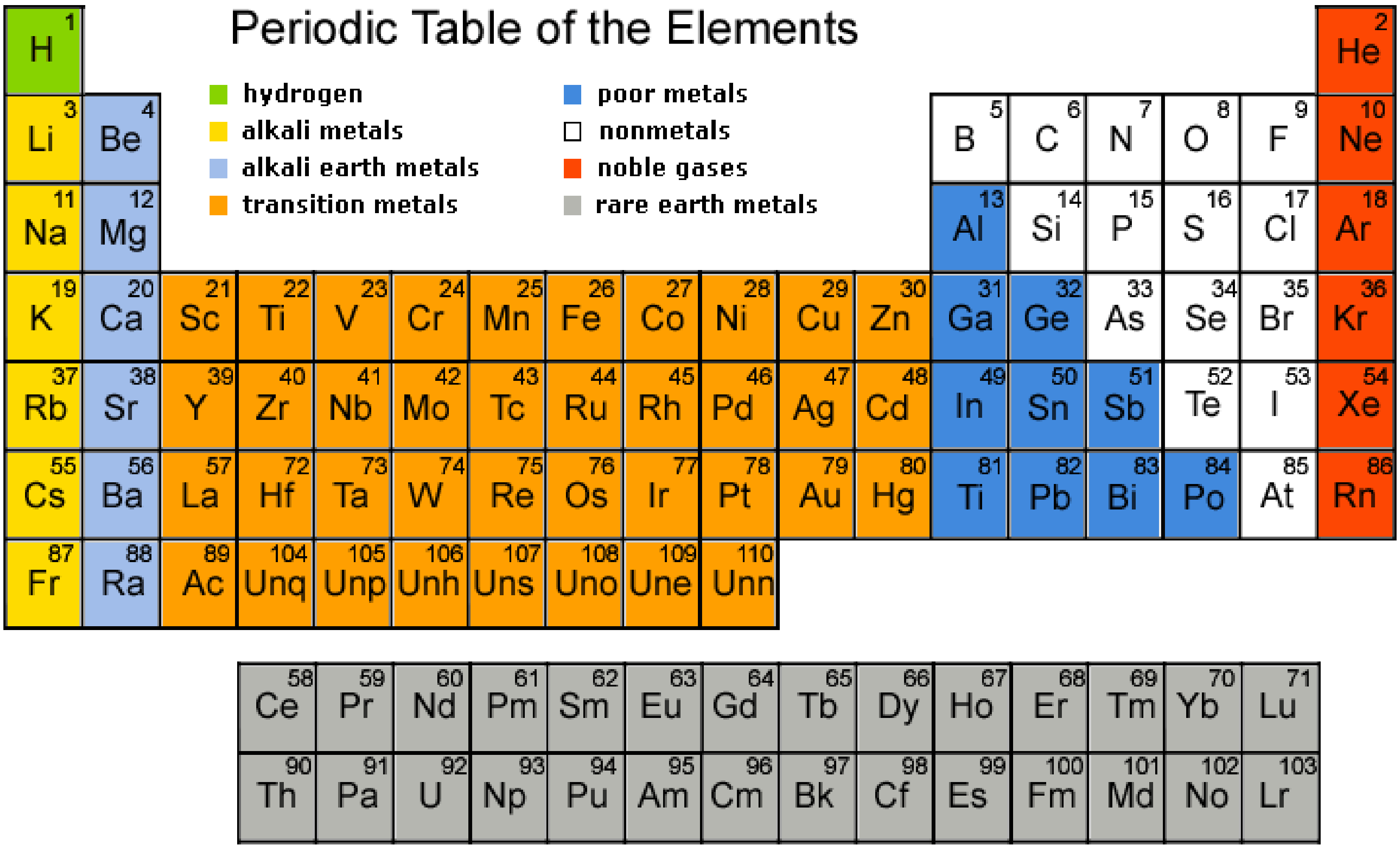
http://eps.mcgill.ca/~courses/c220/



Nucleosynthesis

neutron → electron + proton = é + H^+

$t_{1/2}$ = 12 minutes

H^+ + neutron → Deuterium (D)

2 H^+ + neutrons → Helium (He)

3 H^+ + neutrons → Lithium (Li)

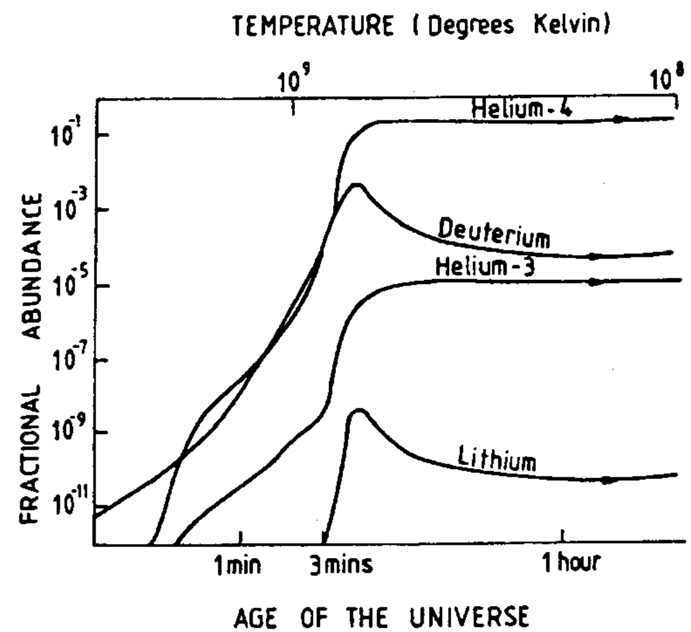
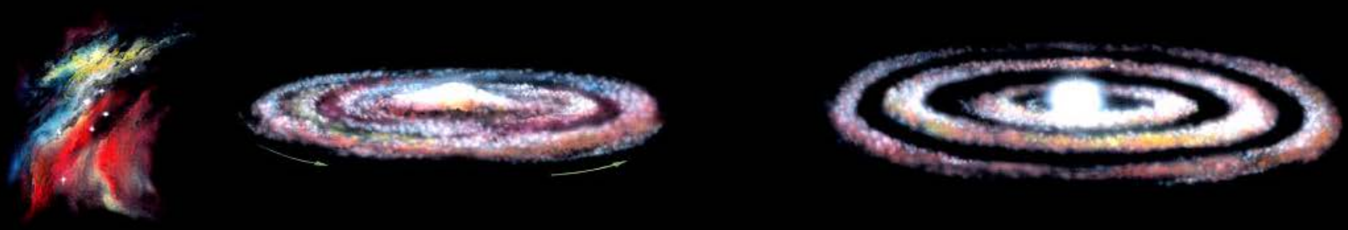


FIGURE 3.4
The detailed production of the lightest elements out of protons and neutrons during the first three minutes of the universe's history. The nuclear reactions occur rapidly when the temperature falls below a billion degrees Kelvin. Subsequently, the reactions are shut down, because of the rapidly falling temperature and density of matter in the expanding universe.

From: W.S. Broecker (1985)
How to build a habitable planet


New born stars

The birth of a star



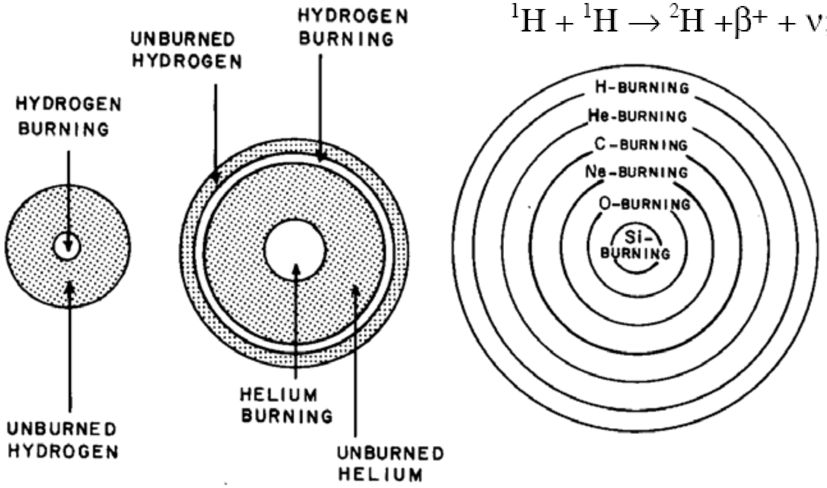
The nebula condenses into a swirling disc, with a central ball surrounded by rings.

The ball at the center grows dense and hot enough for fusion to begin ($>50 \times 10^{6}\ ^{o}C$).
Dust (solid particles) condenses in the rings.

Nucleosynthesis in burning stars

Red Giants

$^{1}H + {}^{1}H \rightarrow {}^{2}H + \beta^{+} + \nu$; $^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$ and $^{3}He + {}^{3}He \rightarrow {}^{4}He + 2{}^{1}H + \gamma$



Name of Process	Fuel	Products	Temperature
Hydrogen-Burning	H	He	60 × 10⁶ °K
Helium-Burning	He	C, O	200 × 10⁶ °K
Carbon-Burning	C	O, Ne, Na, Mg	800 × 10⁶ °K
Neon-Burning	Ne	O, Mg	1500 × 10⁶ °K
Oxygen-Burning	O	Mg to S	2000 × 10⁶ °K
Silicon-Burning	Mg to S	Elements near FE	3000 × 10⁶ °K

Figure 2-5. Three stars with progressively hotter nuclear fires: Like our Sun, the star at the left burns hydrogen to form helium in its core; this core is surrounded by unburned fuel. The middle star is burning helium to form carbon and oxygen in its core. This core is surrounded by a layer of unburned helium. Outside of this is a layer in which hydrogen burns to produce helium. Finally there is an outer layer of unburned hydrogen. The star on the right has a multilayered fire. The successive nuclear fires are separated by layers in which no reaction occurs. These layers contain the same fuel as is being consumed in the underlying fire. These layers are depleted in the ingredient being consumed in the overlying fire. The approximate temperatures required to ignite the successive fuels are also given.

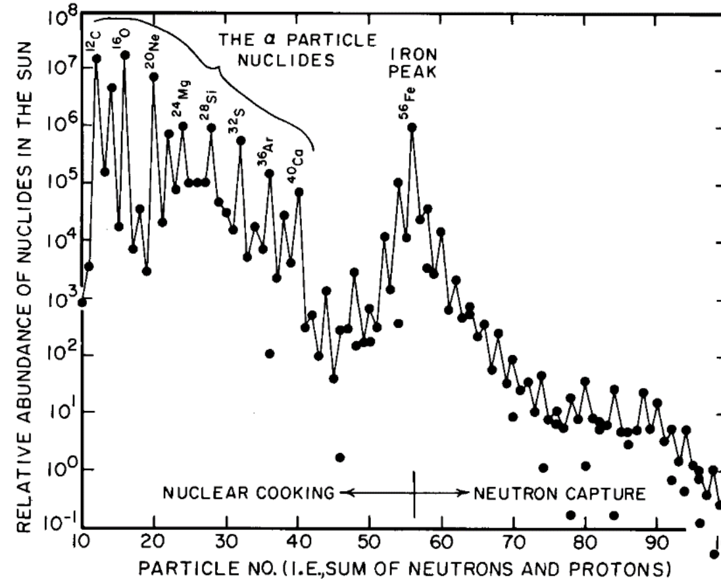


Figure 2-10. Relative abundances of individual nuclides: In the mass range 10 to 50, nuclides with particle numbers divisible by 4 (i.e., 12, 16, 20, 24, 28, 32 . . .) have abundances far above those of their neighbors. They are referred to as the *α*-particle nuclides. In the particle number range 50 to 100 the abundances of nuclides with an even particle number stand about a factor of 3 above those for their odd-numbered neighbors. Where more than one point is shown at a given mass number, two different nuclides with the same neutron-plus-proton number exist.

From: W.S. Broecker (1985) How to build a habitable planet

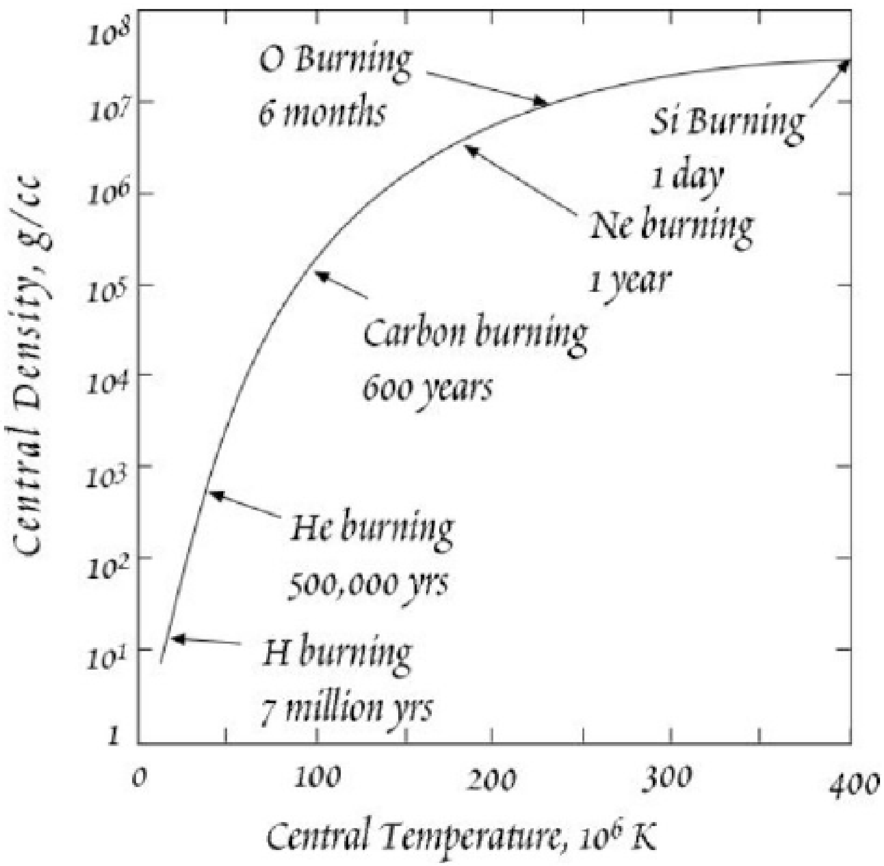


Figure 10.4. Evolutionary path of the core of star of 25 solar masses (after Bethe and Brown, 1985). Note that the period spent in each phase depends on the mass of the star: massive stars evolve more rapidly.

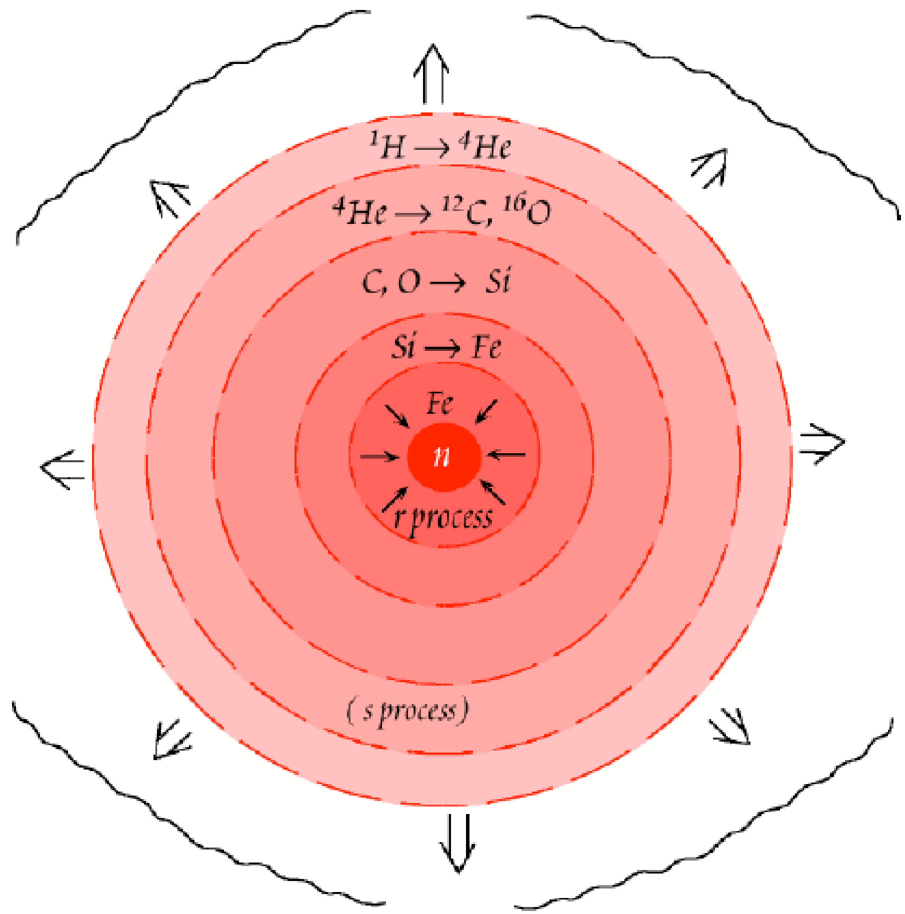
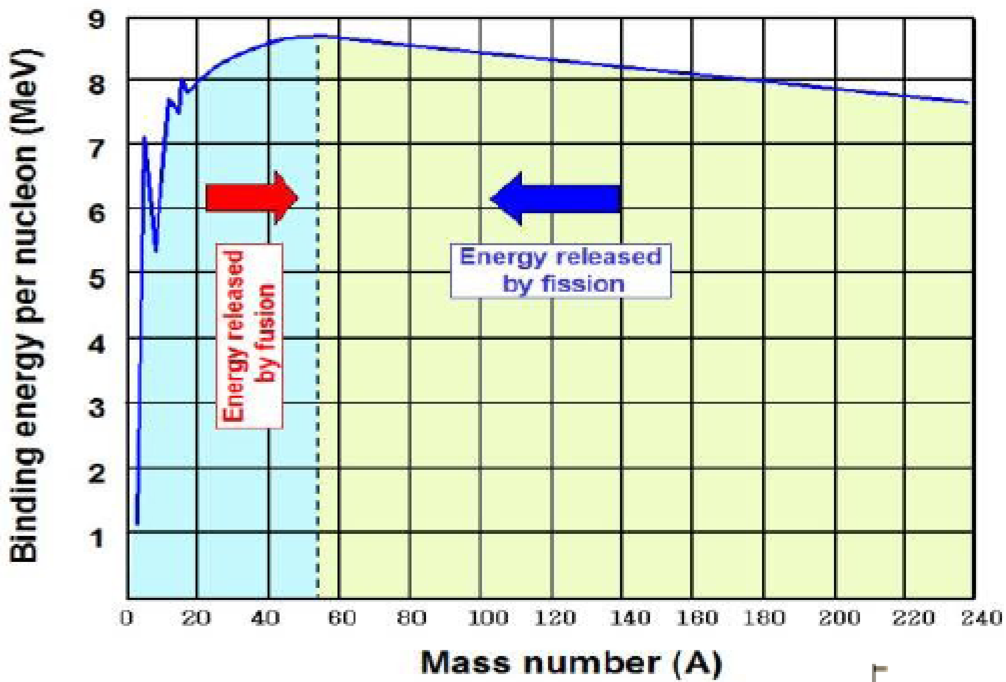
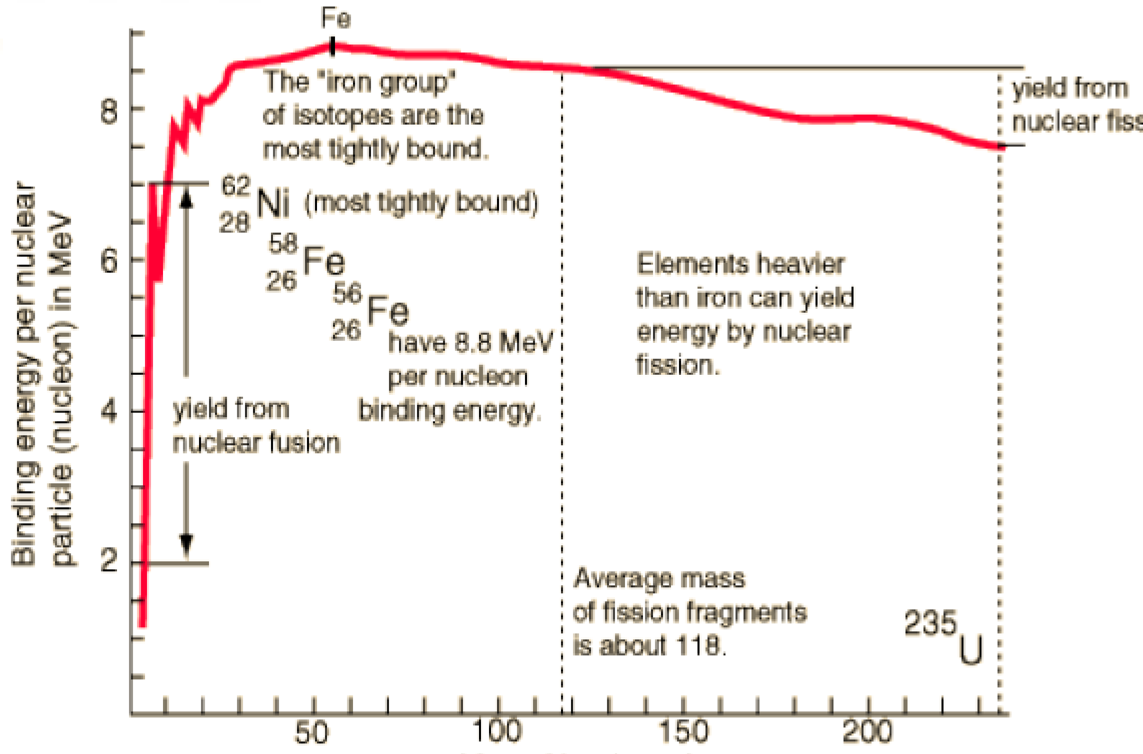


Figure 10.5. Schematic diagram of stellar structure at the onset of the supernova stage. Nuclear burning processes are illustrated for each stage.


Binding energy per nucleon (MeV)
Energy released by fusion
Energy released by fission
Mass number (A)


Fe
The "iron group" of isotopes are the most tightly bound.
yield from nuclear fiss
62 28 Ni (most tightly bound)
58 26 Fe
56 26 Fe
have 8.8 MeV per nucleon binding energy.
Elements heavier than iron can yield energy by nuclear fission.
yield from nuclear fusion
Binding energy per nuclear particle (nucleon) in MeV
Average mass of fission fragments is about 118.
235 U

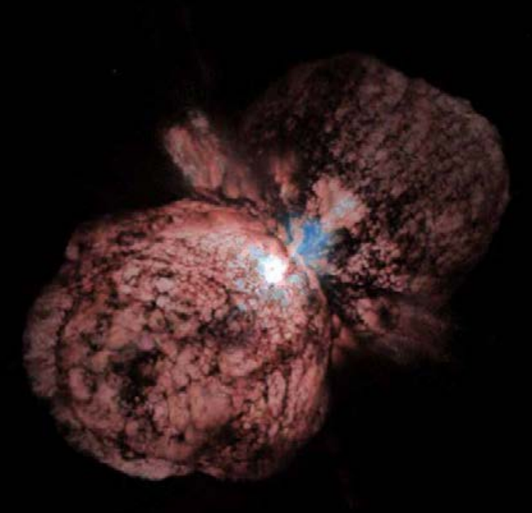
Death of a Star

If a star is ~ 8 times mass of our sun, after evolving into a red giant it will collapse into a white dwarf.

If larger, after collapsing, it will explode to form a supernova and leave behind a neutron star or even a black hole

Eta Carinae

First observed in 2003
at 2 billion light years

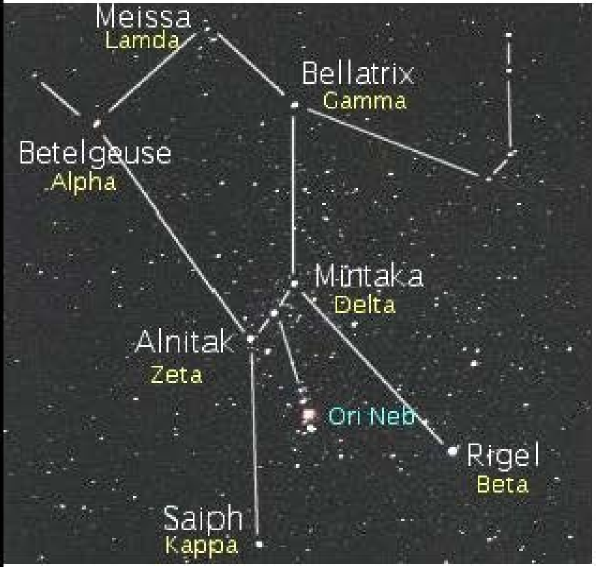


Photographed as the explosion occurred – a supernova caught in the act.

Crab Nebula

First observed AD 1066
At 63,000 light years

Star and Planet Birth in the Winter Skies



Orion Nebula--1,500 light years from Home
(in the dagger of the constellation Orion)

Nucleosynthesis by slow neutron bombardment
The s-process

It is during a supernova explosion that elements heavier than iron are formed by neutron capture.
Since the neutron has no charge, it is not repelled by any nucleus it encounters and it can freely enter the nucleus regardless of how slowly it is moving.

The stable nuclide with the most neutrons and protons is ^{209}Bi (Z=83), all nuclei with more than 209 neutrons and protons in their nucleus are radioactive.

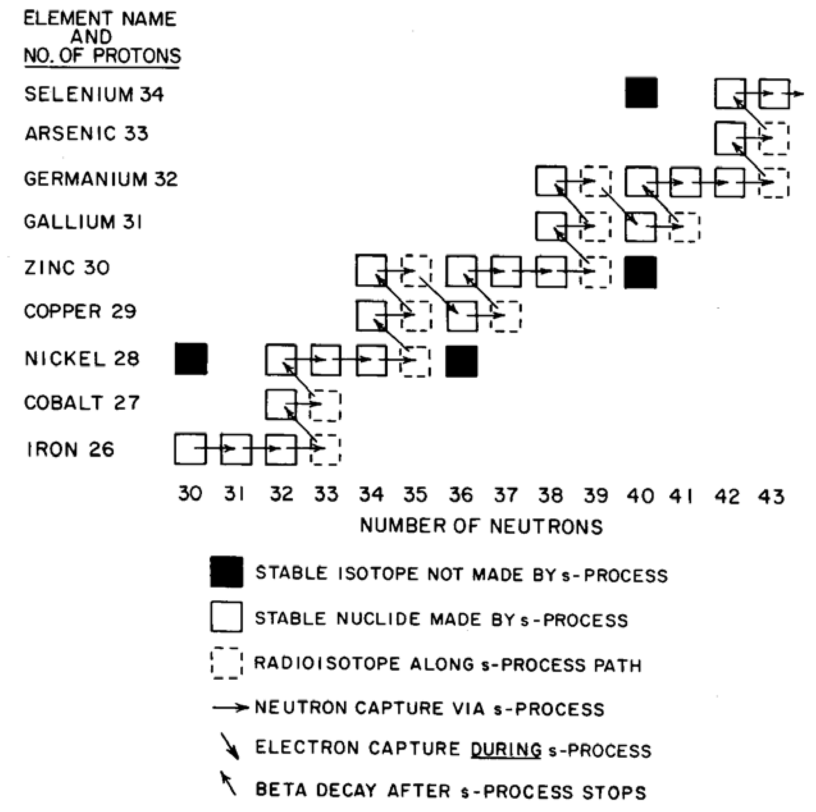


Figure 2-8. Details of the s-process path: Each time neutron capture produces a radioactive isotope, radiodecay occurs changing either a neutron into a proton or a proton into a neutron. Not all of the stable isotopes found in solar-system matter can be produced in this way. Those stable isotopes lying below the s-path are produced by the r-process. Those stable isotopes lying above the s-path are produced by proton bombardment.

From: W.S. Broecker (1985) How to build a habitable planet

Nucleosynthesis by rapid neutron bombardment
The r-process

If the flux of neutrons is very large there is a good chance that the radioactive isotope, before it has time to undergo decay, will capture another neutron. Nevertheless, as some point, the neutron: proton ratio becomes so unstable that the nucleus decays through a series (cascade) of consecutive beta decays.

The process is terminated by the onset of nuclear fission which occurs near A = 276 and the fission products as injected back into the cycle.

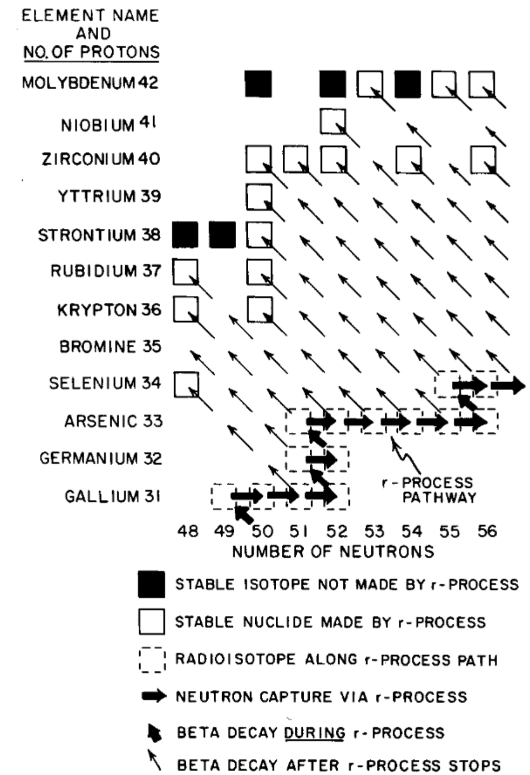


Figure 2-7. A segment of the r-process pathway: Rapid-fire neutron bombardment adds neutrons until a nuclide cannot hold any more. Only then does the nuclide undergo beta decay to become the next heavier element. This process—neutron capture to saturation followed by beta decay—is repeated over and over again, producing successively heavier elements. The r-process buildup occurs during the explosion that destroys the red giant. Hence it ends abruptly. The neutron flux stops and the highly radioactive isotopes on the r-process pathway emit beta particles one after another until stability is achieved. Note that in the case of those isobars for which two stable nuclides exist, only the neutron-rich nuclide of the pair is produced by the r-process.

From: W.S. Broecker (1985) How to build a habitable planet

R- , S- and P-Processes

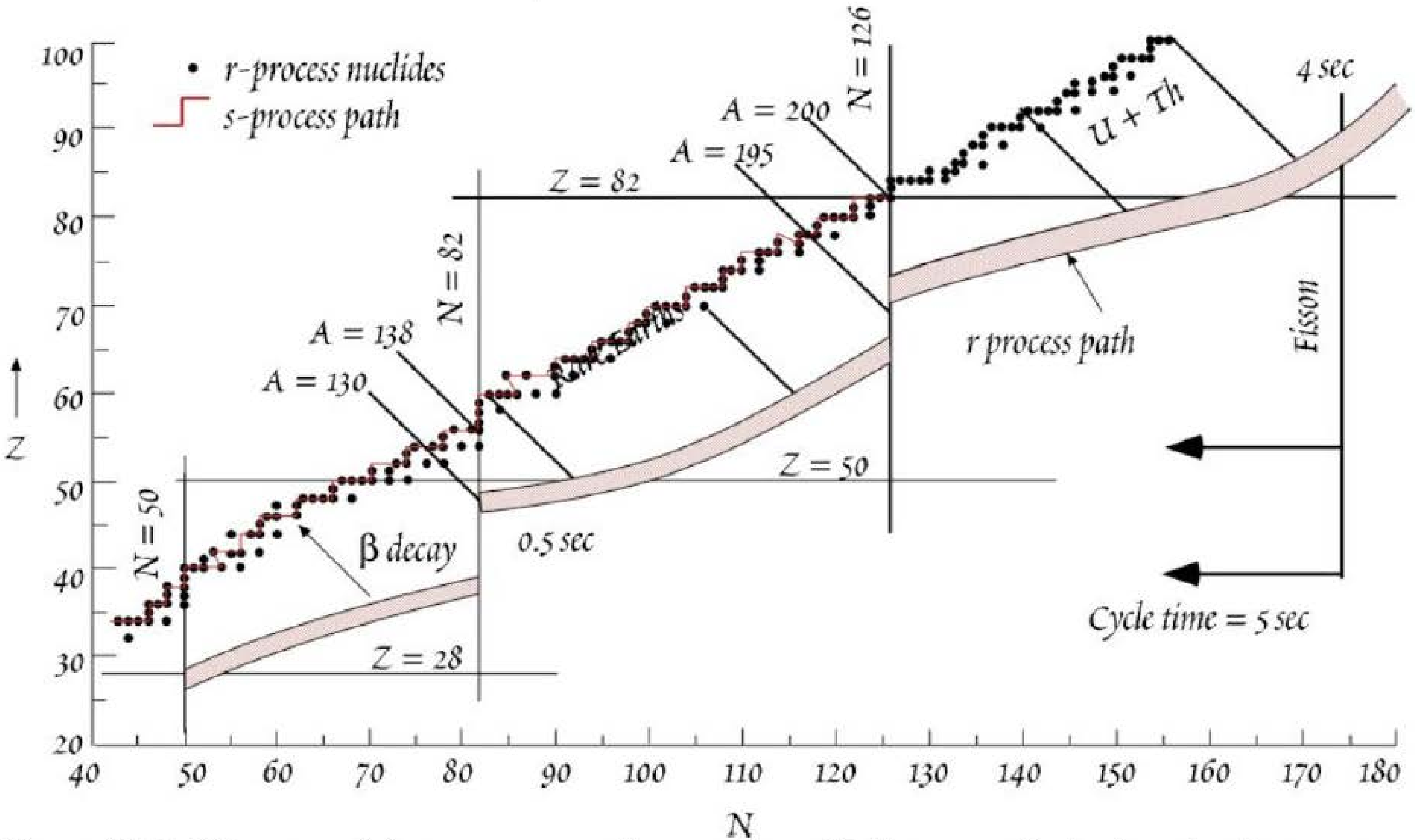
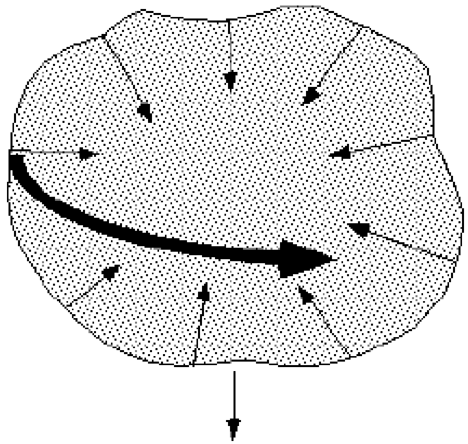


Figure 10.7. Diagram of the r-process path on a Z vs. N diagram. Dashed region is r-process path; solid line through stable isotopes shows the s-process path.

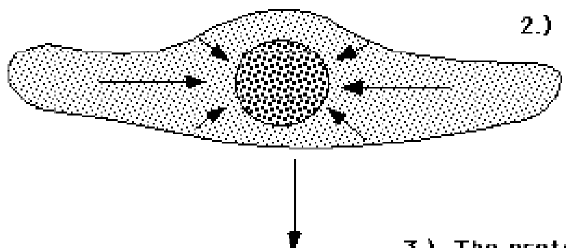
Evolution of the solar system

Forming the solar system, according to the nebula hypothesis: A second- or third-generation nebula forms from hydrogen and helium left over from the Big Bang, as well as from heavier elements that were produced by fusion reactions in stars or during the explosion of stars.

The nebula condenses into a swirling disc, with a central ball surrounded by rings. 99.9% of the mass of the nebula was drawn into the central body - the Sun - and, thus, the Sun has a composition identical to the original dust cloud from which it formed (dominated by H and He – 99%).

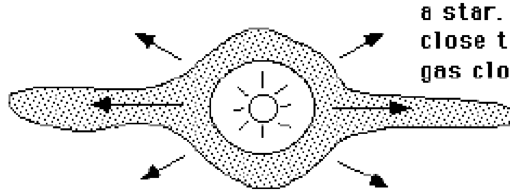


1.) There is a slowly rotating cloud of gaseous molecules called a "nebula". This nebula begins to collapse.

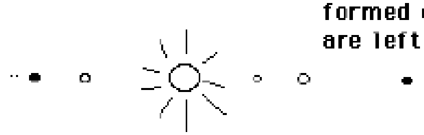


2.) A "Protostar" forms out of gas, and planet_elements or "planetismals" form out of dust, as the cloud continues to condence and flatten into a pancake shape.

3.) The protostar "turns on" and becomes a star. When this happens, dust close to the star is vaporized, and gas close to the star is blown away.

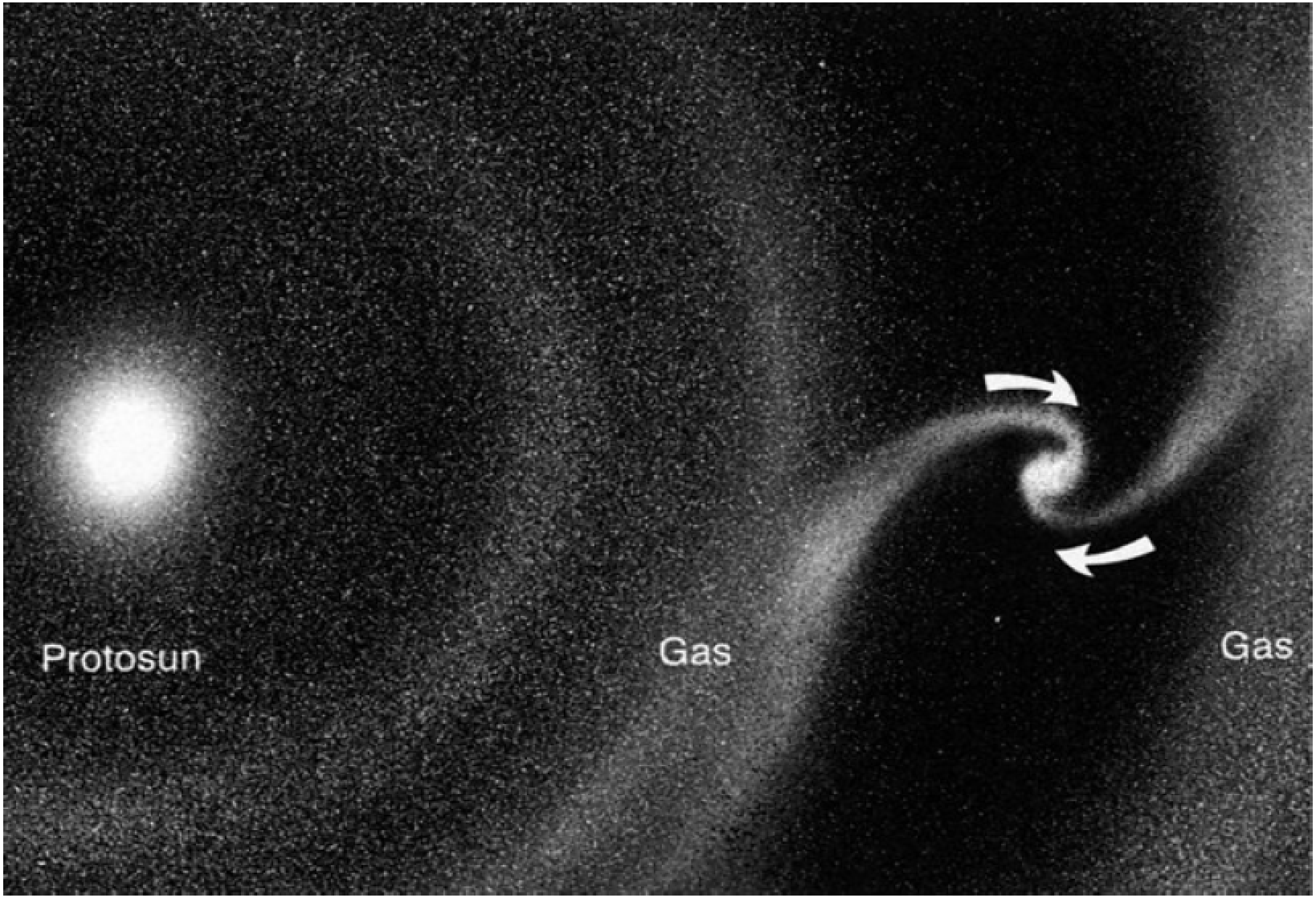


4.) The nebula clears away and only the star, and planets which formed out of the planet_elements are left.



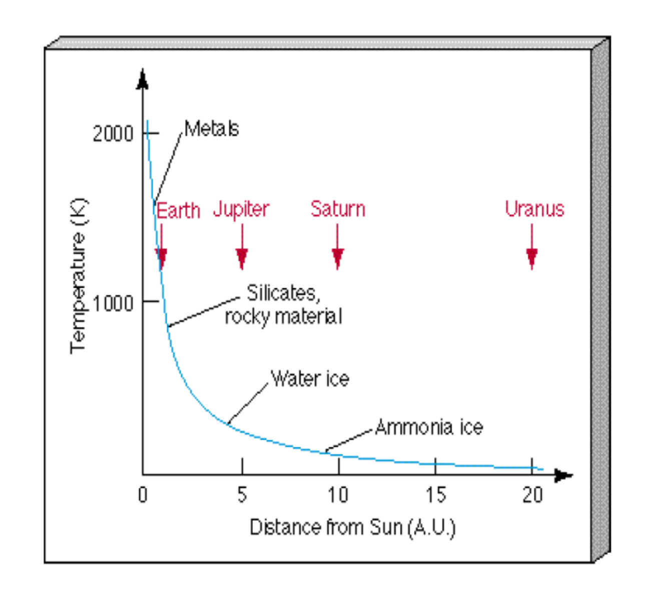
Condensation of Planetesimals from Dust and Gas

First by electrostatic forces then later by gravity

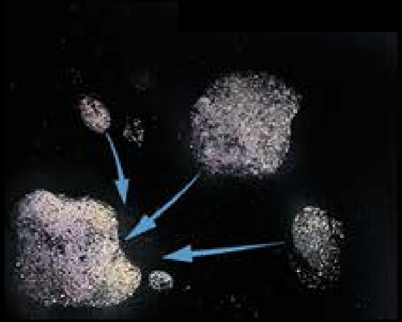


Evolution of the solar system

The ball at the center grows dense and hot enough for fusion to begin (> 50 x10^6 ^oC). It becomes the Sun. Dust condenses in the rings.

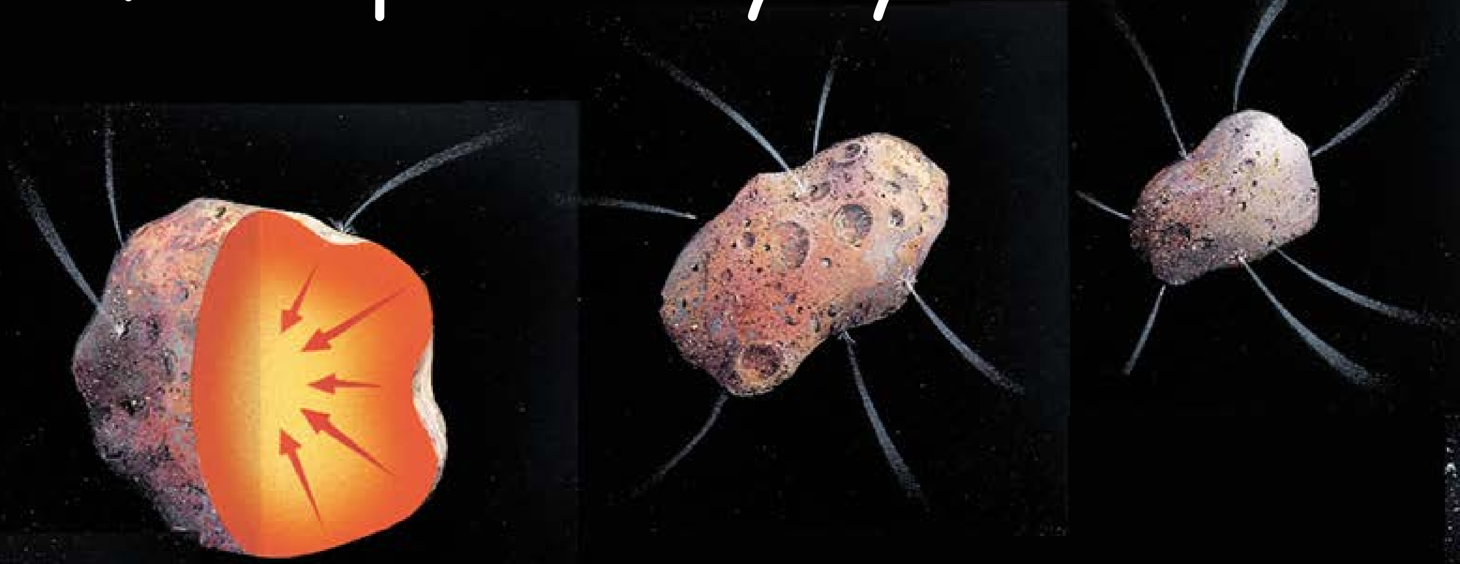


The nature of the matter condensed depends on temperature. At a distance of Earth from Sun, temperature ~1500^{o}C. Iron (melting point 1538^{o}C) and olivine ($(Fe,Mg)_2SiO_4$; melting point 1500 – 1700^{o}C) condense. At a distance of Jupiter, water ice (melting point 0^{o}C) and ammonia (melting point -78^{o}C) condense, and at a distance of Neptune, methane (melting point –182^{o}C) condenses.

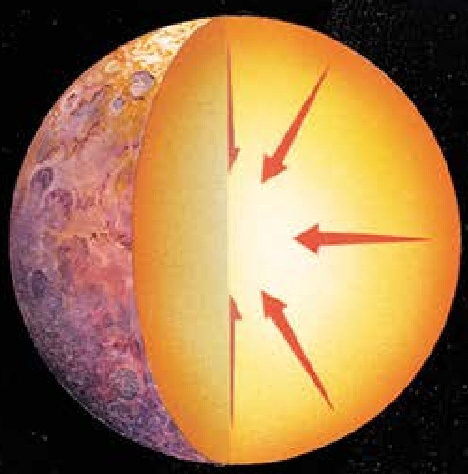


Dust particles collide and stick together, forming planetesimals.

Evolution of the planetary system

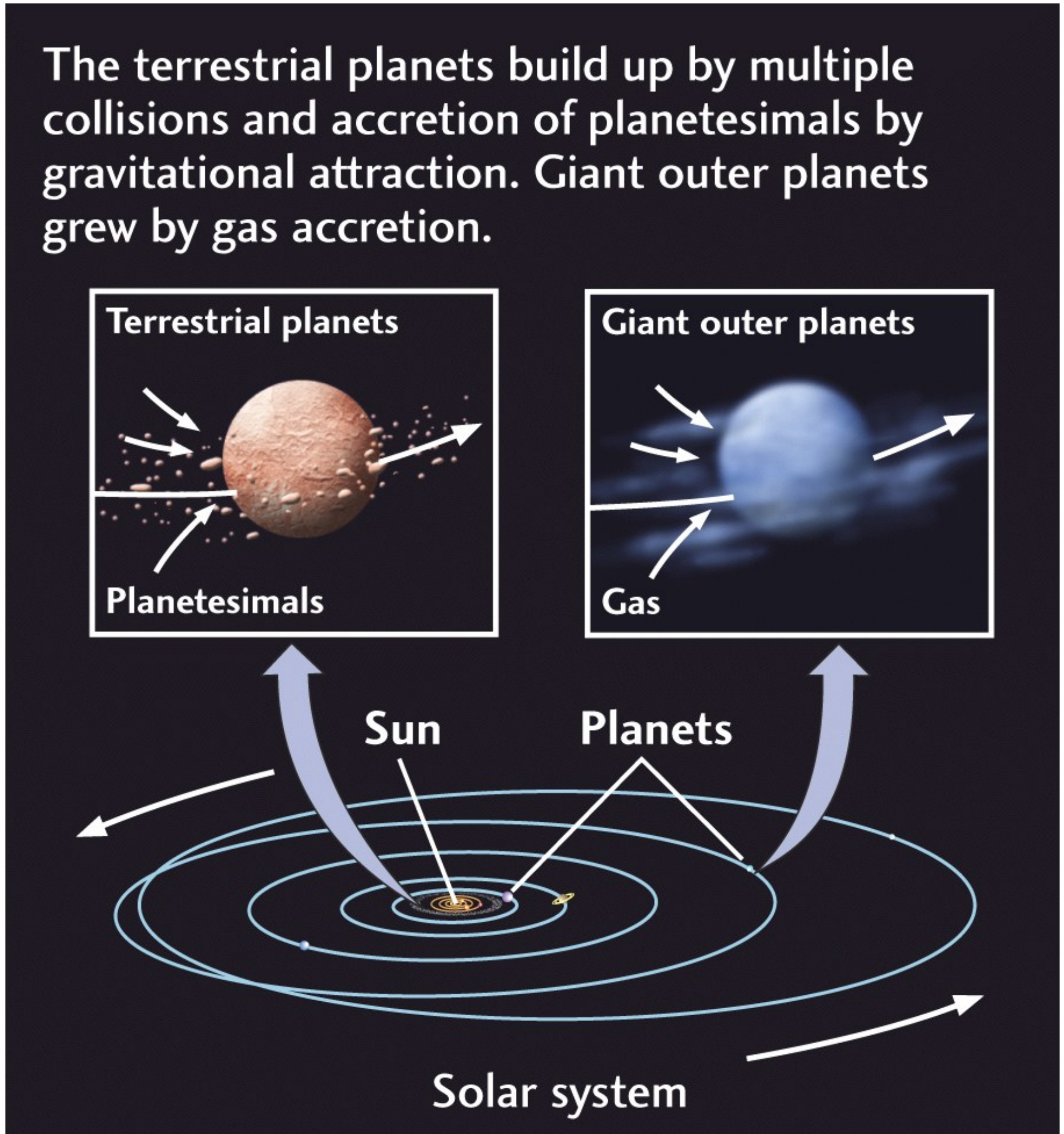


Planetesimals (> 1 km in diameter) grow by continuous collisions. Gradually a protoplanet develops.



Gravity reshapes the protoplanets into a sphere.

Evolution of the planetary system



Stellar winds around our own Sun

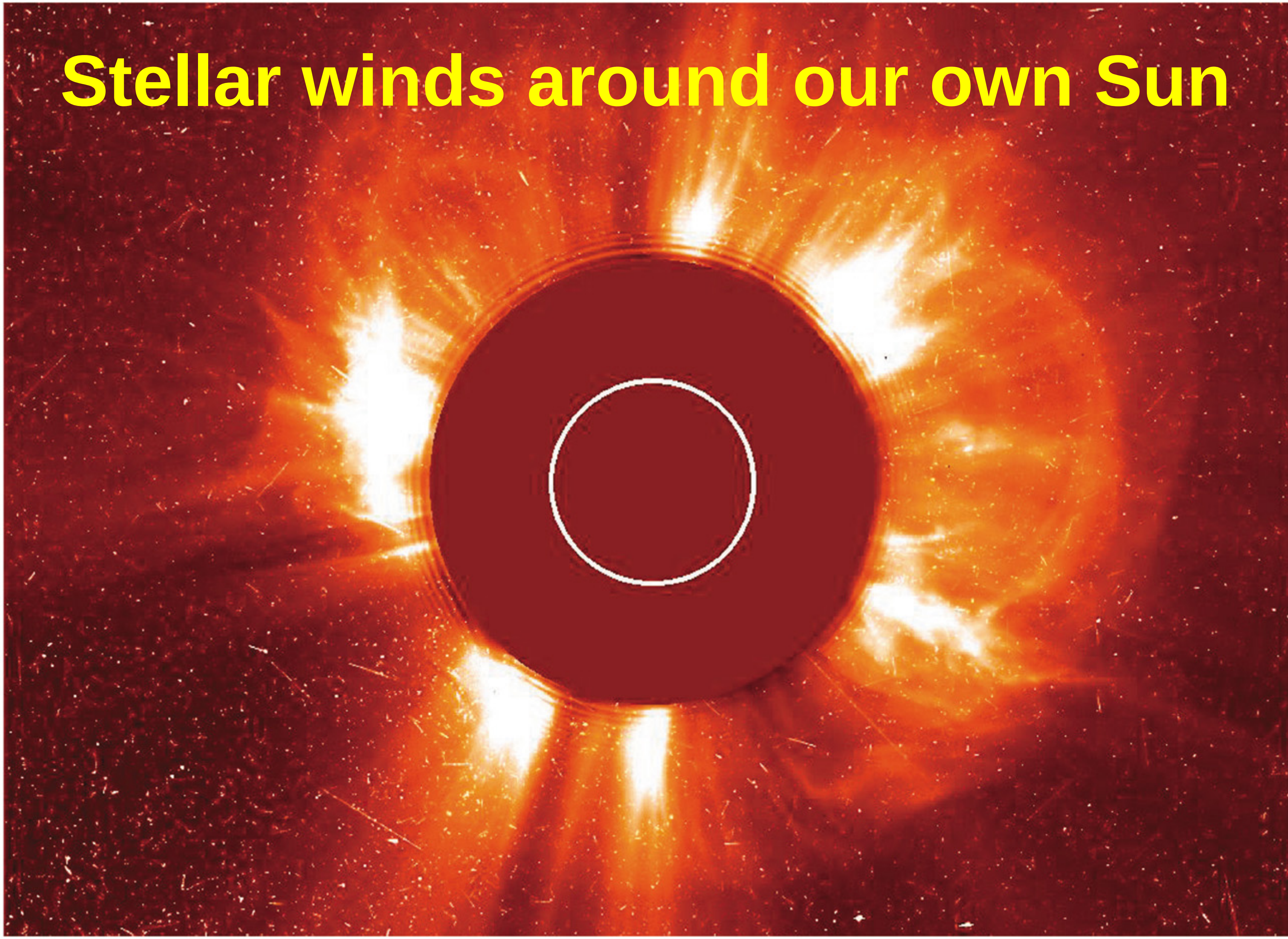
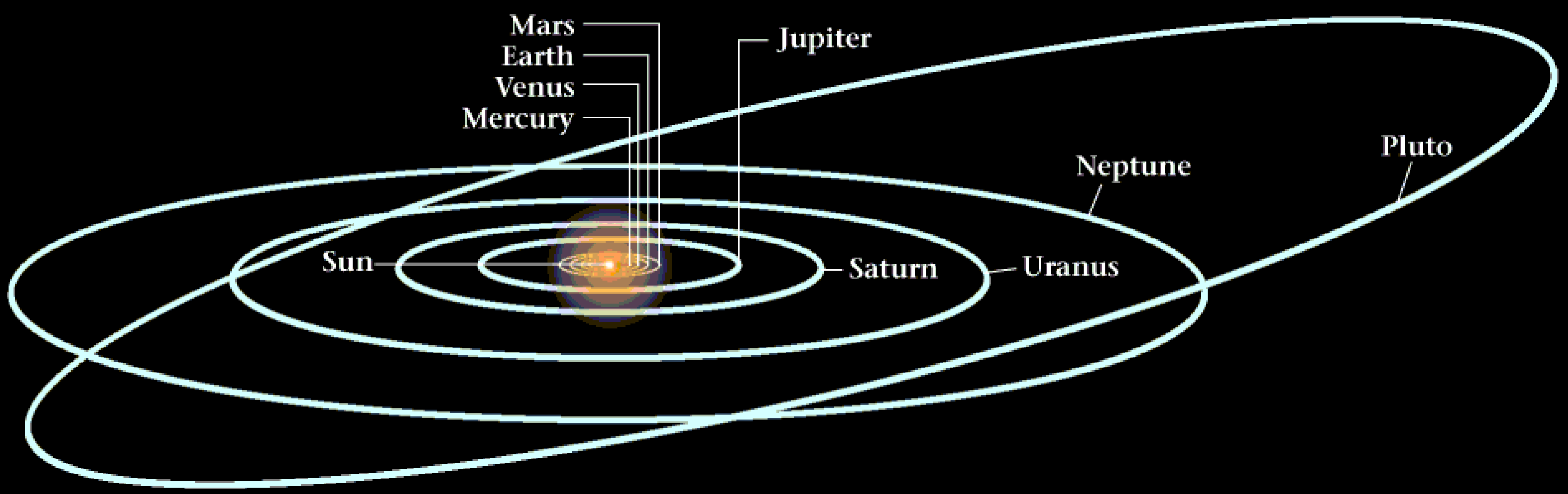
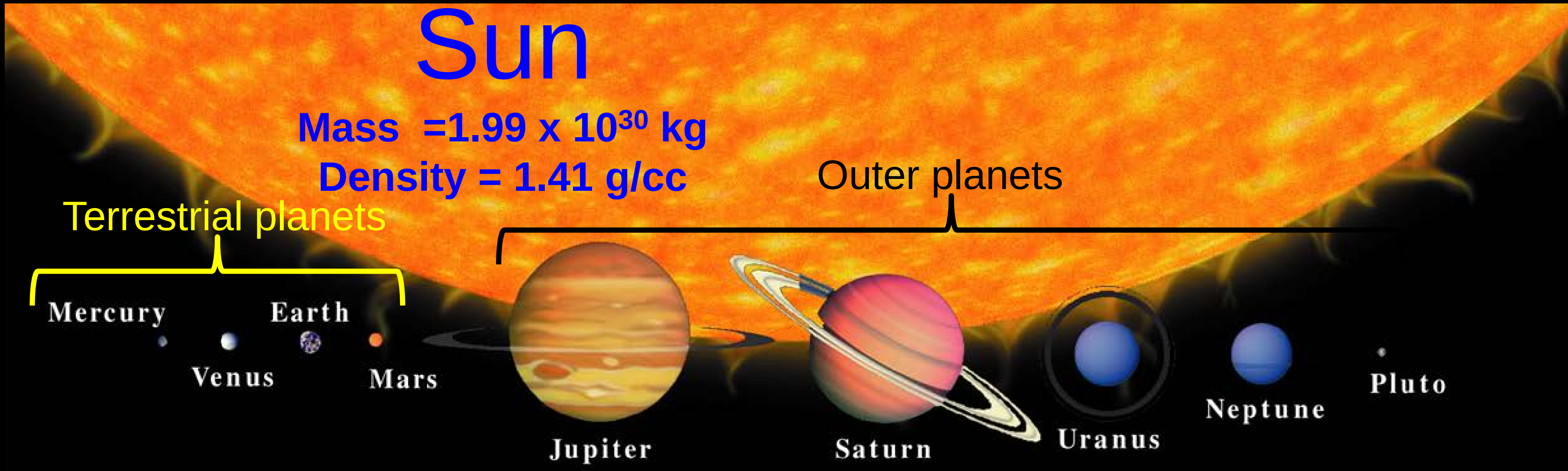


FIGURE 1.11

Earth: Portrait of a Planet, 2nd Edition

The Solar System





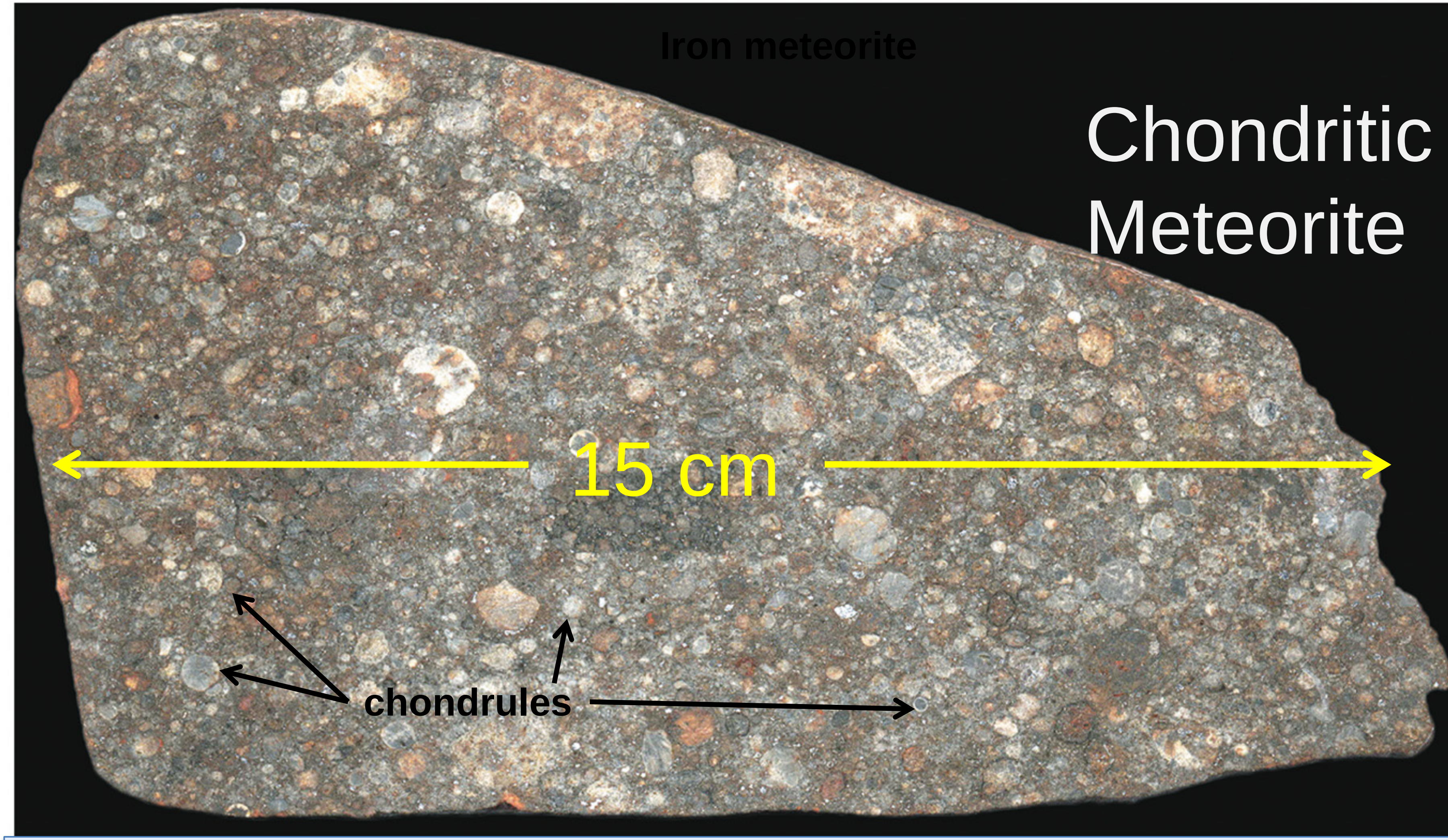
Sun

Mass =1.99 x 10^{30} kg

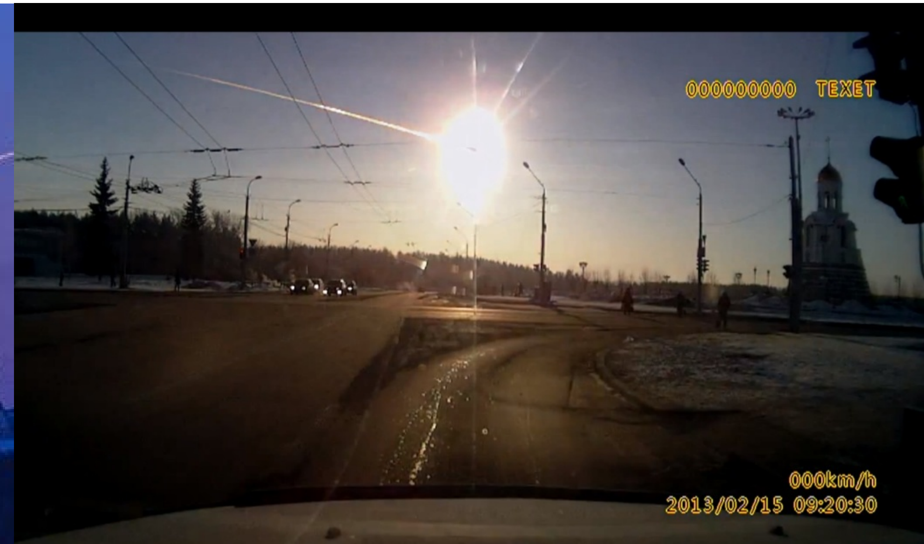
Density = 1.41 g/cc

Outer planets

Terrestrial planets



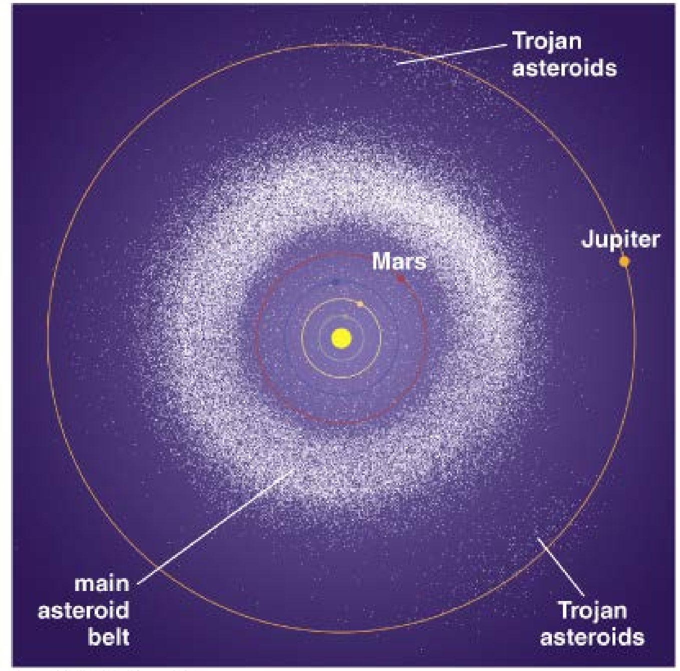
Meteorite = solid extraterrestrial material that survives passage through the Earth’s atmosphere and reaches the Earth’s surface as a recoverable object.

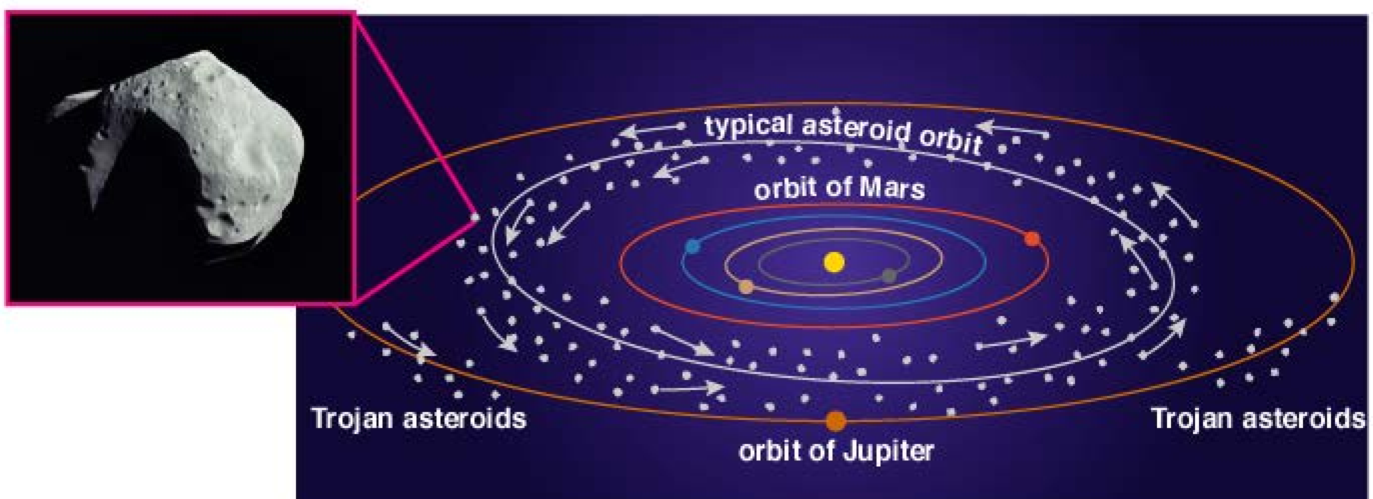


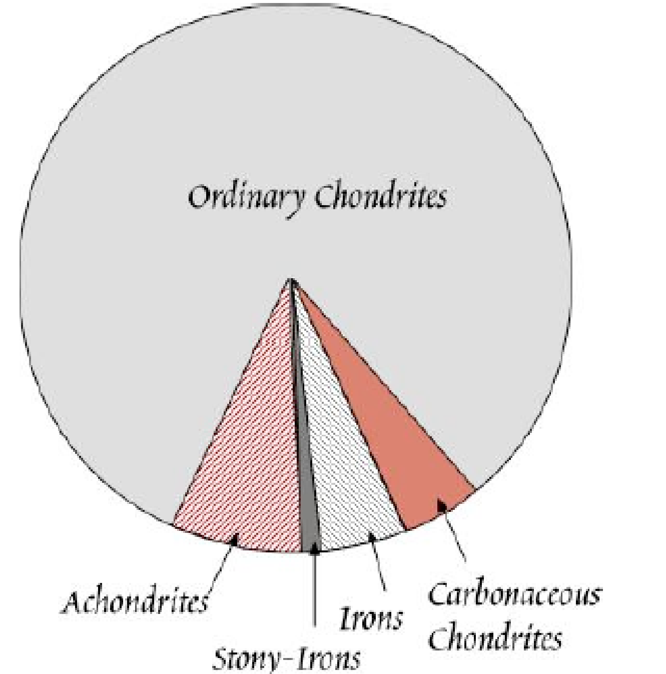
Meteorite = solid extraterrestrial material that survives passage through the Earth’s atmosphere and reaches the Earth’s surface as a recoverable object.

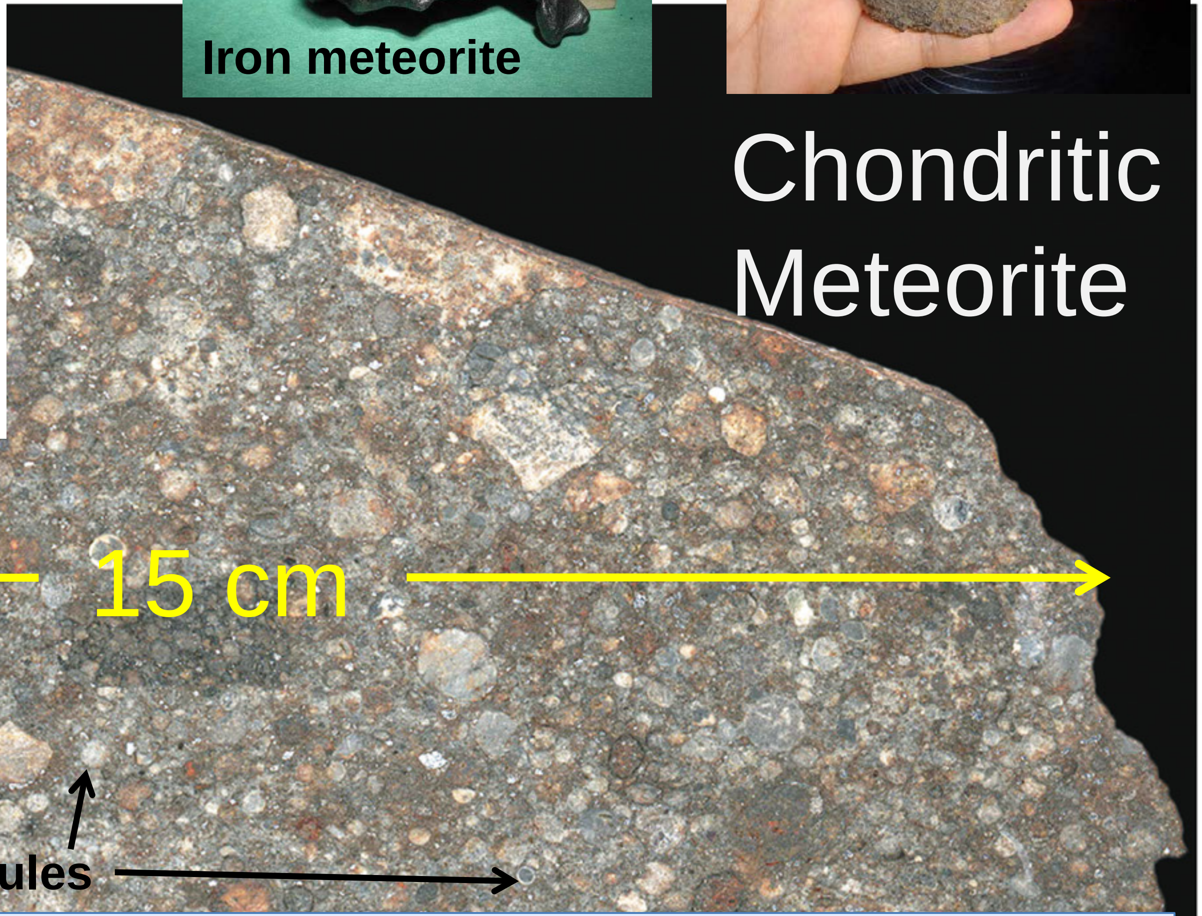
Asteroid Belt

Most meteorites are pieces of rocks broken off asteroids during their collisions with one another. As a result of collisions, their orbit around the Sun is modified and some of these pieces can enter the Earth's gravitational field.









Meteorite = solid extraterrestrial material that survives passage through the Earth's atmosphere and reaches the Earth's surface as a recoverable object.

Carbonaceous chondrites are believed to represent the initial composition of the material from which the Sun and the planets formed. They contain minerals that are unstable > 100 °C.

Relative abundances of non-volatile elements in carbonaceous chondrites

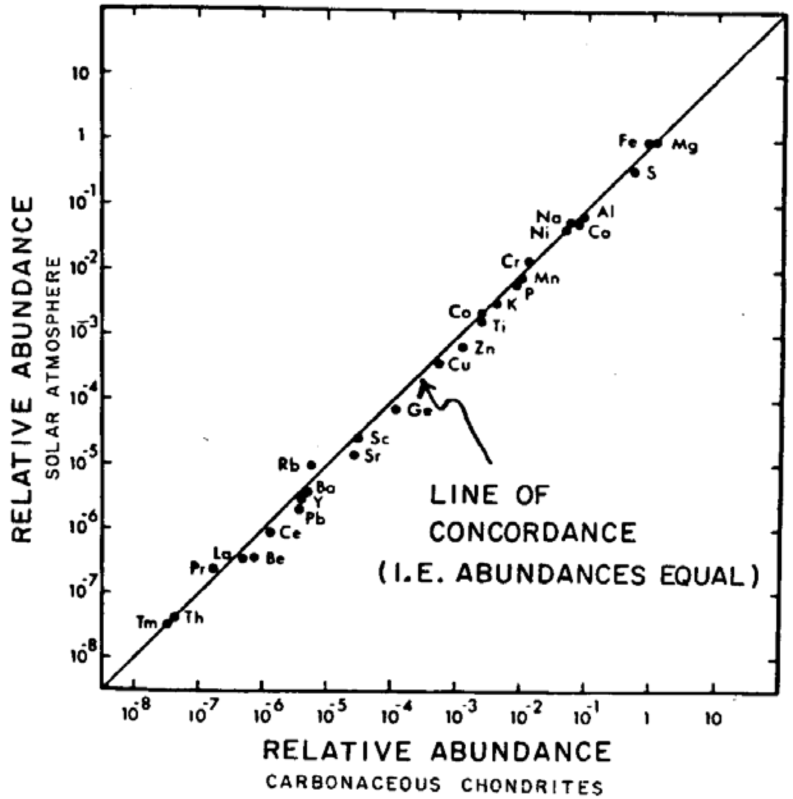


Figure 3-2. Comparison of the relative abundances of elements of low and moderate volatility in the Sun's atmosphere with those in carbonaceous chondrites: Clearly for these elements, carbonaceous chondrites provide a chemically unbiased sample of bulk solar system matter. Because the element silicon is the reference for comparison, it does not appear in the diagram.

From: W.S. Broecker (1985) How to build a habitable planet

The age of our solar system

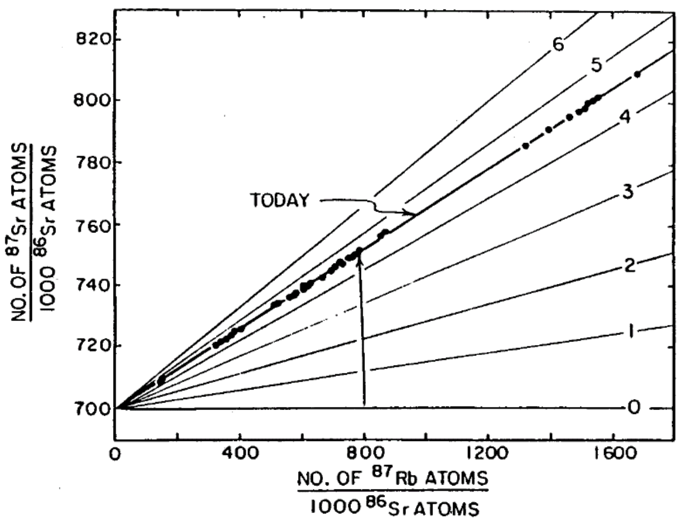


Figure 4-2. Evolution of strontium isotope composition in minerals of differing rubidium contents: The light lines on this diagram show the evolution with time (billions of years) of the ^{87}Sr and ^{87}Rb in meteorites. The measurements on mineral grains separated from chondritic meteorites tell us two things. First, they tell us that there were 700 ^{87}Sr atoms for each 1000 ^{86}Sr atoms in the strontium present in the solar nebula. Second, they tell us that these meteorites formed very close to 4.56 billion years ago. The former is derived from the intercept of the straight line that passes through the measured values. The latter is derived from the slope of the line passing through these points. Each grain followed a time trend parallel to that for the arrow shown on the diagram. At the time the solar system formed all the grains had compositions falling along the line marked zero, i.e., they had a range of ^{87}Rb to ^{86}Sr ratios, but all had 700 ^{87}Sr atoms per 1000 ^{86}Sr atoms. With time each grain increased in ^{87}Sr content (and decreased in ^{87}Rb content). This increase was in proportion to its ^{87}Rb content.

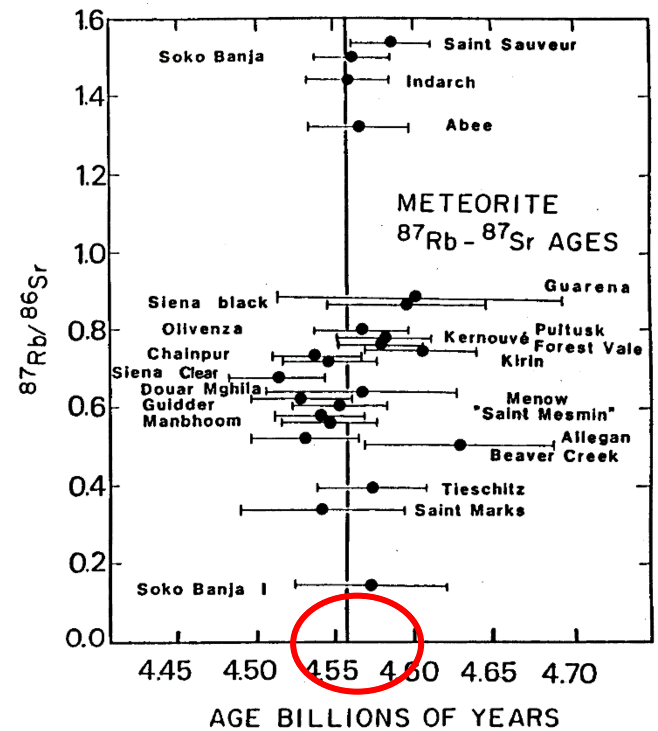


Figure 4-4. Summary of ^{87}Rb-^{87}Sr ages obtained on 19 different meteorites: As can be seen, all the results lie between 4.52 billion and 4.63 billion years. The mean of all the measurements is 4.56 billion years (shown by vertical black line). As the uncertainty in each measurement (shown by horizontal bars) in all but three cases spans this mean, there is no evidence for significant differences in the age of these objects.

^{87}Rb → ^{87}Sr + electron + energy

Half-life of ^{87}Rb = 47 billion years

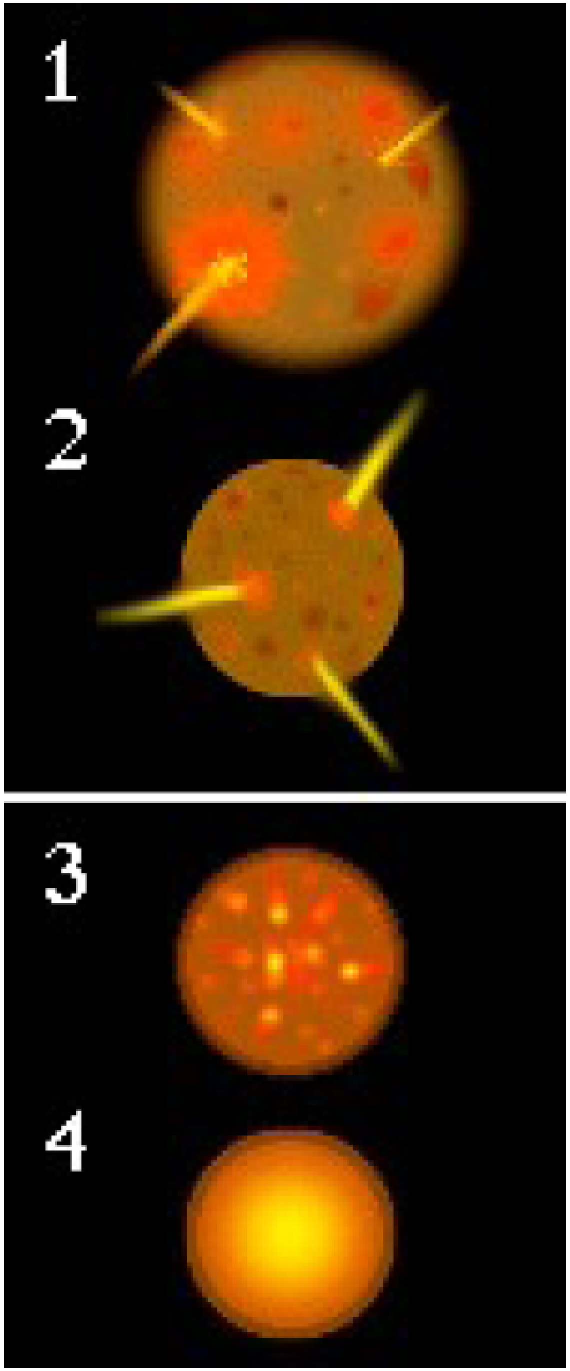
It is believed that our Sun is a third or fourth generation star. None of the material available to us from Earth could have been used to date the solar system since all of them have been remelted and recrystallized one or more time since the planet formed.

From: W.S. Broecker (1985) How to build a habitable planet.

Origin of the Earth and other planets of our solar system

The nebula condenses into a swirling disc, with a central ball surrounded by rings.

Accretion of planetesimals (> 1 km) and protoplanets of fairly homogeneous composition (10 – 200 million years).



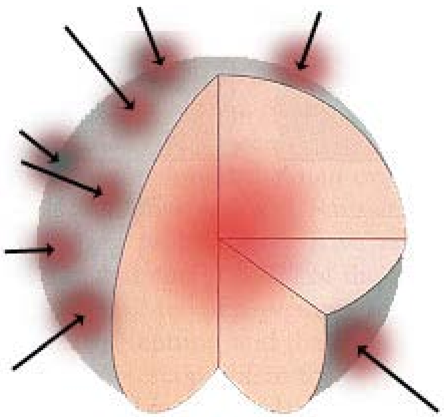
The Earth grew by accreting planetesimals through gravitational attraction

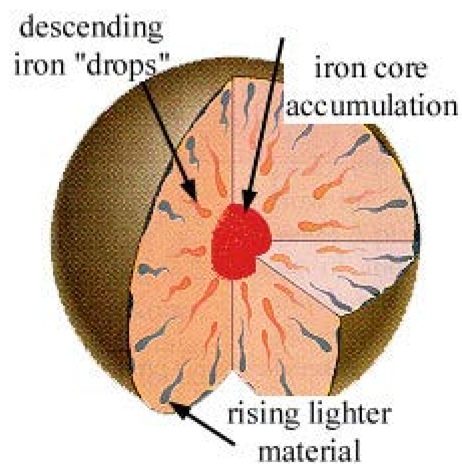
This was not a tranquil process!!

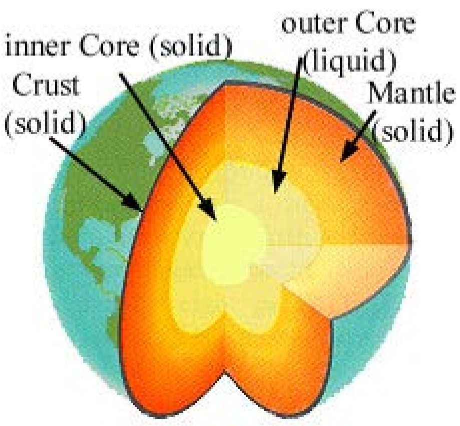
The Earth was bombarded by millions (?) of smaller bodies resembling present day meteors and comets.

The bombardment heated the Earth (slap your hands together) and that heating was aided by gravitational contraction. Partial to total melting of Earth ensued creating a magma ocean and the denser, Fe-rich, material settled to Earth's centre.

Earth differentiation







Early Earth heats up due to radio-active decay, compression, and impacts. Over time the temperature of the planet interior rises beyond the melting point of iron.

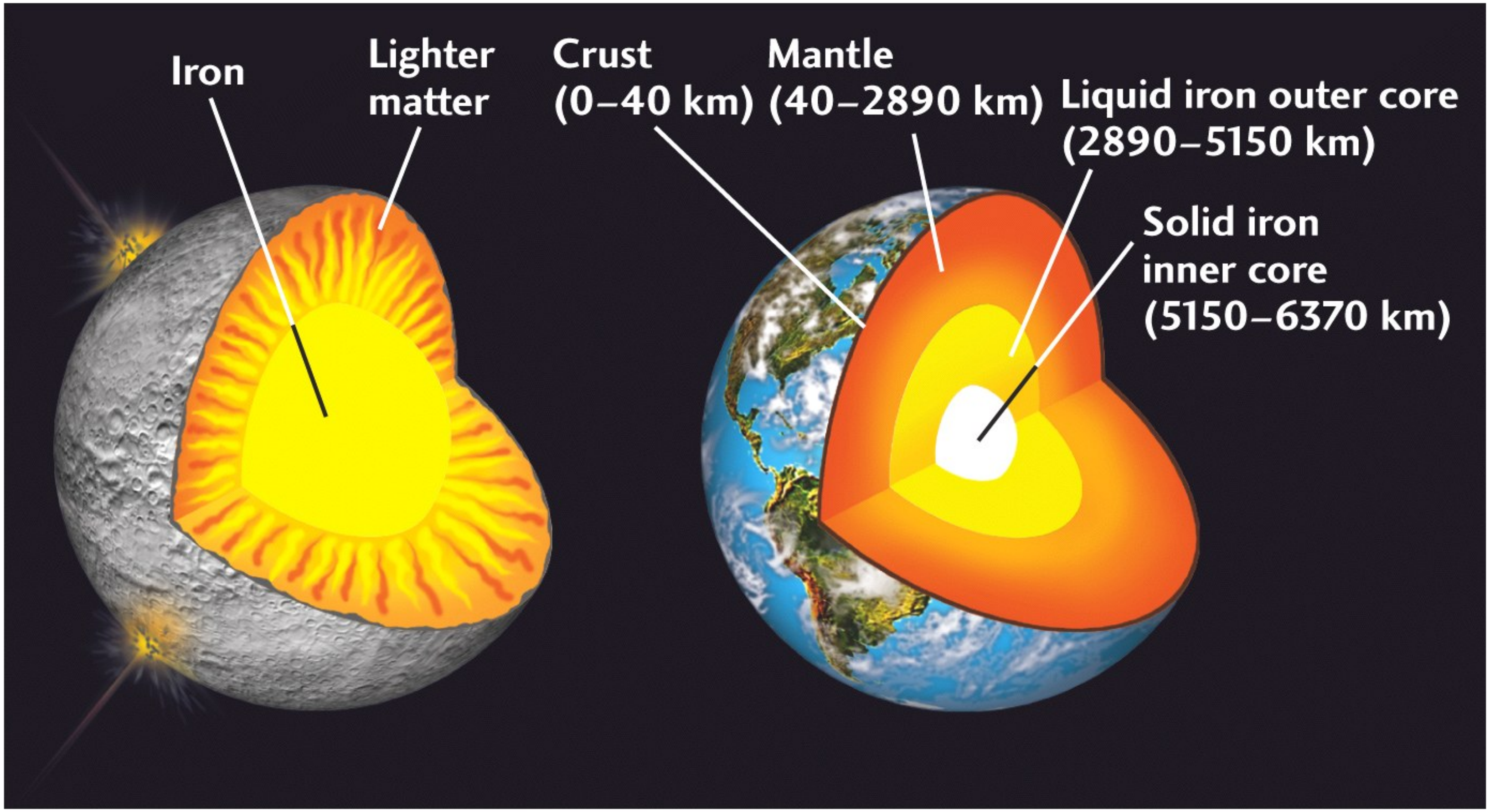
The iron "drops" follow gravity and accumulate towards the core. Lighter materials, such as silicate minerals, migrate upwards in exchange. These silicate-rich materials may well have risen to the surface in molten form, giving rise to an initial **magma ocean**.

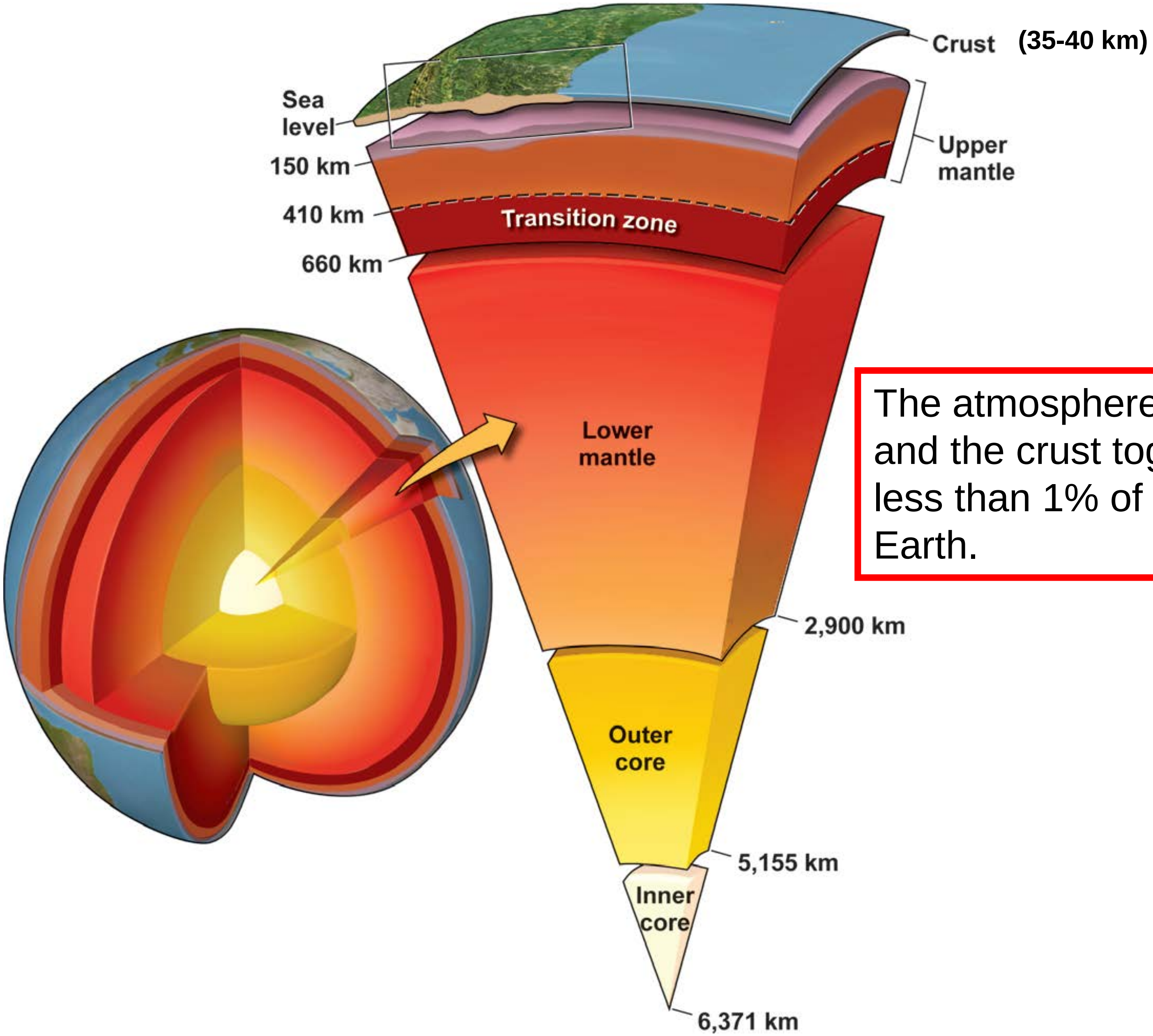
From: http://www.indiana.edu/~geol105/images/gaia_chapter_3/earth_differentiation.htm

A magma ocean in the late stages of differentiation

Global Chemical Differentiation

This global chemical differential was completed by about 4.3 billion years ago, and the Earth had developed a inner and outer core, a mantle and crust.





The atmosphere, the hydrosphere and the crust together make up less than 1% of the mass of the Earth.

Kola Superdeep Borehole (KSDB-3/ 12,261 m deep)

Relative abundances of non-volatile elements in carbonaceous chondrites

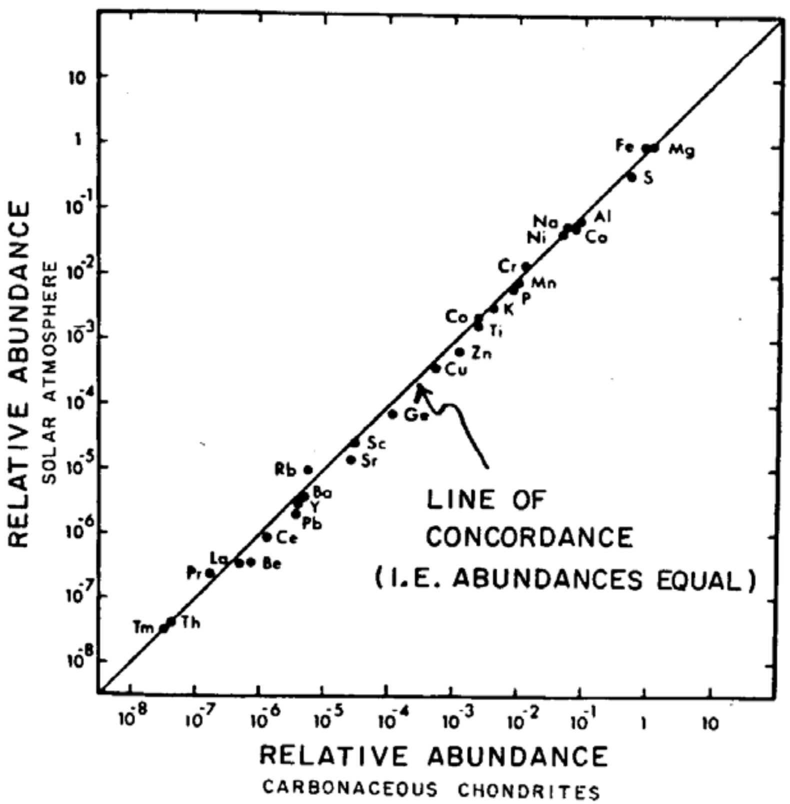
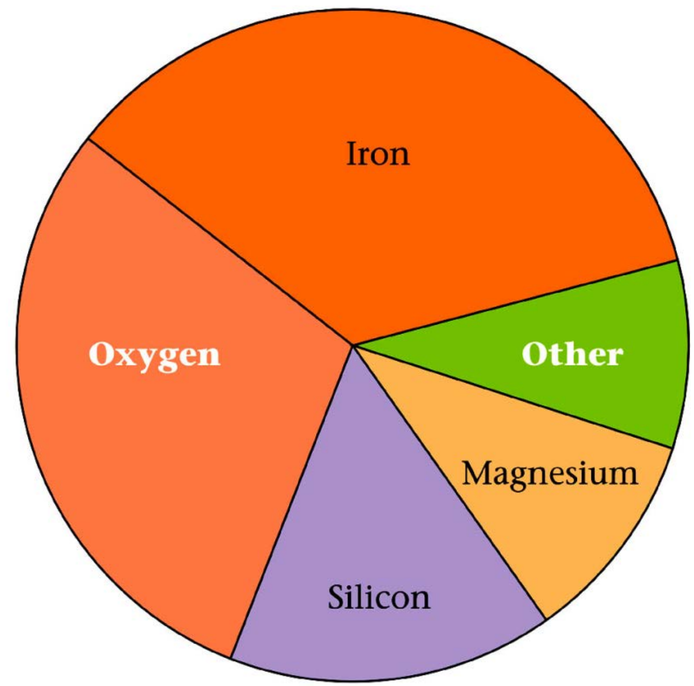
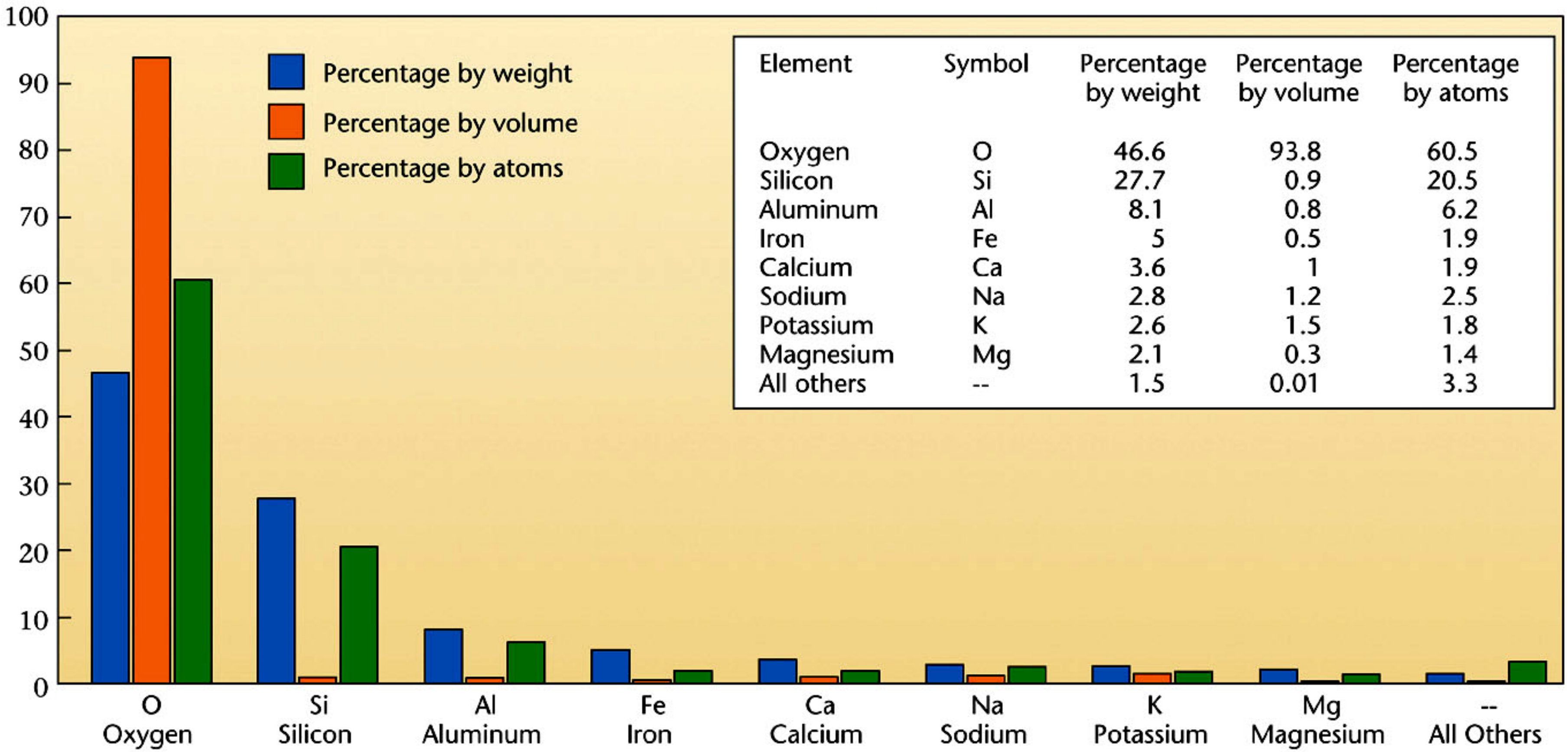


Figure 3-2. Comparison of the relative abundances of elements of low and moderate volatility in the Sun's atmosphere with those in carbonaceous chondrites: Clearly for these elements, carbonaceous chondrites provide a chemically unbiased sample of bulk solar system matter. Because the element silicon is the reference for comparison, it does not appear in the diagram.



From: W.S. Broecker (1985) How to build a habitable planet

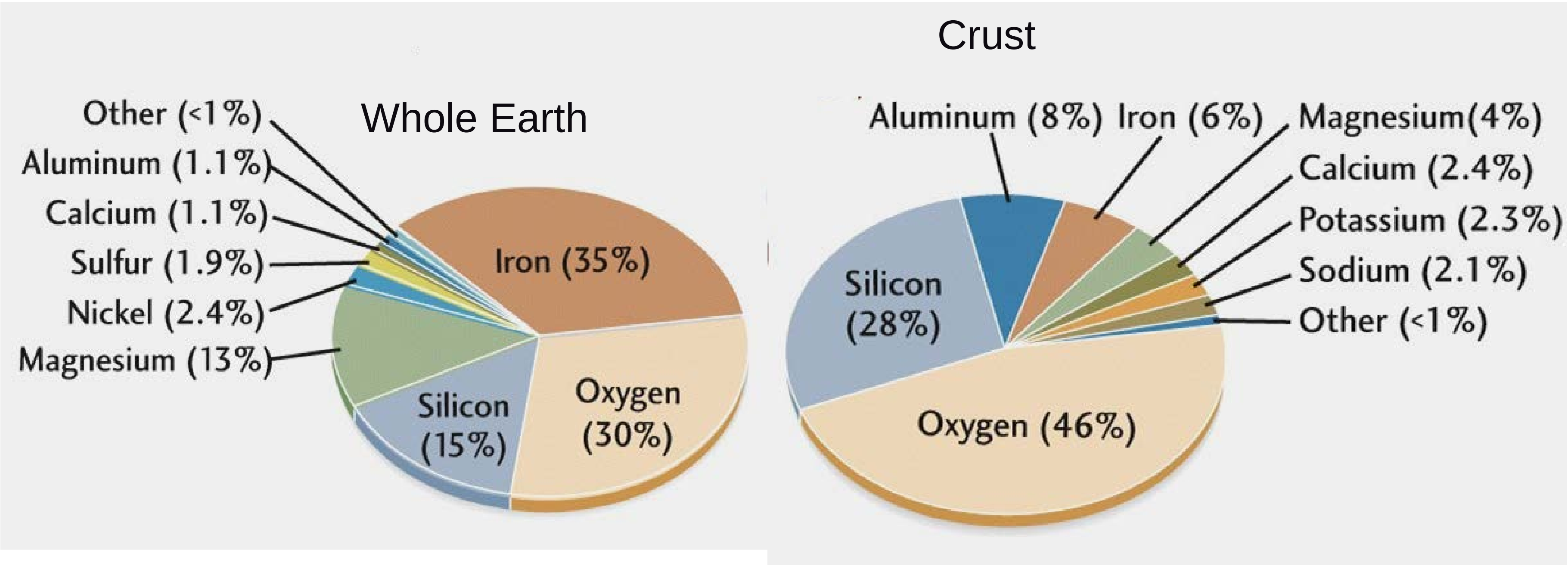
Elemental abundances in the Earth's crust



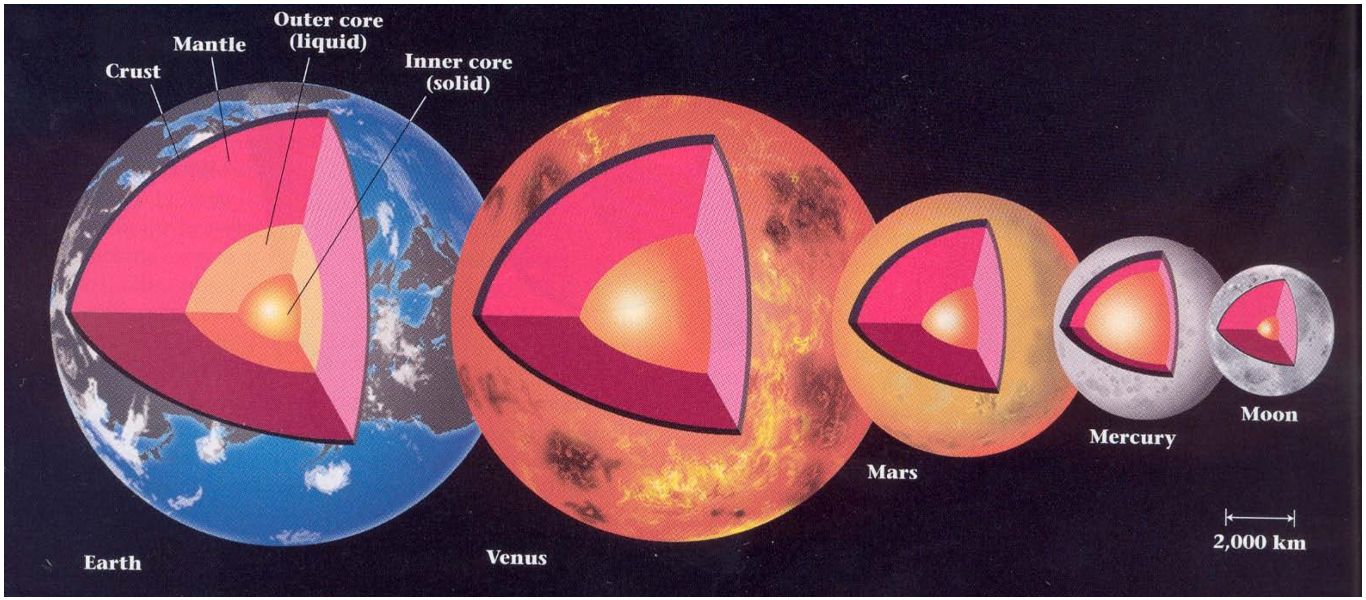
Element	Symbol	Percentage by weight	Percentage by volume	Percentage by atoms
Oxygen	O	46.6	93.8	60.5
Silicon	Si	27.7	0.9	20.5
Aluminum	Al	8.1	0.8	6.2
Iron	Fe	5	0.5	1.9
Calcium	Ca	3.6	1	1.9
Sodium	Na	2.8	1.2	2.5
Potassium	K	2.6	1.5	1.8
Magnesium	Mg	2.1	0.3	1.4
All others	--	1.5	0.01	3.3

Chemical Composition of Earth

The crust is composed preferentially of the lightest elements and the core of the heaviest elements. Their absolute abundances reflect those of the solar system, with heavier elements being much less common than light elements.



The bulk density of the terrestrial planets and their stone:metal ratio



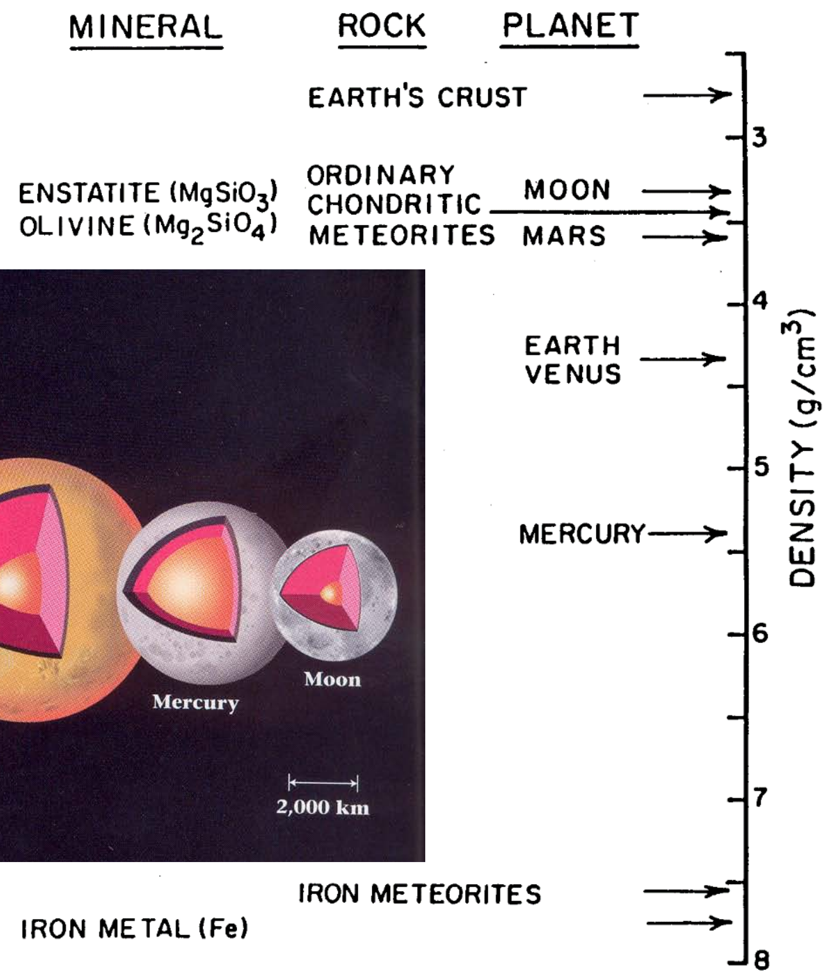
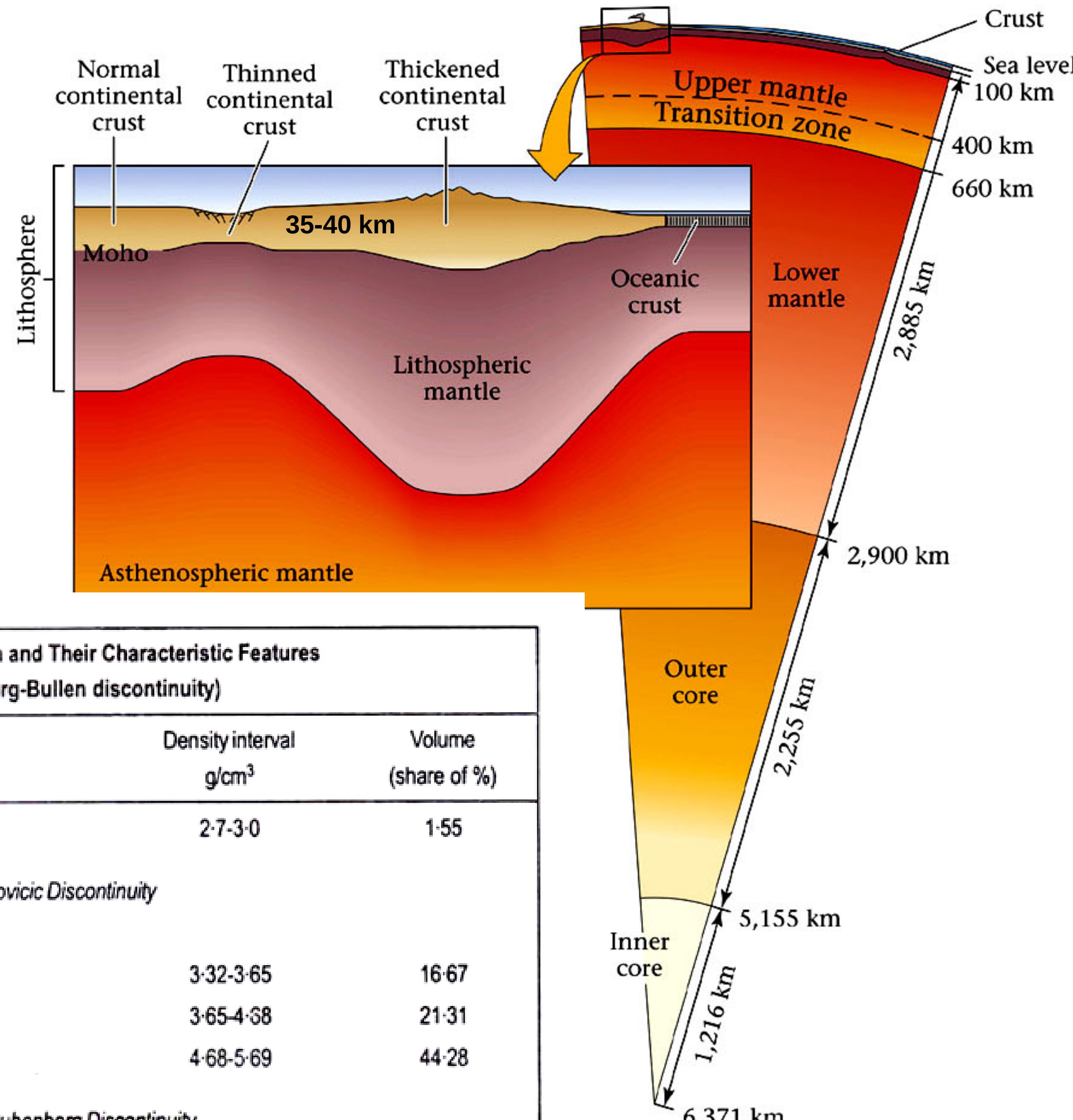


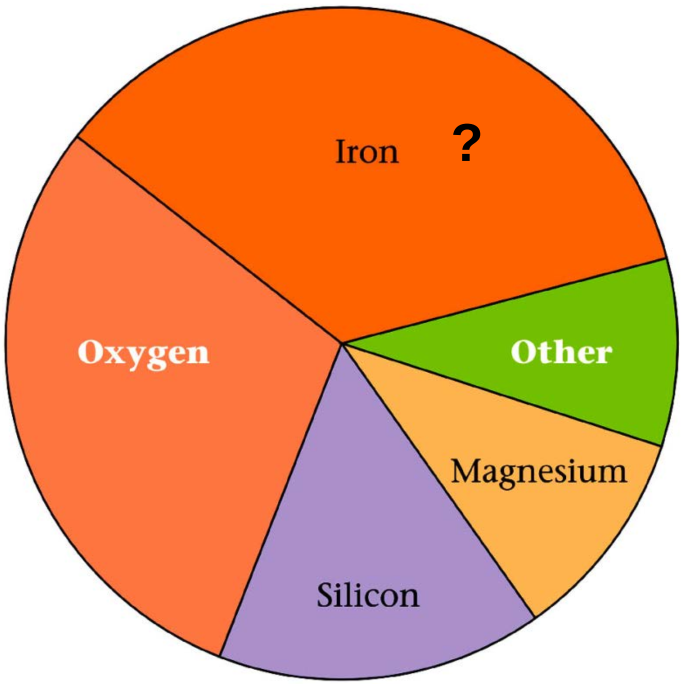
Figure 3-5. Bulk densities of various minerals, rocks, and planets: In the case of the planets, the densities shown have been corrected for gravitational compaction. The planet-to-planet density differences are in part the result of differences in the Fe/Mg+Si ratio and in part the result of differences in the iron/iron oxide ratio.

From: W.S. Broecker (1985) How to build a habitable planet



Layers of the Solid Earth and Their Characteristic Features (The Gutenberg-Bullen discontinuity)			
Geosphere	Depth interval in km.	Density interval g/cm³	Volume (share of %)
Earth's crust	0-33	2·7-3·0	1·55
	Mohorovicic Discontinuity		
Mantle			
Outer mantle	33-410	3·32-3·65	16·67
Transit layer	410-1,000	3·65-4·68	21·31
Lower mantle	1,000-2,900	4·68-5·69	44·28
	Weichert-Gubenberg Discontinuity		
Core			
Outer core	2,900-4,980	9·4-11·5	15·16
Transitory zone	4,980-5,120	11·5-12·0	0·28
Inner core	5,120-6,370	12·0-12·3	0·76

Element abundance on Earth



Silicate Minerals

Classified on the basis of their silicon: (iron + magnesium) ratio.
In decreasing order of silicon content:
- Felsic (or silicic)
- Intermediate
- Mafic
- Ultramafic

Density increases with decreasing silicon content. Consequently, felsic rocks are less dense than mafic rocks.

Compounds found on Earth

- **Organic chemicals**: Carbon-based compounds, where two or more carbon atoms are bond together and carbon atoms are bond to hydrogen and, in some cases, oxygen, nitrogen and other elements (e.g., living tissue, oils, plastics, rubber).
- **Minerals**: Solids in which the atoms are organized in an orderly pattern. Most minerals are inorganic, like halite (NaCl), quartz (sand).
- **Glasses:** Solids in which atoms are not arranged in an orderly pattern. Typically form when a liquid freezes very fast (e.g., silica glass).
- **Rocks**: An assemblage of minerals or a mass of natural glass, a mixture of minerals or glasses.
    - Igneous rocks: formed upon cooling of molten rock or magma/lava
    - Sedimentary rocks: broken pieces of pre-existing rocks or precipitates
    - Metamorphic rocks: pre-existing rocks subjected to high T and/or P
- **Melts**: Formed when solid materials are heated and transformed into a liquid (magma, lava).
- **Volatiles:** Materials that easily transform into gases at the relatively low temperatures found at the Earth's surface (e.g., CO_2, CH_4, H_2O)

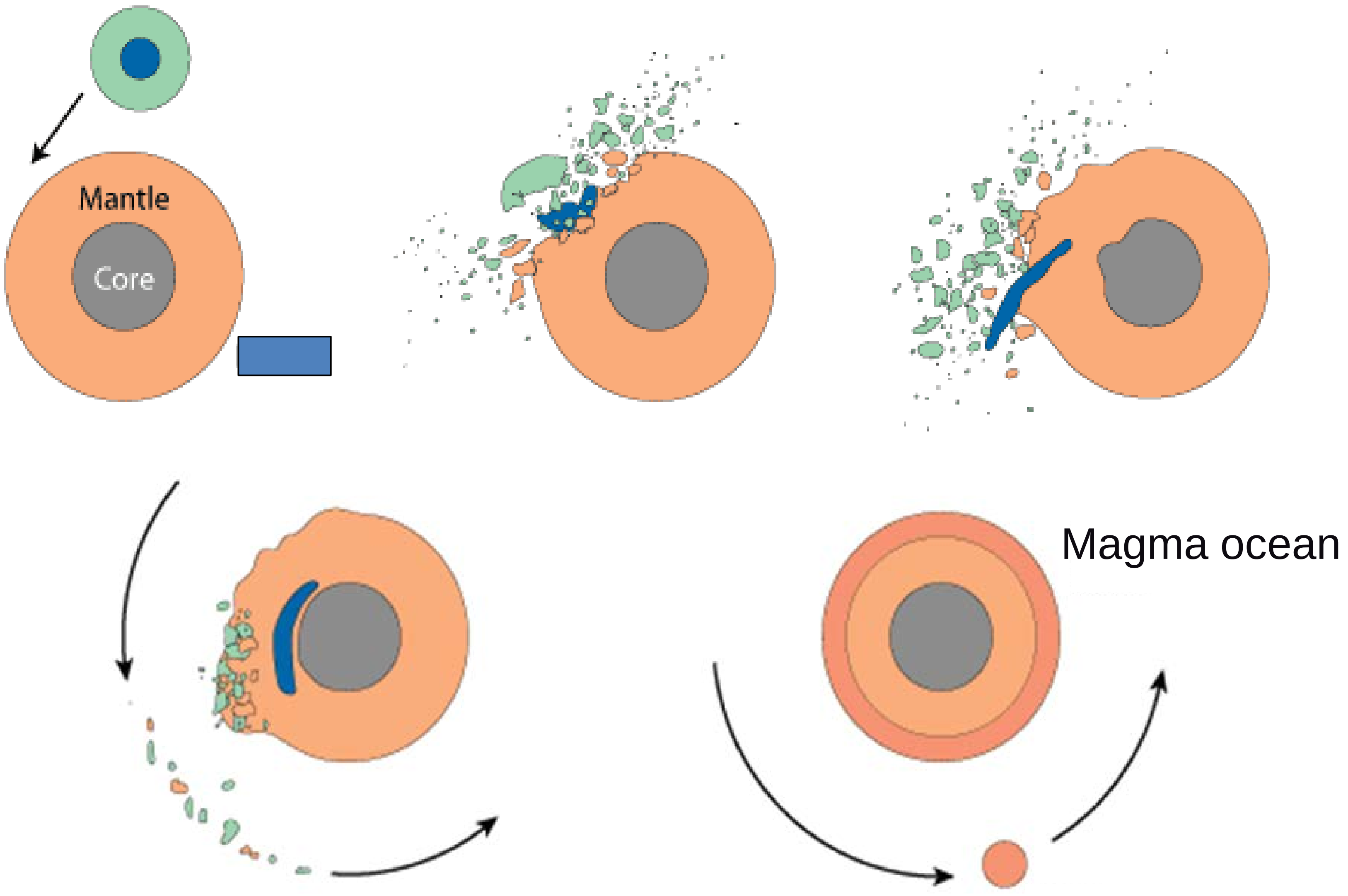
Birth of the Moon

Soon after Earth formed, a small planet (Mars-sized) collided with it, blasting debris that formed a ring around the Earth

The Moon formed (~100,000 years) from the ring of debris

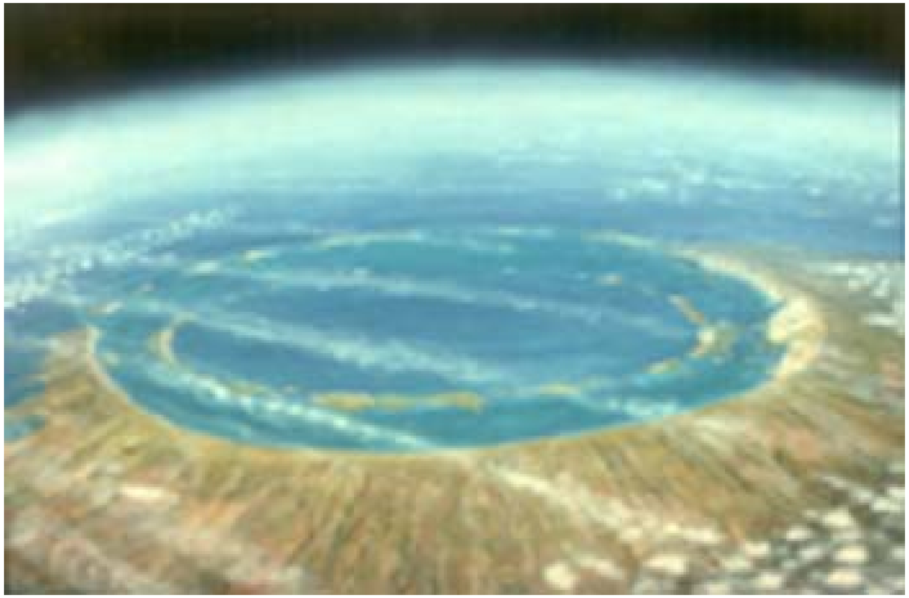
Constrained by the age of the oldest Moon rocks recovered by the Apollo missions, the Moon was formed about 4.47 Ga ago.

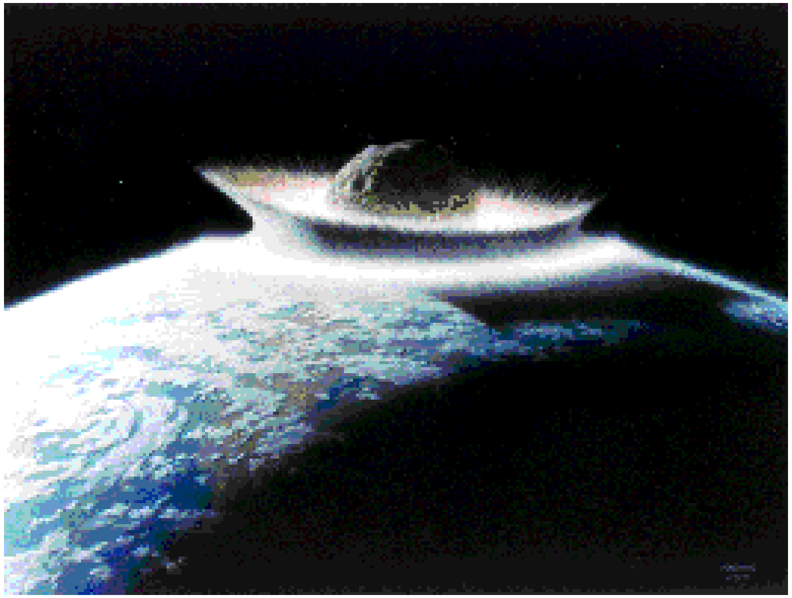
Simulated Formation of the Moon



Bombardment From Space

For the first half billion years of its existence, the surface of the Earth was repeatedly pulverized by asteroids and comets of all sizes. However, no evidence has been preserved because of resurfacing.





Formation of the Atmosphere and Oceans

Eventually the atmosphere developed from volcanic gases (mainly H_2O and CO_2). As the Earth cooled, moisture condensed, it rained, and the oceans formed.

And here we are now . . .

living on one of the few geologically active bodies in our solar system

where geochemical processes control all aspects of the Earth system from the core to the atmosphere