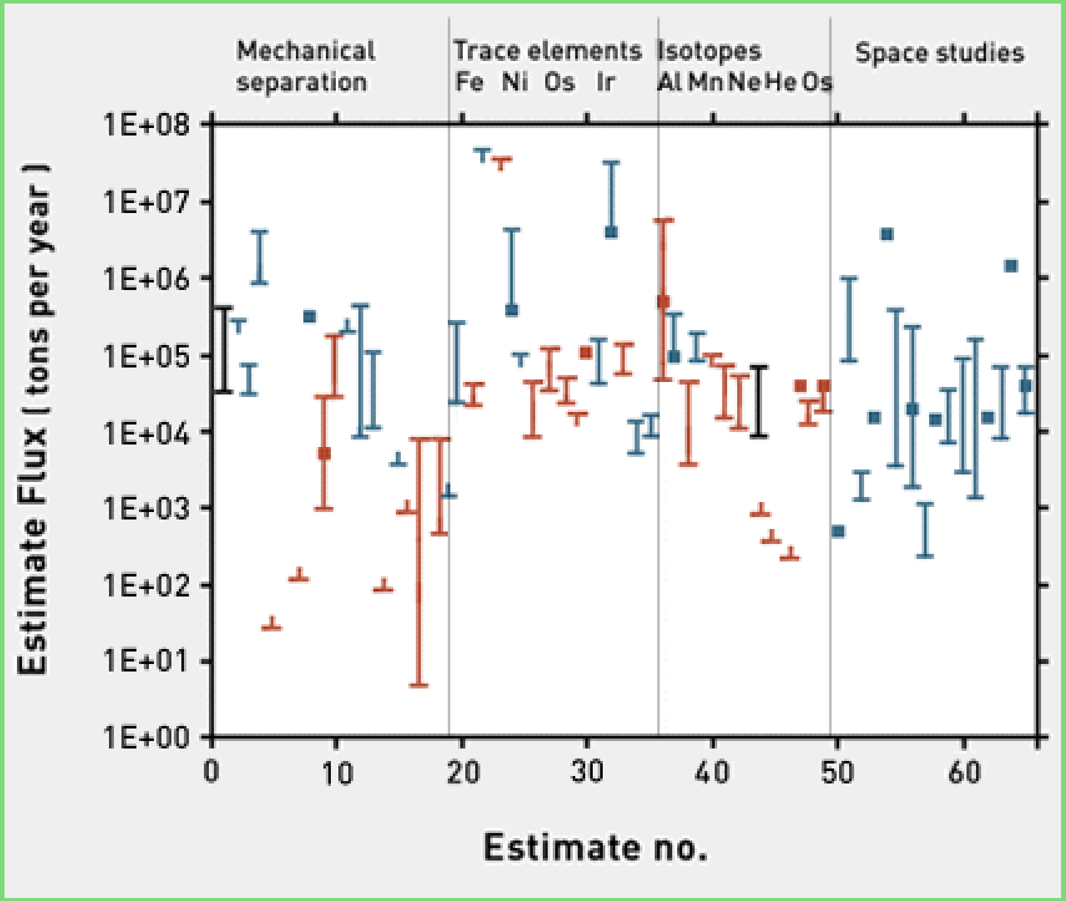
Meteor (Barringer) Crater, Arizona

- 1 km diam. crater
- 40-m diam. Fe-meteorite
- 50 kyr BP
- 300,000 Mton
- 15 km/s

Interplanetary Dust Accumulation

Image removed due to copyright restrictions.

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



$40 \pm 20 \times 10^4$ metric tons/ yr (40×10^{10} g) interplanetary dust accretes every year…

Courtesy of Bernhard Peucker-Ehrenbrink, the Noble Metal Group, WHOI.

Used with permission.

http://www.whoi.edu/science/MCG/pge/project4.html

Image removed due to copyright restrictions.

Kump et al. (1999)

Size & Frequency of Impacts

- 100 m object impacts every 10 kyr

- 10 km object every 100 Myr

The Asteroid Belt

Images removed due to copyright restrictions.

- 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

Image removed due to copyright restrictions.

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

Basics of Geology

Lithospheric Plates

- 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)

Image removed due to copyright restrictions.

From Stanley (1999)

Convection Drives Plate Movements

Image removed due to copyright restrictions.

From Stanley (1999)

Tectonic Activity in the South Atlantic

Image removed due to copyright restrictions.

from Stanley (1999)

Image removed due to copyright restrictions.

Rock Basics

Igneous + metamorphic = Crystalline Rocks

from Stanley (1999)

The Rock Cycle

Image removed due to copyright restrictions.

From Stanley (1999)

Igneous Rocks

Extrusive:
cools rapidly; small crystals

Intrusive:
cools slowly; large crystals

Mafic: Mg-, Fe-rich. Dark-colored, high-density. Most oceanic crust. Ultramafic rock (more dense) forms mantle below crust.

Felsic: Si-,Al-rich. Light-colored, low-density. Feldspar (pink) & quartz (SiO_2)-rich. Most continental crust. Granite most abundant.

Image removed due to copyright restrictions.

Stanley (1999)

Basalt
(Oceanic Crust)

Granite
(Continental Crust)