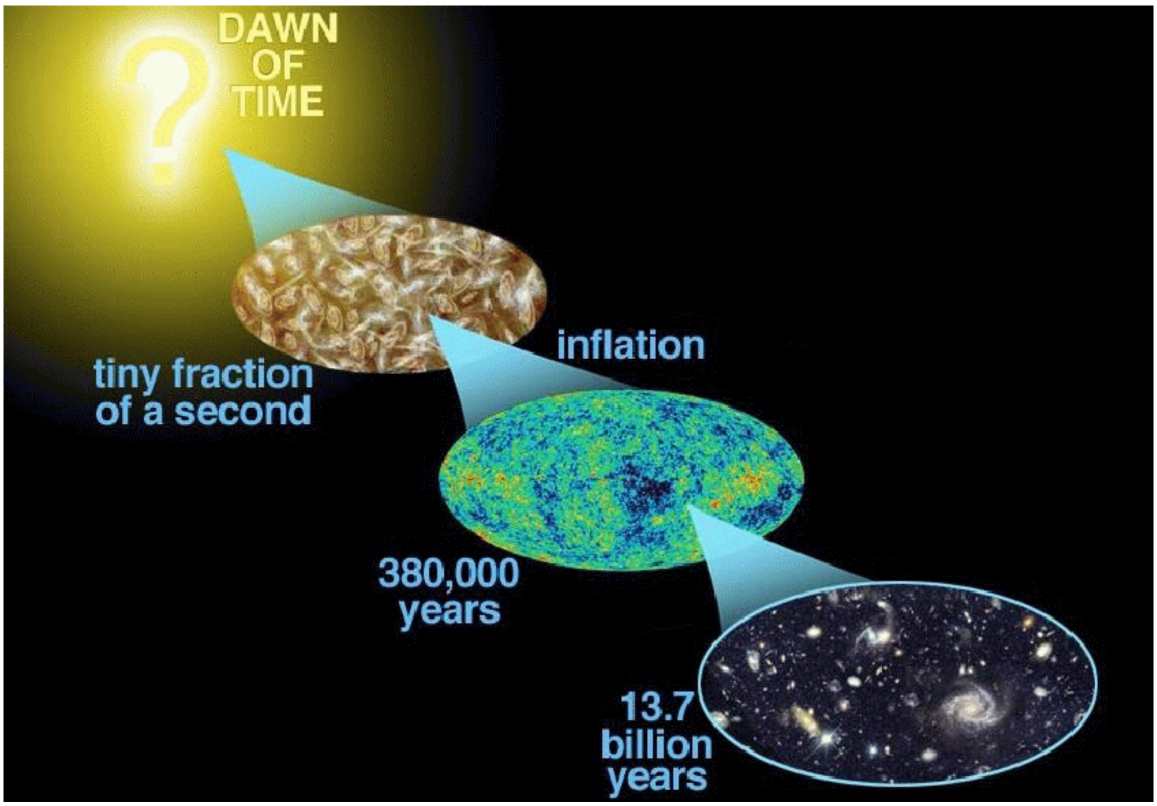
Elements and Minerals

(RED)

Natural Environment Option



Synopsis

Lecture 1: Nuclear Chemistry, Stability of nuclei.
Lecture 2: The Big Bang, Synthesis of the elements I
Lecture 3: Star birth and death, Synthesis of the elements II
Lecture 4: Solar system and Earth formation
Lecture 5: Rocks and Minerals
Lecture 6: Silicates
Lecture 7: Gemstones

Learning Objectives: by the end of the course you should be able to

i) Calculate binding energies for nuclei.
ii) Understand common radiaoactive decay mechanisms (alpha and beta decay).
iii) Describe the main nuclear processes relevant to the big bang and the main supporting evidence for the big bang theory.
iv) Describe the cycle of star birth and death.
v) Apply the Hertzsperg-Russell diagram to the star birth/death cycle.
vi) Understand the main process occurring in stars leading to synthesis of heavy and superheavy elements.
vii) Outline the main processes that have lead to synthesis of the elements in the universe.
viii) Describe how differentiation of the elements occurred during formation of the earth.
ix) Describe how differentiation of the elements occurred during evolution of the earth.
x) Understand and interpret basic phase diagrams.
xi) Understand the concepts of polymorphism, solid solutions and non-stoichiometry.
xii) Describe the basic structure types of silicates.
xiii) Understand and describe the structure of olivines, pyroxenes and feldspars.
xiv) Understand the origin of colour in gemstones and the concepts of intrinsic and extrinsic defects.

Bibliography:

P.A. Cox, The Elements, OUP (1990)
A.R. West, Solid State Chemistry and its Applications, Wiley (1984)
R. Gill, Chemical Fundamentals of Geology, Unwin Hyman (1989)
S.F. Mason, Chemical Evolution, Clarendon Press (1991)
N.N. Greenwood, A. Earnshaw, Chemistry of the Elements, (1984)
J. Silk, The Big Bang, Freeman, 2e (1989)
S. Weidberg, The First Three Minutes, Fontana, (1986)

There are many introductory textbook on astronomy in the Morrell Library. All cover much the same material in a similar order and there is little to choose between any of them! They are shelved in the Quarto T section of the library and include;
W.J. Kaufmann and R.A. Freedman, Universe, W.H. Freeman (1998)
G.O. Abell, D. Morrison and S.C. Wolff, Exploration of the Universe, Saunders (1993)
J.M. Pasachoff, Astronomy, Saunders (1993)
M. Zeilik, Astronomy, the Evolving Universe, Wiley, (1994)
The Stars and Interstellar Medium, The Open University S281 Book 1, (1994)
S. R Taylor, Solar System Evolution, Cambridge University press (1992)

Introductory geology books include:
B.J. Skinner & S.C Porter, The Dynamic Earth, Wiley, (1995)
F. Press & R Siever, Understanding Earth, W.H. Freeman, (1994)
C.C. Plummer & D. McGeary, Physical Geology, Wm.C. Brown, (1996)

Some interesting questions

What is the origin of the universe?

How will it all end?

How were the elements formed?

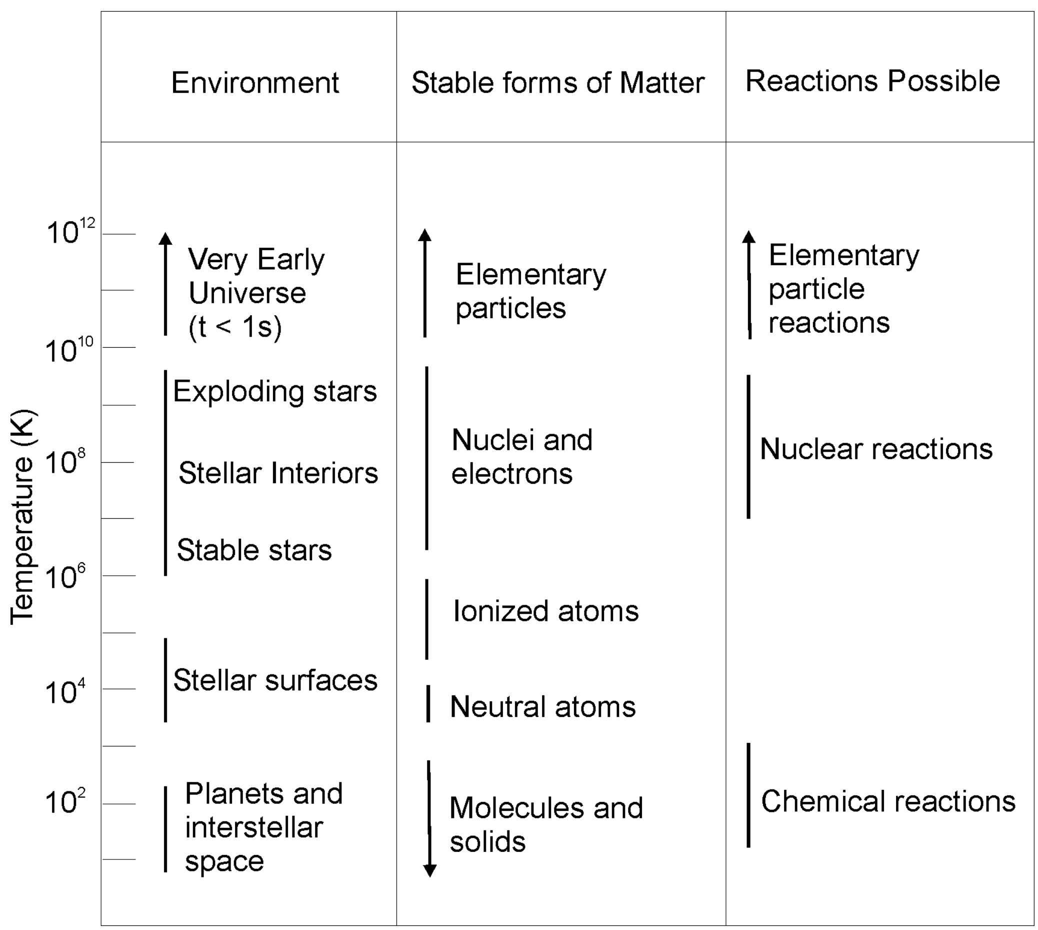
How was the earth formed?

What is the composition of the Earth?

Can we explain the observed distribution of elements in the universe and on earth?

Distinction between chemical and nuclear reactions

Elements are defined by the number of protons in the nucleus and therefore synthesis of the chemical elements will require an understanding of *nuclear* chemistry. It is instructive to compare the relative energies of 'nuclear' and 'chemical' processes.



'Chemical synthesis' requires manipulation of valence electrons 10 – 10^3 K
'Nuclear synthesis' require temperatures > 10^7 K

As we will see later the elements were formed under high-energy conditions.

1. Soon after the **big bang**-cosmological nucleosynthesis
2. **Inside stars**- nucleosynthesis in stellar furnaces
3. From **cosmic rays**-fission in the interstellar medium induced by the very high-energy particles that permeate space.

Why are high energies inherent to nuclear processes?

Compare sizes of atoms and nuclei
Atom ~ 200 pm (2 x 10^{-10} m), Nucleus ~ 10 fm (10^{-14} m)

Coulomb law of electrostatics

$$V = \frac{q_1 q_2}{4\pi\varepsilon_0 r}$$

where V = potential energy, q = charge on interacting particles, r = distance

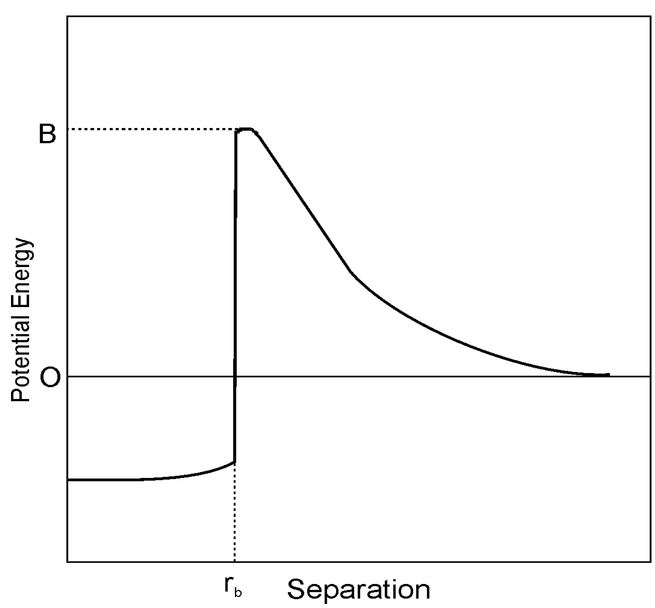
For atoms r = 200 pm, V = 1.2 x 10^{-18} J (7 eV) or ~ 700 kJ mol^{-1}
For nuclei r = 10 fm, V = 1 MeV or 100 GJ mol^{-1}

Note the electrostatic interaction between electrons and nuclei is attractive, whereas the interaction in the nuclei (between protons) is repulsive. (therefore there must be a stronger attractive force holding nuclei together).

The strong interaction

The strong interaction is different from electrostatic interaction in two ways.

1) operates equally between protons and neutrons (actually subatomic particles, quarks, gluons).
2) short range only operating over distance of 2 fm or less.

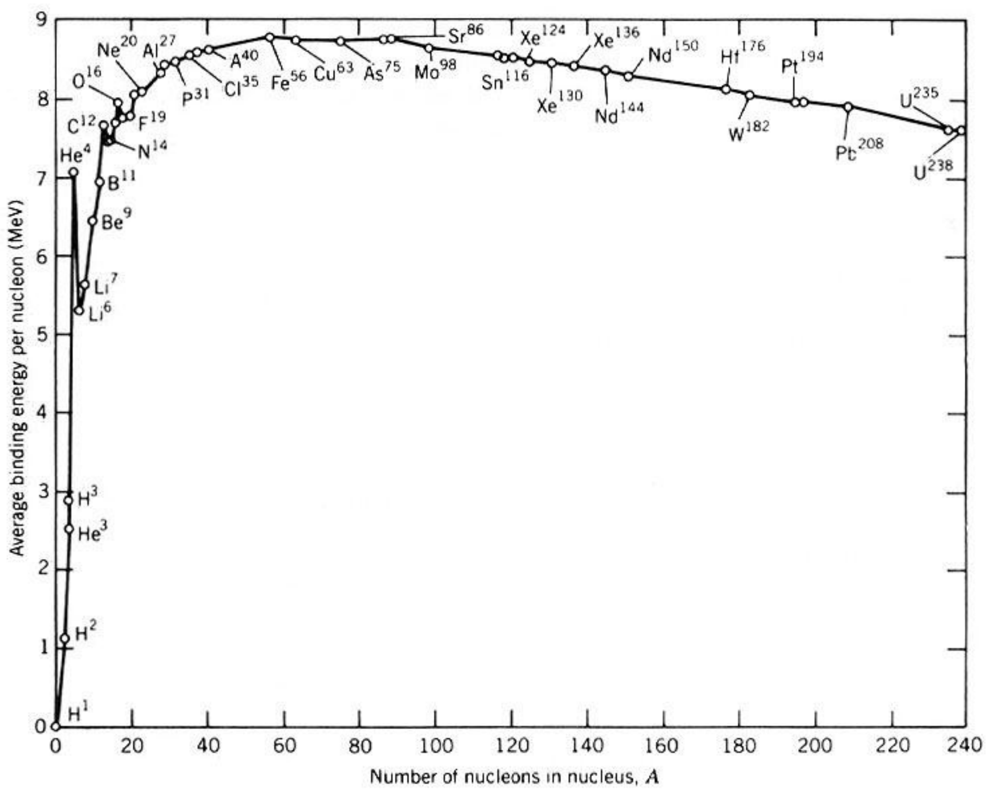


The stability of a nucleus is a balance between the strong interaction (between all nucleons) and repulsive coulombic interaction (between protons). In the diagram for a pair of nuclei coulombic forces dominate to the right of r_b, strong interaction to the left of r_b. The diagram can be viewed as reaction energy for nuclear fusion (right to left) or fission (left to right).

Binding energy

The binding energy is the energy required to break up a nucleus into its constituent nucleons.

Because of the opposition of strong and coulombic interactions the binding energy *per nucleon* for stable nuclei should go through a maximum. ^{56}Fe is the most stable nucleus.



This diagram is important in understanding the abundances of elements in the universe.
The binding energy can be calculated by the mass loss on nucleus formation.
Consider:
Atomic mass unit of ^{12}C = 12 amu(by definition)
Mass of hydrogen atom = 1.00727661 amu, Mass of neutron = 1.00866520 amu

$^{12}C = 6\ ^{1}H$ atoms + 6 neutrons = 6 x 1.00866520 + 6 x 1.00727661 = 12.095651 amu
^{12}C is therefore light by 0.095651 amu.

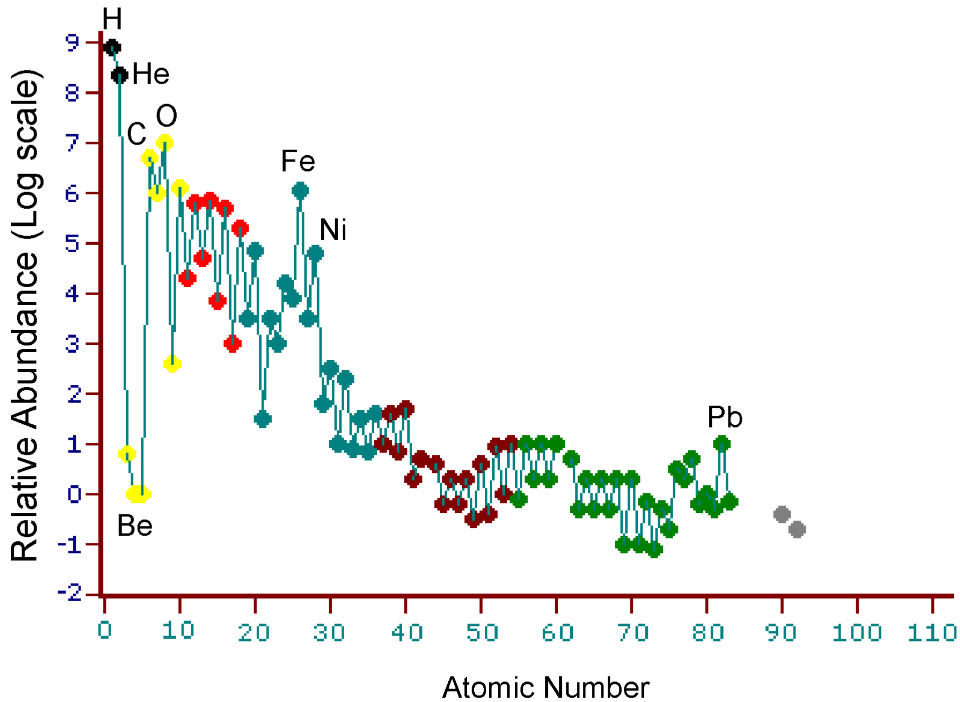
Einstein's Special Theory of Relativity $E = mc^2$ equates mass with energy.
$c^2 = 9 \times 10^{16}$ J kg^{-1} or 931.5 MeV/amu.

For ^{12}C the total nuclear binding energy is 931.5 x 0.95651 = 90.2 MeV

The realisation that nuclear energies are so large (in comparison to chemical (electron) energies) lead to the development of nuclear power sources and weapons.

Stability of Nuclei

Universal abundances of the elements



The abundance of elements is due to several factors including the method of synthesis and inherent stability.

In an analogous way that electrons in atoms are quantized (n, l, m, s), nucleons in nuclei are also quantized. You will receive a more thorough description of this topic in year 3 *f-elements and nuclear chemistry*. Here we will preset the basic conclusions for stability.

1. Nuclei with even numbers of protons and/or neutrons are more stable than with odd numbers.
2. Certain numbers (magic numbers) are particularly stable 2, 8, 20, 28, 50, 82 and 126. These represent 'closed shell nuclear configurations' analogous to 2, 8, 18, 32 closed shell electronic configurations.

Radioactive elements

These elements decay by a number of pathways with the release of energy (gamma) and particles.

The most common are

α emission (loss of a helium nucleus). Occurs via tunnelling through strong interaction/coulomb barrier) All nuclei with Z > 82 are alpha emitters

$$\text{e.g.}\quad {}^{238}_{92}\text{U} \longrightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\alpha$$

beta decay

1. beta (β^-) emission (loss of an electron)

$$^{137}_{55}Cs \longrightarrow ^{137}_{56}Ba + e^- + \bar{\nu}_e$$

2. electron capture (EC) (gain of an electron)

$$^{22}_{11}Na + e^- \longrightarrow ^{22}_{10}Ne + \nu_e$$

3. positron (β^+) emission (loss of an anti-electron)

$$^{22}_{11}Na \longrightarrow ^{22}_{10}Ne + e^+ + \nu_e$$

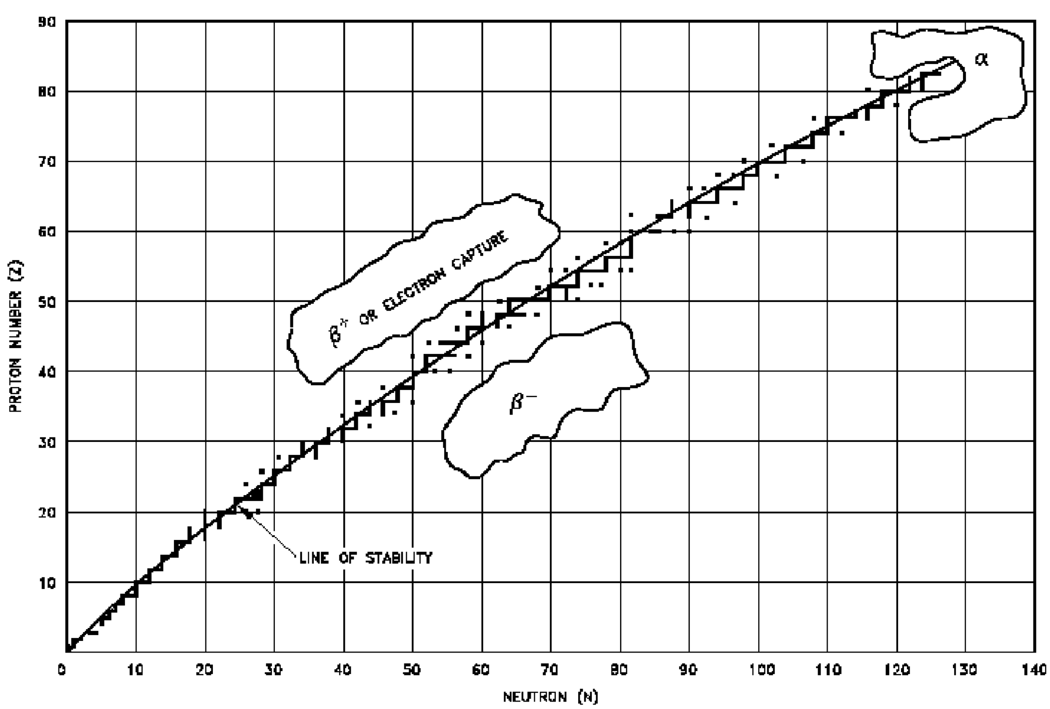
β-decay occurs by the **weak interaction**, which like the strong interaction is short range. Neutrinos can only interact with matter by the weak interaction.

A particular nucleus may decay by more than one mode.

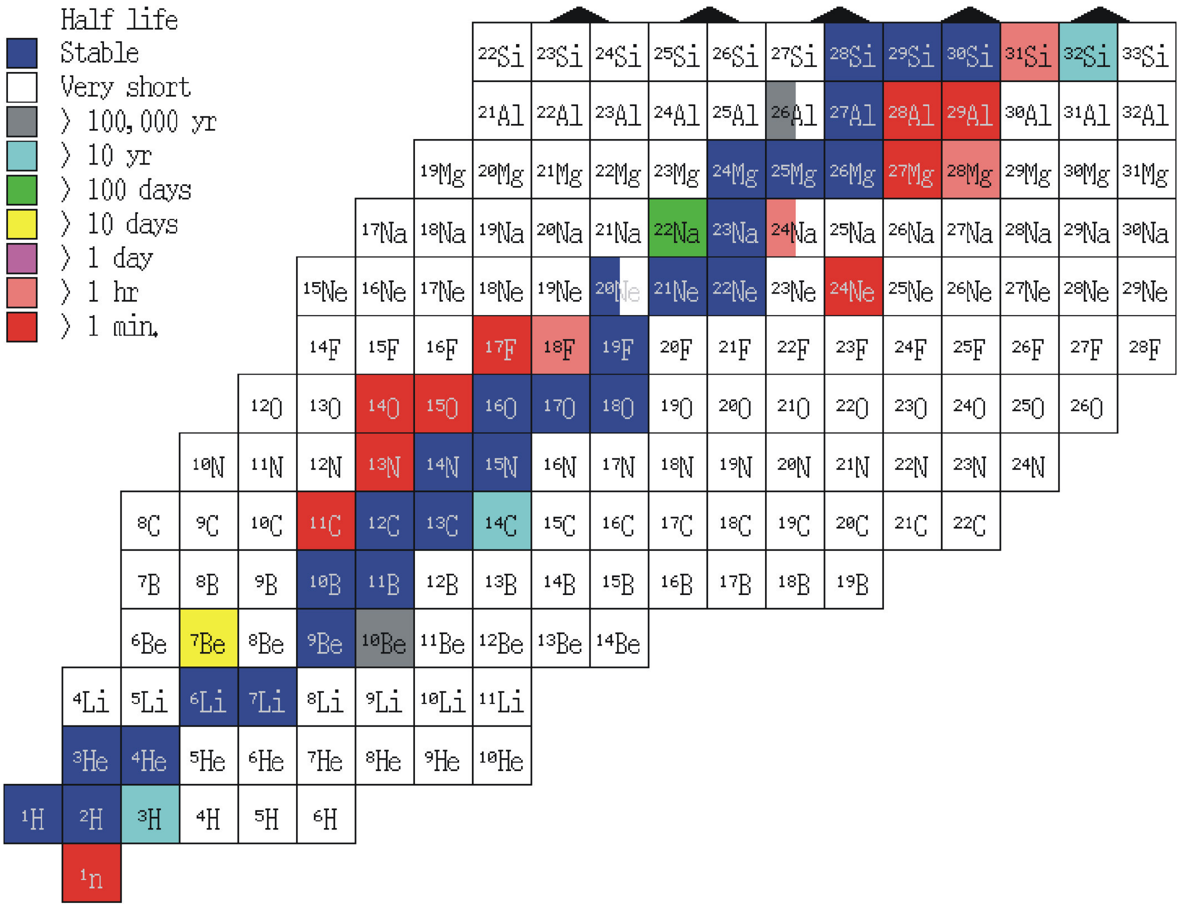
β-decay and the line of stability

There is a, N (neutron number) *vs*. Z (atomic number) backbone of stability.

More neutrons are required at higher Z to reduce the coulombic repulsion between protons. However, the binding energy per nucleon also reduces leading to instability. These effects largely determine the stability of particular isotopes of an element.



The line of stability is depicted on a Segré chart. Above the line nuclei have too few neutrons and either undergo electron capture or positron emission. Under the line nuclei are more likely to undergo beta decay.



Important long-lived radioactive nuclides

Nuclide	Decay mode	Stable products	Half-Life (years)
^{40}K	β, EC	^{40}Ca, ^{40}Ar	1.3×10^{9}
^{87}Rb	β^{-}	^{87}Sr	4.9×10^{19}
^{147}Sm	α	^{143}Nd	1.1×10^{11}
^{187}Re	β^{-}	^{187}Os	4×10^{10}
^{232}Th	α..(series)	^{208}Pb	1.4×10^{10}
^{235}U	α..(series)	^{207}Pb	7.0×10^{8}
^{238}U	α..(series)	^{206}Pb	4.5×10^{9}

These are present in significant abundance on earth.
Fuel geological processes (heat the earth) and can cause genetic mutations driving evolution.

Origin of the universe - The Big Bang

Timeline

t = 10^{-35} s

Universe began 13.7×10^9 years ago
A hot, dense plasma.
$T = 10^{32}$ K
No matter - just radiation, sea of photons and neutrinos.
Radiation described by Planck's blackbody equation ($u_{av} = 2.7$ kT)
Universe expands and cools

t = < 0.5 s

$T = 10^{32}$ K - 10^{13} K
Photons create (materialize) pairs of particles

Photon, Proton, Anti proton

$$2\gamma \rightleftharpoons p^+ + \bar{p}^-$$

$$2\gamma \rightleftharpoons n + \bar{n}$$

$$2\gamma \rightleftharpoons e^- + \bar{e}^+$$

Anti electron (positron)

Photons must have enough kinetic energy to form matter particles

$$E = 2.7kT > 2mc^2$$

t = > 0.5 – 1 s

$T = 10^{13} - 10^9$ K
Photons lack energy to form new protons
Threshold temperature for protons

$$2.7kT_p = 2m_pc^2 \implies T_p \sim 10^{13}\text{ K}$$

No new protons-antiproton pairs materialize
Protons and antiprotons then annihilate each other

$$p^+ + \bar{p}^- \rightleftharpoons 2\gamma$$

But a slight excess of matter over antimatter remains
At equilibrium $[p^+]/[\gamma]10^{-9}$ (true today)

t = 1 – 100 s

Protons and electrons interact to form neutrons and neutrinos

$$p^{+} + e^{-} \longrightarrow n + \nu_e$$

Half-life, $t_{1/2}$ (1/k), depends on temperature and density of Universe
After 1 s, T = 10^{10} K, $t_{1/2}$ > age of Universe therefore neutrons no longer materialize
Ratio frozen in

$$\frac{[n]}{[p^{+}]} \sim \frac{1}{5}$$

Free neutrons now decay, half-life 11 min

$$n \longrightarrow p^{+} + e^{-} + \nu_e$$

Before this can happen, as the temperature falls, neutrons react faster with protons to form stable deuterium

$$n + p^{+} \longrightarrow {}^{2}H^{+} + \gamma$$

All neutrons end up as deuterium, which is reactive

$$n + p^{+} \longrightarrow {}^{2}H + \gamma \quad \text{(slow)}$$
$${}^{2}H + {}^{1}H \longrightarrow {}^{3}He + \gamma \quad \text{(fast)}$$
$${}^{2}H + n \longrightarrow {}^{3}H + \gamma \quad \text{(fast)}$$
$${}^{2}H + {}^{2}H \longrightarrow {}^{4}He + \gamma \quad \text{(fast)}$$
$${}^{3}He + n \longrightarrow {}^{4}He + \gamma \quad \text{(fast)}$$
$${}^{3}H + {}^{1}H \longrightarrow {}^{4}He + \gamma \quad \text{(fast)}$$
$$2\,{}^{1}H + 2\,n \longrightarrow {}^{4}He + \gamma \quad \text{(net reaction)}$$

$${}^{3}He + {}^{4}He \longrightarrow {}^{7}Be + e^{-} \longrightarrow {}^{7}Li + \gamma \quad \text{(minor reaction)}$$

Process blocked - no stable nucleus of mass 5 or 8

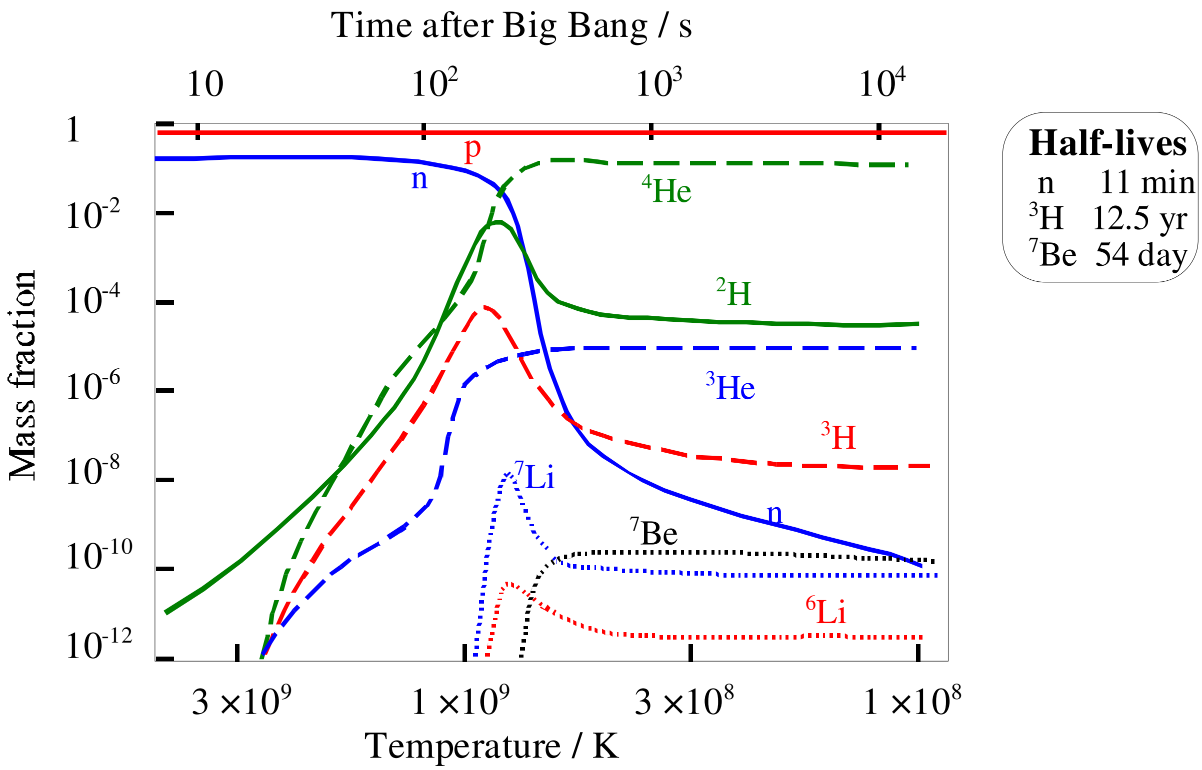
^{2}H synthesis slow because of low binding energy (2.2 MeV)
After 3 min, nothing happens for 10^{6} years!
100s after big bang [H]:[He] ~ 8:1

Evidence

There are three principal pieces of evidence in support of big bang theory.

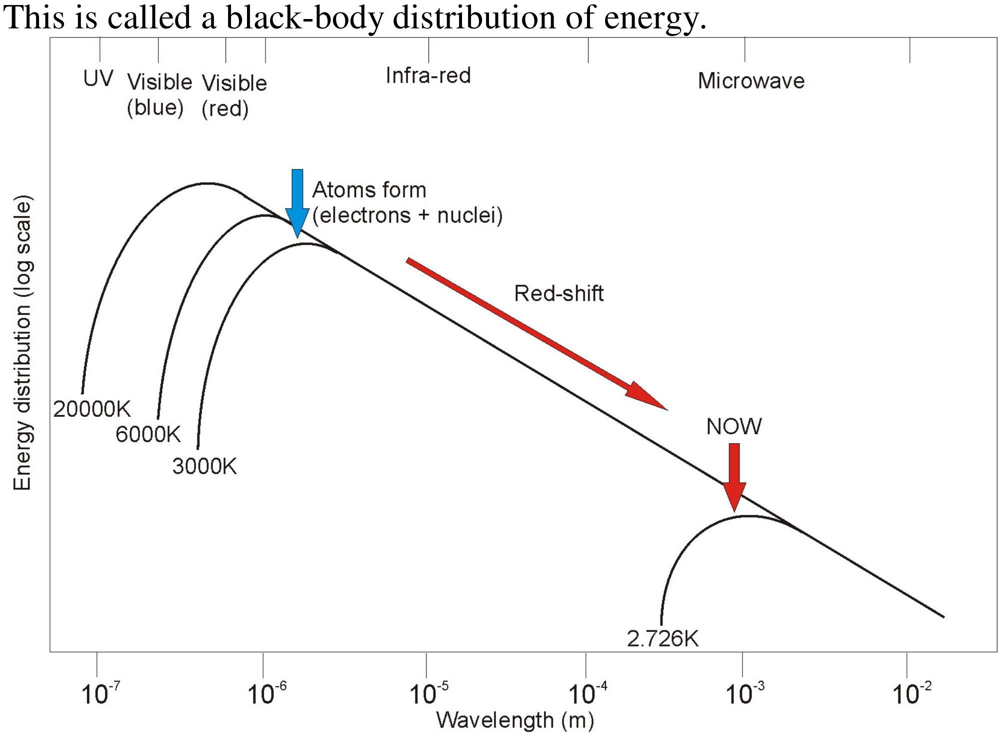
1. Abundance of lighter elements

Big bang theory correctly predicts the relative concentration of the lighter elements particularly [H]:[He]. ~ 8:1

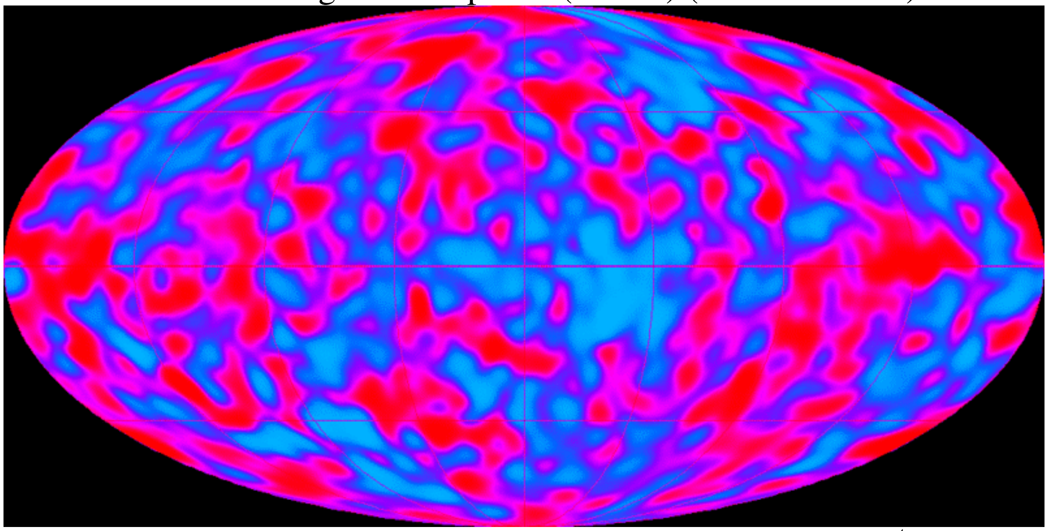


2. Cosmic Microwave Background (CMB)

Big bang theory predicts that between 100s and 4 x 10^5 yr radiation (γ) and matter in equilibrium, i.e. thoroughly mixed and almost smoothly distributed in a plasma. This is called a black-body distribution of energy.

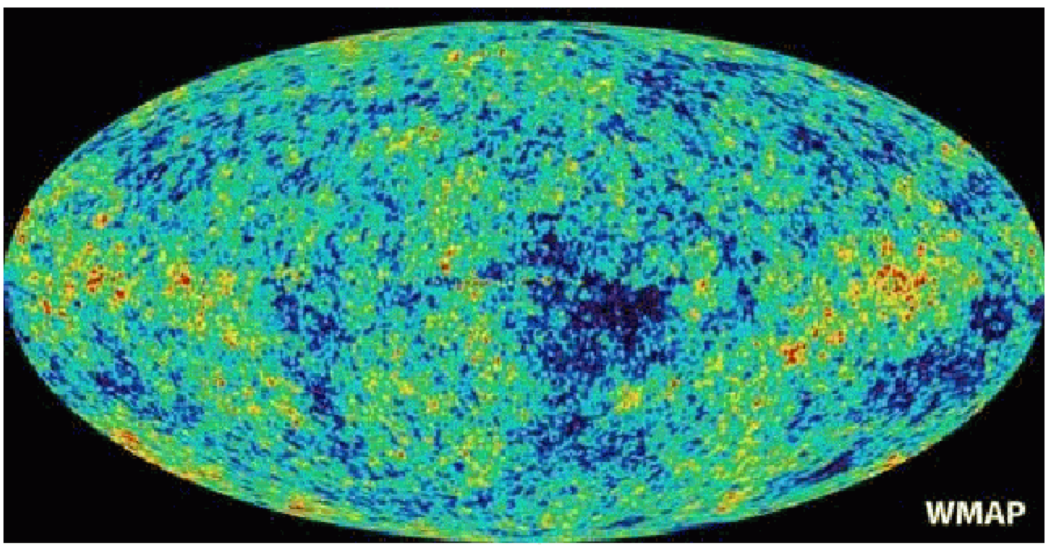


Cosmic Background Explorer (COBE) (launched 1989)



The variation in the strength of the 2.7 K radiation over the Sky (1st 'rough direct measurement), shown in the coordinate system of the Milky Way.

Wilkinsons Microwave Anisotropy Probe (WMAP) (launched 2001) for more refined measurement



There are only μK fluctuations but these lead to large-scale structure today
These are the oldest photons we can ever observe

3. The Universe is Expanding

Spectroscopic measurement of emission or absorption lines of elements in other galaxies show a red-shift which can be explained by expansion of the universe. The red-shifts show that the speed of recession of a galaxy is proportional to its distance. Hubble's law.

$$v = H_0 d$$

v = velocity, H_0 = Hubble's constant (71km s^{-1} Mpc^{-1}), d = distance
(Mpc = mega parsec)

t = 100 s – 4 x 10^5 years

nucleons: $^1H^+$, $^4He^{2+}$, $^2H^+$, $^3H^+$, $^7Be^{2+}$, $^7Li^+$, n, and leptons: e^-, ν (neutrinos)
radiation: interact with free e-: plasma – universe opaque
radiation and matter in equilibrium, i.e. thoroughly mixed and almost smoothly distributed
wait 4 x 10^5 years as universe expands and cools

$$^1H^+ + e^- \rightleftharpoons {}^1H$$

$$x \Rightarrow 0 \text{ at } T = 3\times10^3 \text{ K}$$

Fraction ionized, x

$$\frac{x^2}{1-x} = \frac{(2\pi m_e kT)^{3/2}}{nh^3} e^{-I/kT}$$

T < 3×10^3 K, all electrons bound in atoms
Bound electrons scatter weakly
Matter decoupled from radiation (background CMB 'echo of big bang')
Matter and radiation no longer in equilibrium-universe transparent

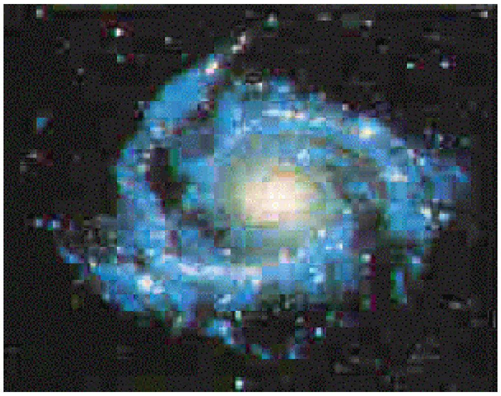
t > 4 x 10^5 years

Hydrogen and helium atoms evenly spread over the universe
too cold for nuclear reactions
no chemistry
gravity begins to be felt
Shapes universe
Releases energy

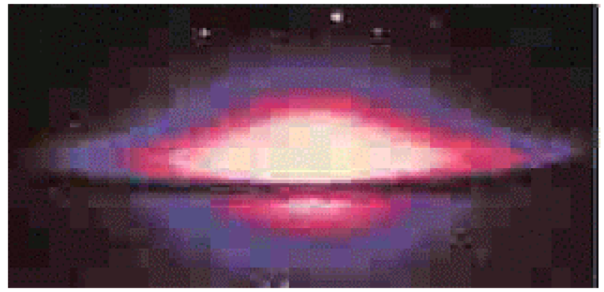
Space continues to expand - not uniformly
Matter (mainly 1H and 4He atoms) clumps leading to the formation of:
Galaxies - elliptical, spiral (Milky Way)

And **STARS**

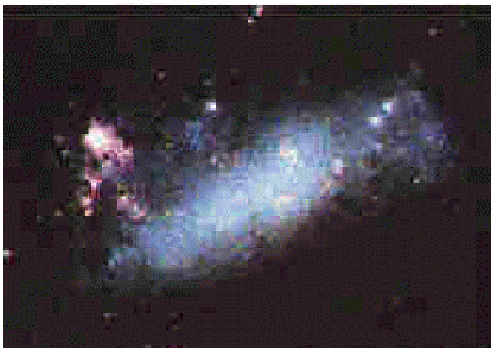
Stars are where nearly all the nucleons other than ^1H, ^4He, ^2H, ^3H, ^7Be, ^7Li, n, are created



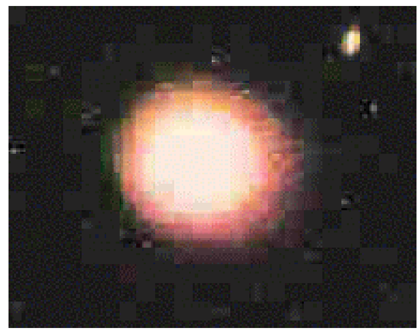
Spiral Galaxy (e.g. Milky Way)



Edge-on Spiral Galaxy



Irregular Galaxy (e.g. Magellanic Cloud)



Elliptical Galaxy

Star formation

Nebula M16

Molecular clouds located in spiral arms of galaxies. Dense regions collapse under gravity to form protostars

Gravitational energy converted to kinetic energy

Temperature rises to T ~10^7 K nuclei begin to fuse to form heavier elements

Star begins to shine

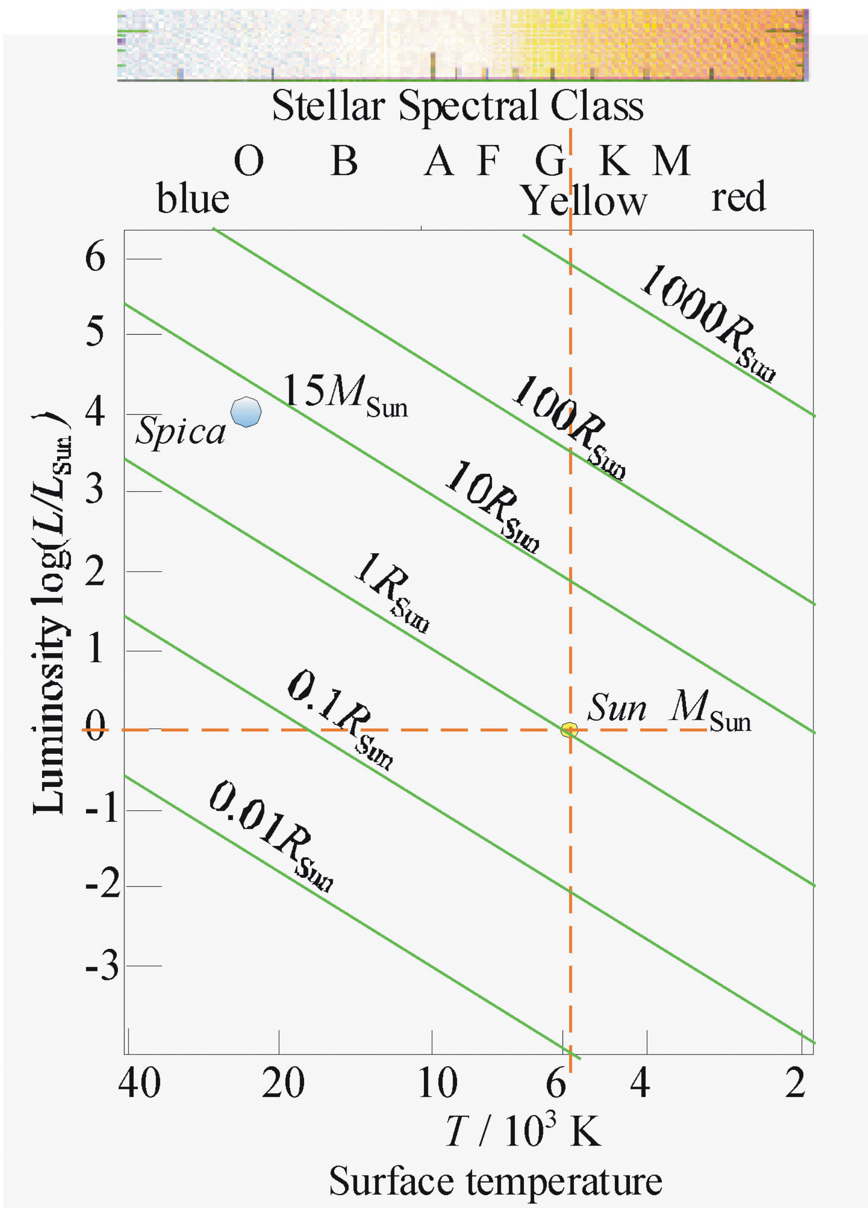
What are stars?

Luminosity, L = (brightness × distance^2) ∝ mass

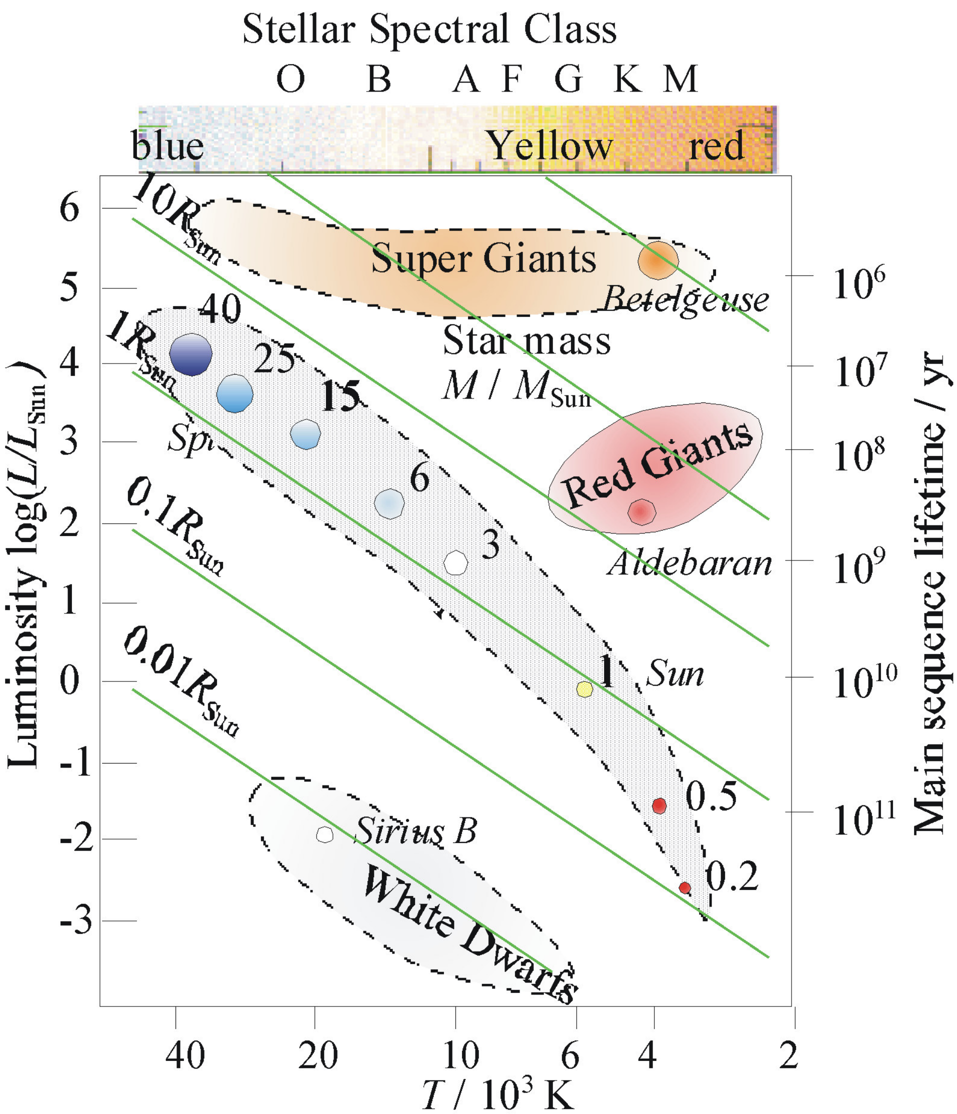
Spectral type colour gives surface temperature T

$L \propto R^2T^4$ (R = Radius of star) (Stefan's Law)

Cool stars with a high luminosity must be very large and hot dim stars must be small



Astronomers Periodic Table: Hertzsprung-Russell Diagram



Hertzsprung-Russell Diagram

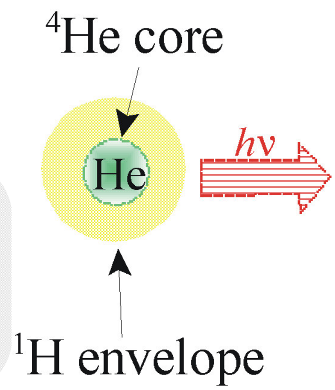
Many stars lie on the "Main Sequence" (MS)
Lifetime of star depends inversely on mass
The Sun: lifetime = 10^{10} y; age = 4.5×10^{9} y
Other types of star: White dwarfs, Red giants, Supergiants

Nucleosynthesis

Stars are hot enough for nuclear reactions to start up for the second time.
The first time the right conditions lasted for only 3 mins.
This time the right conditions last for millions even billions of years!
Slow reactions now important. $T=10^7$ K but no neutrons.

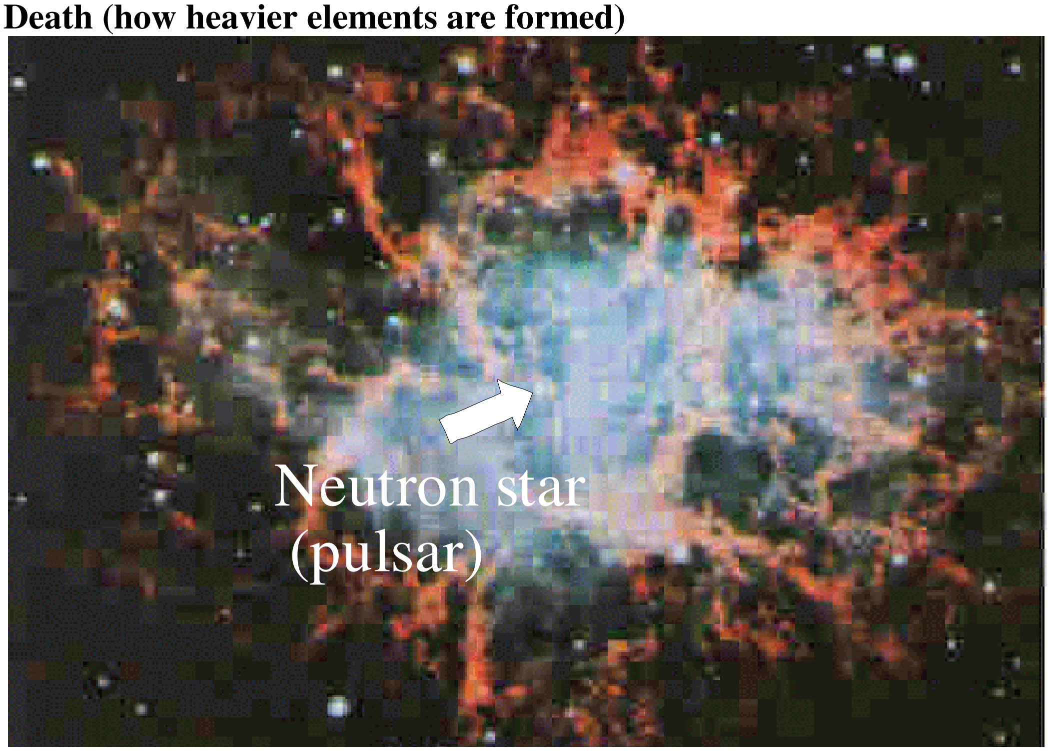
Main Sequence stars (H-Burning, PPI Chain)

$$^{1}H + ^{1}H \Rightarrow ^{2}H + e^{+} + \nu \qquad \text{slow } t_{1/2} \approx 10^{10} \text{ y}$$
$$^{2}H + ^{1}H \Rightarrow ^{3}He + \gamma \qquad \text{fast } t_{1/2} = 0.6 \text{ s}$$
$$^{3}He + ^{3}He \Rightarrow ^{4}He + 2\,^{1}H \qquad \text{fast } t_{1/2} = 10^{6} \text{ y}$$
$$\text{Overall} \quad 4\,^{1}H \Rightarrow ^{4}He + 2\,e^{+} + 2\nu + 2.58 \text{ GJ mol}^{-1}$$



Core of ^{4}He forms
Energy generated balanced by escape of radiation
Star supported against gravity by thermal pressure of hot gas - $T \propto M / R$
Main sequence stars are not contracting or expanding much (in hydrostatic balance)
Rate of fuel burning (lifetime) depends on L and M

Star Death (how heavier elements are formed)



Crab Nebula (remnant of supernova). Observed in China 1054 AD

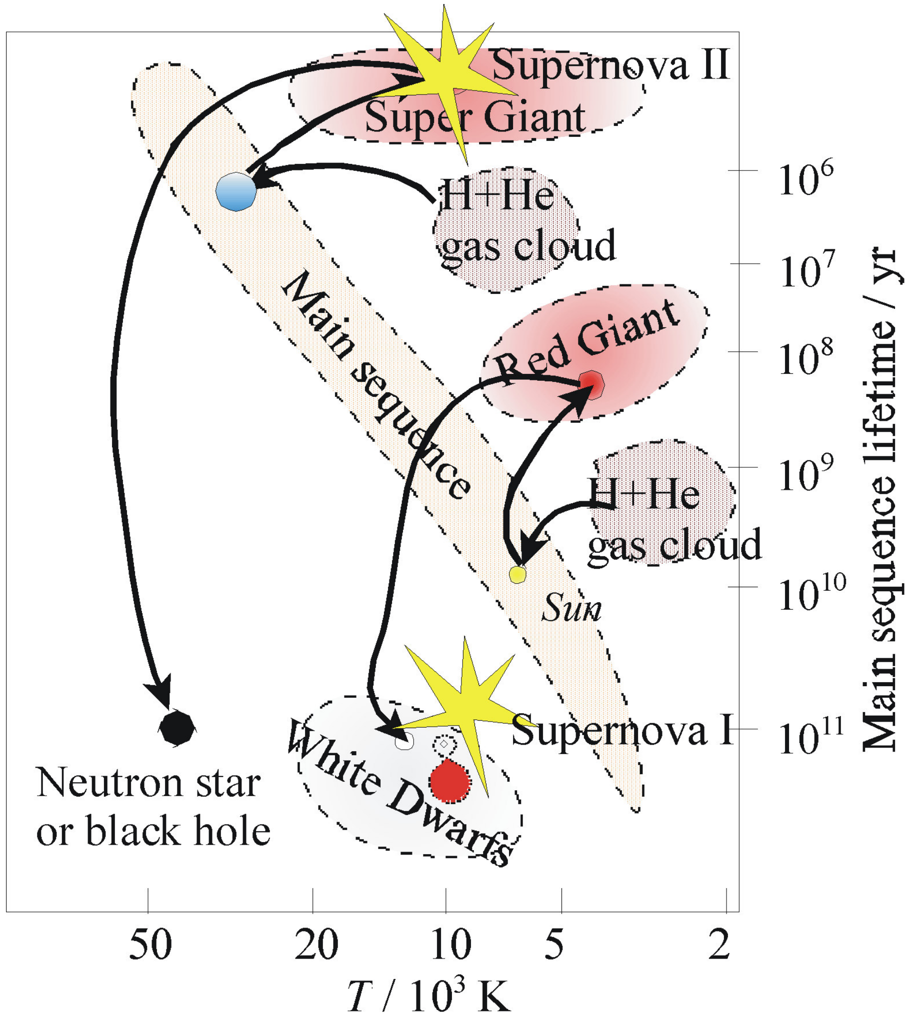
1. Low-mass stars

Red giant carbon star - ejects C (source of most ^{12}C in universe)
Corpse: white dwarf – of $^{12}C + ^{16}O$
Very dense, degenerate electron pressure prevents further collapse, 'Diamond'
or If there is a nearby star (binary) with red giant can give mass transfer leading to thermonuclear runaway and Type I supernova

2. High-mass stars

Super giant C, Ne, O, Si burning
^{56}Fe core collapse
Corpse: neutron star or black hole
Type II supernova

Star Birth and Death



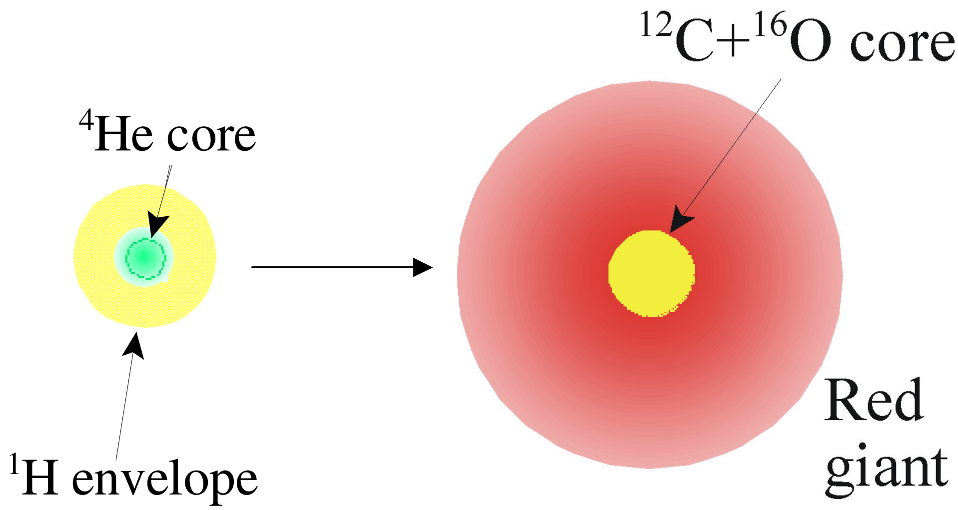
Hertzsprung-Russell Diagram

Red Giant Stars- (He-burning) (main source of ^{12}C and ^{16}O)
When ^{1}H fuel becomes exhausted in the core the thermal pressure can't support the gravity and core contracts, raising T to 10^{8} K, helium starts to burn.

$$^{4}He + {}^{4}He \Rightarrow {}^{8}Be + \gamma$$
$$^{4}He + {}^{8}Be \Rightarrow {}^{12}C + \gamma$$
$$^{4}He + {}^{12}C \Rightarrow {}^{16}O + \gamma$$

^{8}Be
$t_{1/2} \approx 10^{-18}$ s

Energy released blows out the envelope to form Red Giant (releasing mainly ^{12}C)
After ca. 10^{7} years He exhausted and the star evolves into a white dwarf



Super Giant Stars
Core of ^{12}C and ^{16}O contracts, T > 3×10^{9} K.

Fusion forms heavier nuclides, envelope swells

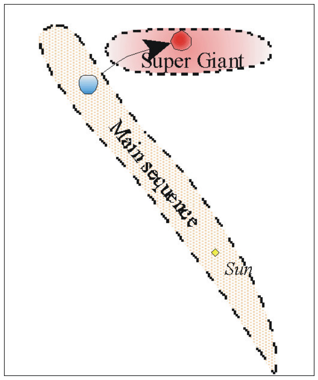
$$^{12}C + {}^{12}C \Rightarrow {}^{20}Ne + {}^{4}He \quad ({}^{23}Na + {}^{1}H,\ {}^{24}Mg + n....)$$
$$^{16}O + {}^{16}O \Rightarrow {}^{28}Si + {}^{4}He \quad ({}^{31}P + n,\ {}^{32}S + \gamma\ ...)$$

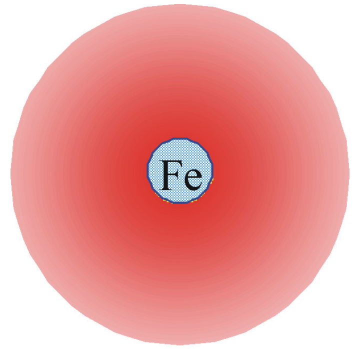
^{4}He capture

$$^{28}Si \Rightarrow 7\ {}^{4}He$$
$$^{28}Si + {}^{4}He \Rightarrow {}^{32}S \Rightarrow ...\ {}^{56}Ni$$
$$^{56}Ni \Rightarrow {}^{56}Co + \beta^{+} + \gamma \Rightarrow {}^{56}Fe + \beta^{+} + \gamma$$

Neutron capture - slow process (**s-process**), absorbs energy

$$^{56}Fe \Rightarrow {}^{57}Fe \Rightarrow ...{}^{60}Co,\ {}^{60}Ni,\ ...\ {}^{99}Tc...{}^{108}Ag...{}^{197}Au...{}^{209}Bi$$





Super giant

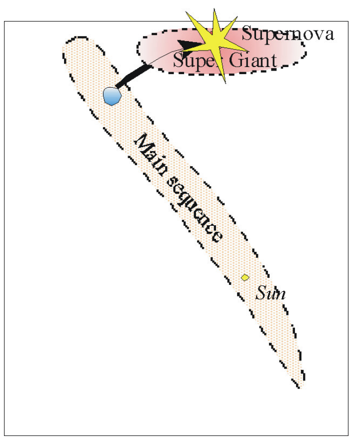
Explosive nucleosynthesis

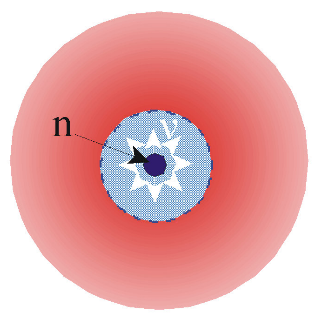
When the iron core develops, all the fuel is exhausted. Thermal energy cannot support the weight. Catastrophic gravitational collapse occurs in seconds. Core disintegrates $T \sim 10^{10}$ K.

$$^{56}Fe \Rightarrow p + n$$
$$p + e^{-} \Rightarrow n + \nu$$

Neutrinos carry off 10^{46} J (= lifetime output of Sun)

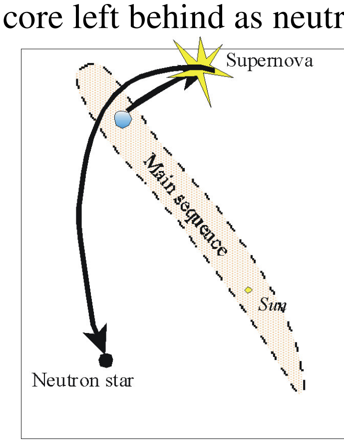
Outer part of core bounces off hard central part and shock wave leads to explosion of the star.

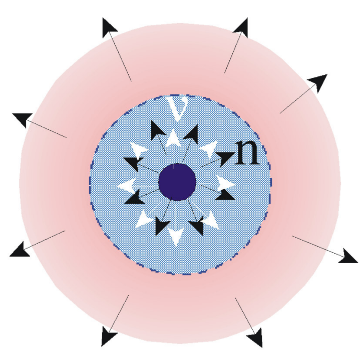




Supernova

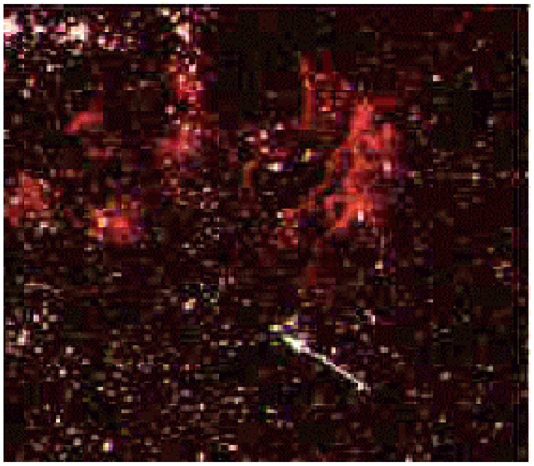
During explosion neutron capture causes rapid nucleosynthesis (**r-process**). Forms all heavier elements up to ^{232}Th, ^{238}U and superheavies. Explosion spews out matter into space and core left behind as neutron star or black hole.

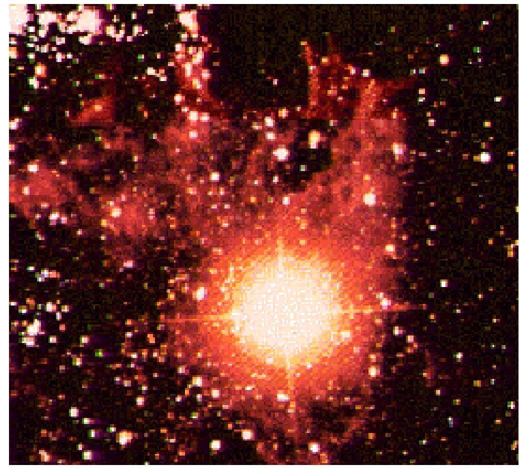




Supernova

SN 1987A: February 24 1987





Before **After**

In Large Magellanic Cloud, SN 1987A exploded 170,000 y ago.
10^{46} J carried away by neutrinos, 20 (!) detected on earth.

Young and Old Stars

Old main sequence stars form from debris of Big Bang - contain ^{1}H and ^{4}He only.

PPI cycle catalyzed by ^{2}H

$$4\,^{1}H \Rightarrow {}^{4}He + 2\,e^{+} + 2\nu$$

Young main sequence stars form from debris of supernovae - metal rich

H burning catalyzed by ^{12}C - the CNO cycle

$$^{12}C + {}^{1}H \Rightarrow {}^{13}N \Rightarrow {}^{13}C \Rightarrow {}^{14}N \Rightarrow {}^{15}O \Rightarrow {}^{15}N \Rightarrow {}^{19}F$$

$$^{15}N + {}^{1}H \Rightarrow {}^{12}C + {}^{4}He \quad \text{etc}$$

The sun is a young. Young stars are important source of ^{13}C, ^{14}N, ^{15}N, ^{17}O

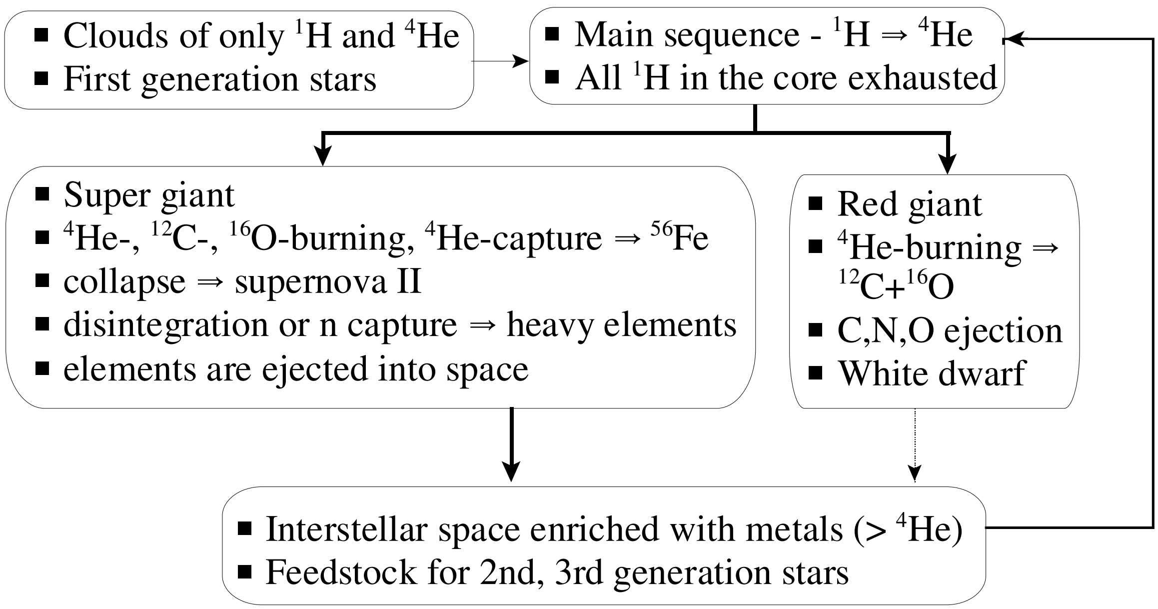
Nucleosynthesis in Interstellar Medium

A few nucleons (elements) are not formed in stars (or Big Bang)
^{6}Li, ^{9}Be, ^{10}B, and ^{11}B are not formed by any of the process described so far and are easily destroyed in stellar interiors. Formed as fragments by collisions (spallation) of very energetic galactic cosmic rays, including neutrinos, ^{1}H, ^{4}He, ^{12}C and ^{16}O, with interstellar gas. Cosmic rays are accelerated by shock waves driven by the rapidly moving ejecta of supernovae in the Galaxy. Can be thought of as naturally occurring fission.
^{15}N, ^{17}O, ^{18}O, ^{19}F and ^{21}Ne are also spallation products. (Important NMR nuclei)

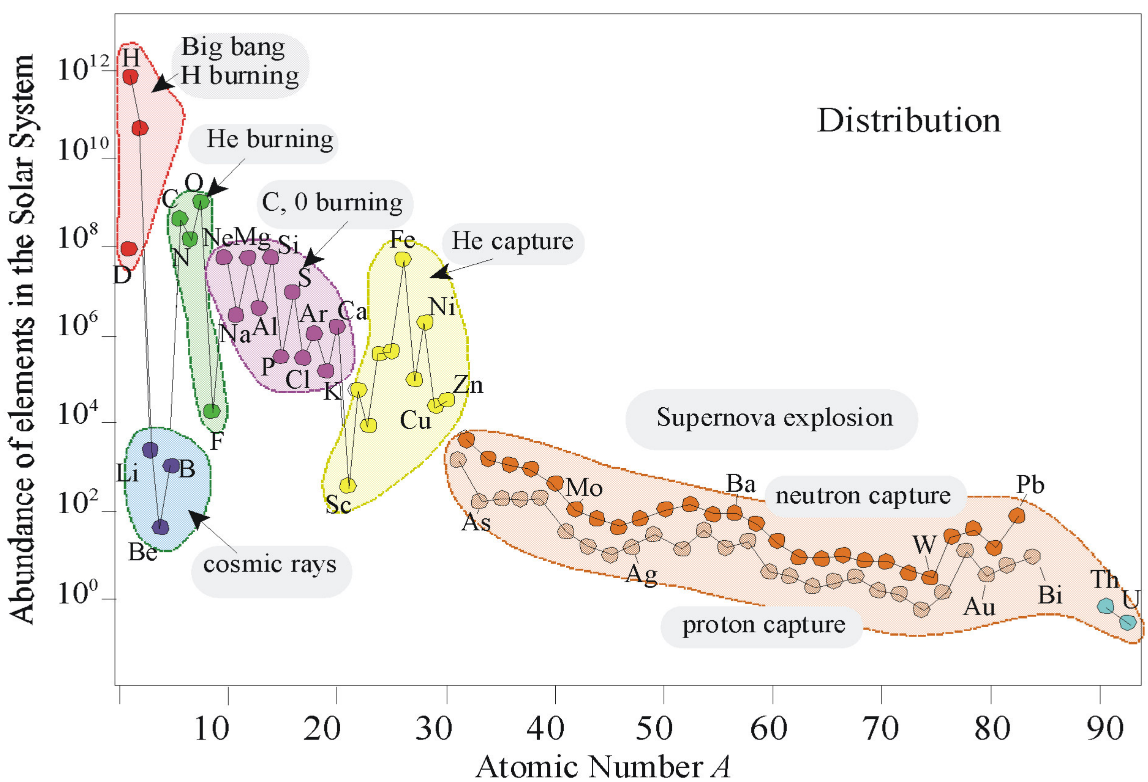
Summary of Nucleosynthesis

Big bang occurred 13-14×10^9 y ago resulted in a Universe of radiation and elementary particles. Light elements created 3 min after Big Bang.

First stars appear 200 million years later. Heavier elements formed >10^9 y after big bang in stars made during birth and death of generations of stars then scattered across space by supernova explosions.



Solar system formed 4.6×10^9 y ago and the composition is typical of Universe. (meteorites and spectroscopic evidence).



Composition of the Universe

Radiation: massless (or nearly massless) particles moving at speed of light, photons, neutrinos...

Ordinary (baryonic) matter: protons, neutrons, electrons, (that form the elements). 4% by mass.

Dark matter: exotic non-baryonic matter, interacts weakly with ordinary matter. 25% by mass. (still a puzzle)

Dark energy: causes expansion of universe to accelerate. 73% by mass (an even bigger puzzle)

How did our solar system form?

The Solar System

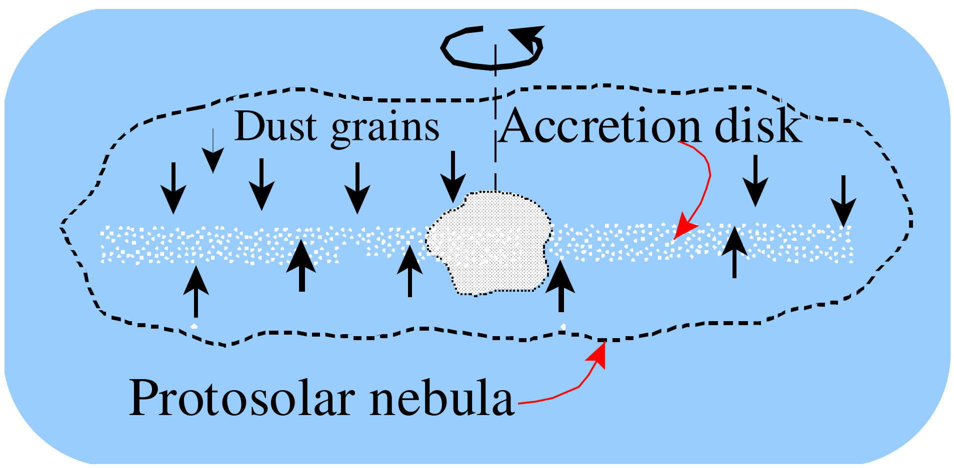
Solar system is isolated - distance to nearest stars exceeding $5{\times}10^4$ times its diameter
Solar system formed only 4.6×10^9 y ago - it didn't exist for most of the history of the universe (13.7×10^9 y)
It is now agreed that sun and planets have a common origin

Solar system origin

Nebular theories (Descartes 1644, Swedenborg 1734, Laplace 1796, current model)
Planets form either concurrently of consecutively from the same nebula as the sun.

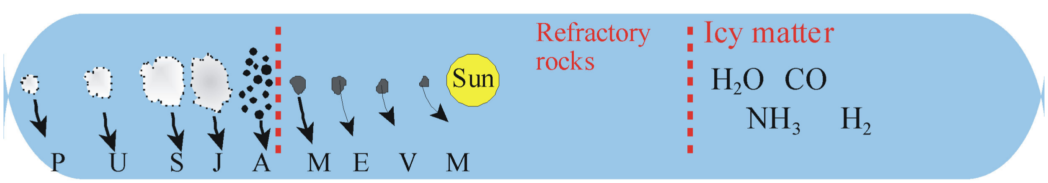
Condensation Hypothesis

4.6×10^9 y ago, small fragment of a dusty molecular cloud, not spinning rapidly, detached from arm of spiral galaxy (Milky Way) triggered by nearby supernova.
Cloud condenses towards centre under gravity.
Dust settles by gravity to midplane of rotating disk
Angular momentum transferred outwards (like water down a plug hole)



Formation of Planets

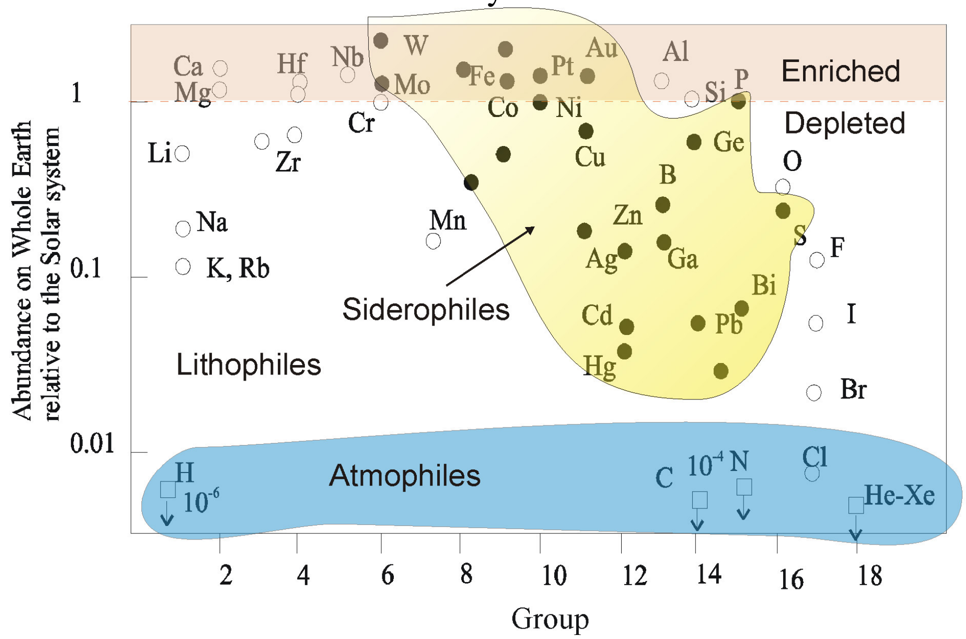
Centre of nebula heated by gravitational contraction at 10^7 K nuclear reactions (H burning) starts and surface temperature increases to 4000 K, i.e. Sun is visible as a star



Turbulent gas eddies cause dust to aggregate into planetesimals <1 km diameter Gases not incorporated into boulders, cleared from inner parts of disk by heat (~ 600 K) and solar wind. Surviving rocky planetesimals slowly assemble into four inner terrestrial planets

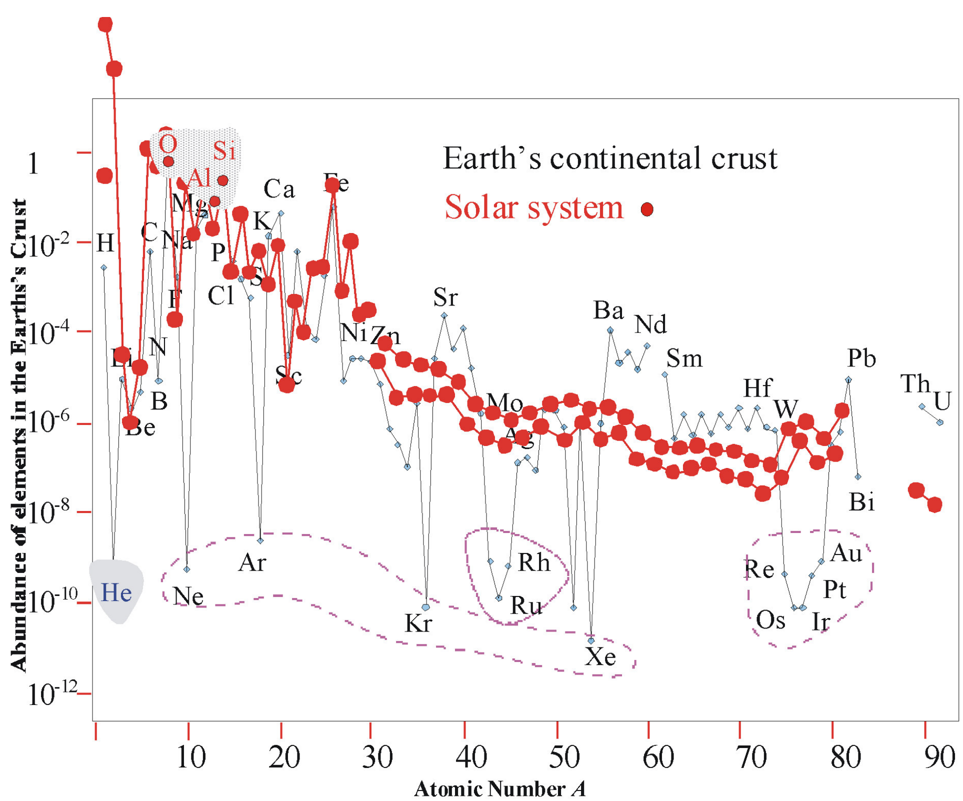
Composition and structure of the Earth
How did the earth form?
Why so highly differentiated? (elements not homogeneously distributed)
Is complex life rare?

Composition of the Earth relative to Solar System

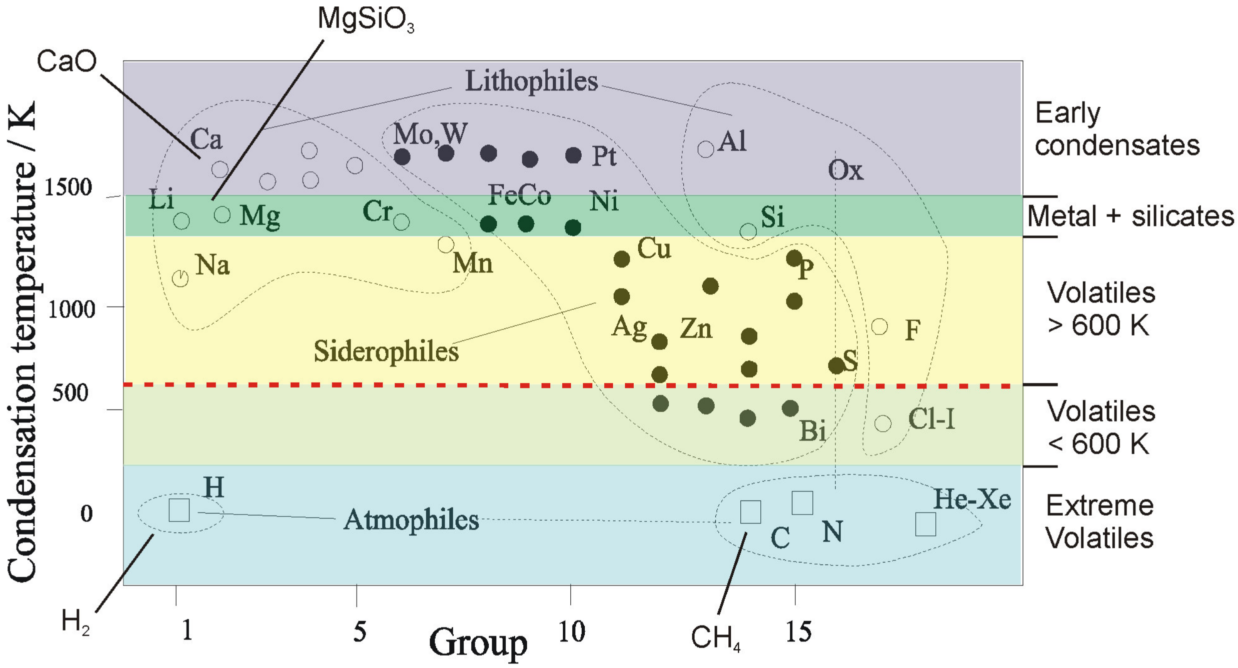


Composition of the Earth's Crust vs Solar System

Some abundances in crust are different from Solar System O, Al and Si are still the most abundant. Odd-even alternation signature still present.



Formation of Earth



Earth formed at about 600 K on average

Elements condense at different temperatures due to enthalpies of vapourisation and chemistry

Lithophiles (rock-loving) found predominantly as oxides in crust.

Siderophiles (iron loving) found predominantly as metals in core.

Atmophiles are volatiles found in atmosphere or oceans.

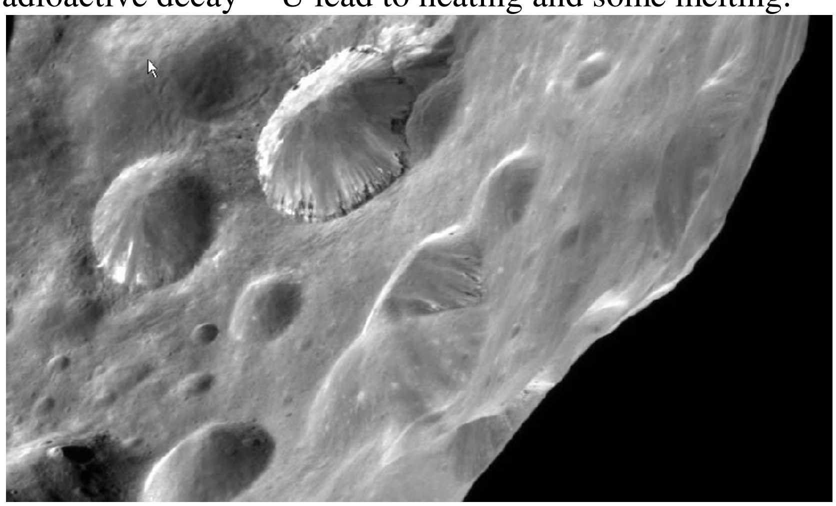
There is strong correlation between the chemical form in which elements are found on earth today and the way in which they are predicted to condense.

Chemical Evolution of the Earth

Early history

Accretion (coagulation of dust) 4.6 x 10^9 years ago

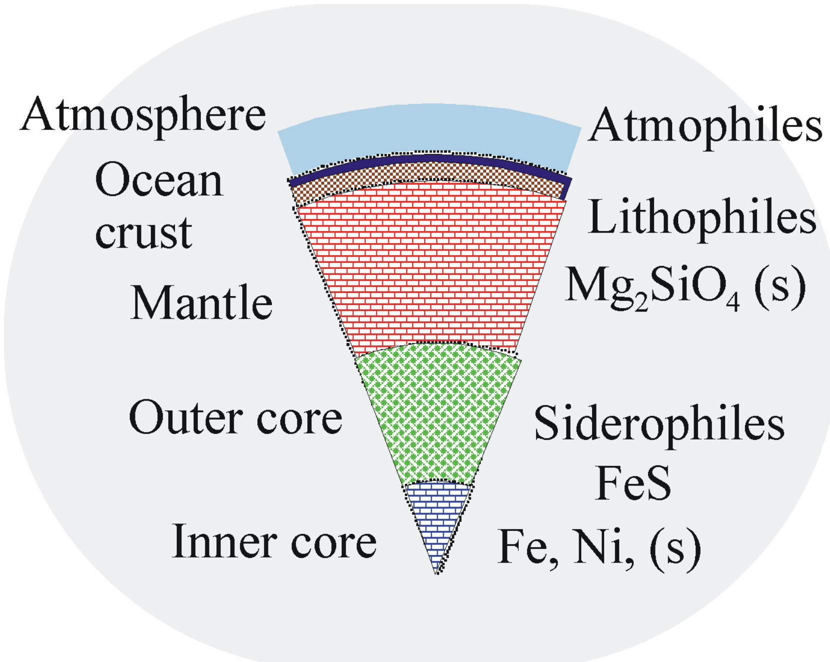
Impacts and radioactive decay ^{238}U lead to heating and some melting.



One of Saturn's 30+ moons, Phoebe, pitted by impacts

Fe and Ni form core and a crust forms on an ocean of magma. Giant impact era ends 3.9 x 10^9 y ago and supercontinent forms (2.7 x 10^9 y ago) and plate tectonics become operational.

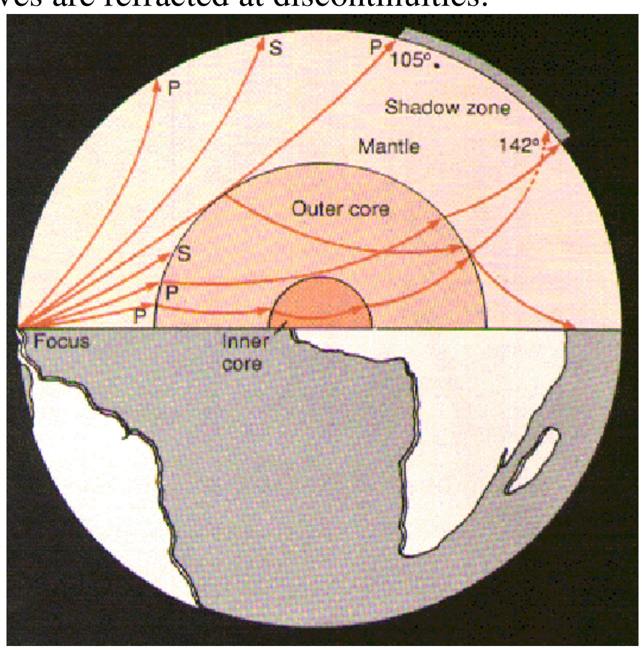
Present compositional layers



Crust: continental (30-70 km thick), oceanic (8 km thick)
Mantle (70-5000 km),
Core (5000 - 6370 km) Outer liquid, Inner solid

Internal Structure of the Earth

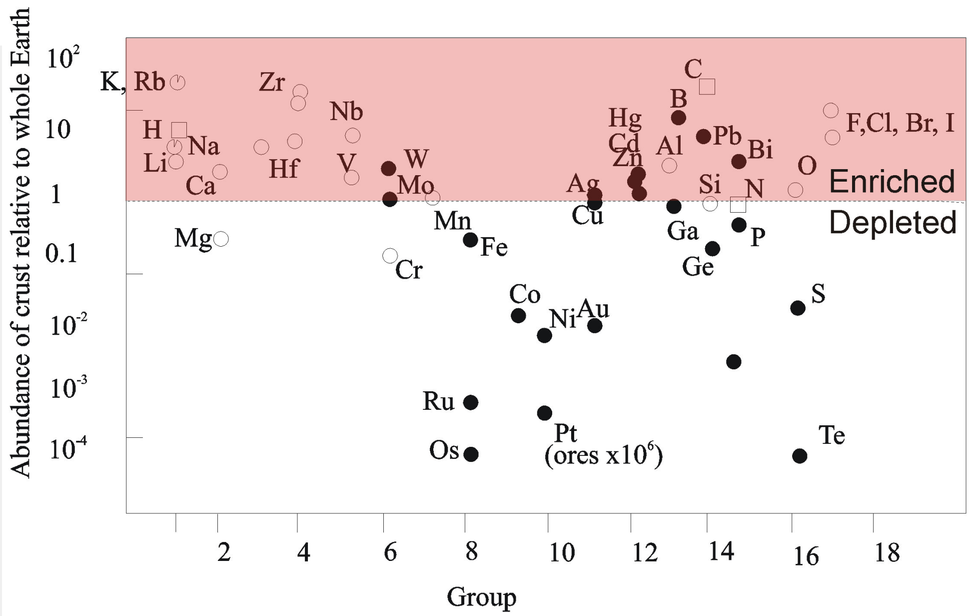
Determined using seismology. Wait for an earthquake and detect shockwaves around the world. Shockwaves are refracted at discontinuities.



Crustal Abundance Relative to Whole Earth

Continental crust

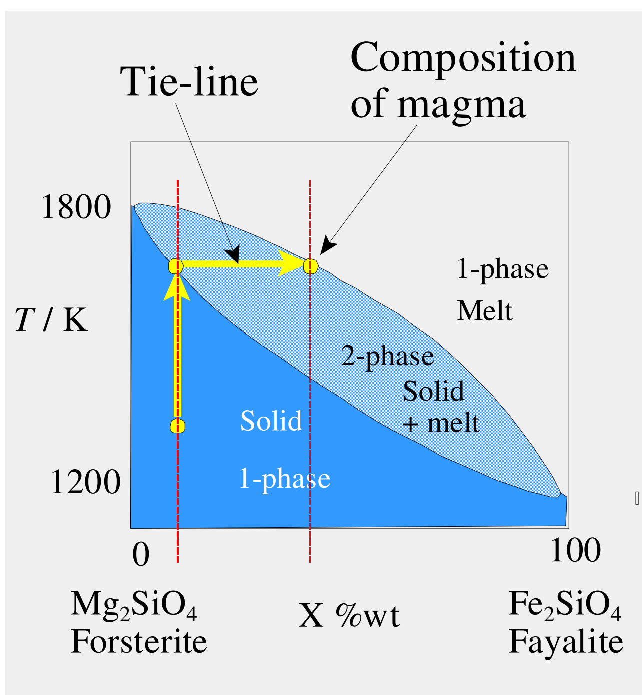
Element	%wt
O	50
Si	26
Al	8
Fe	5
Ca	4
Na	3
K	2
Mg	2
H	1



Crust & mantle - different composition

Possible mechanism

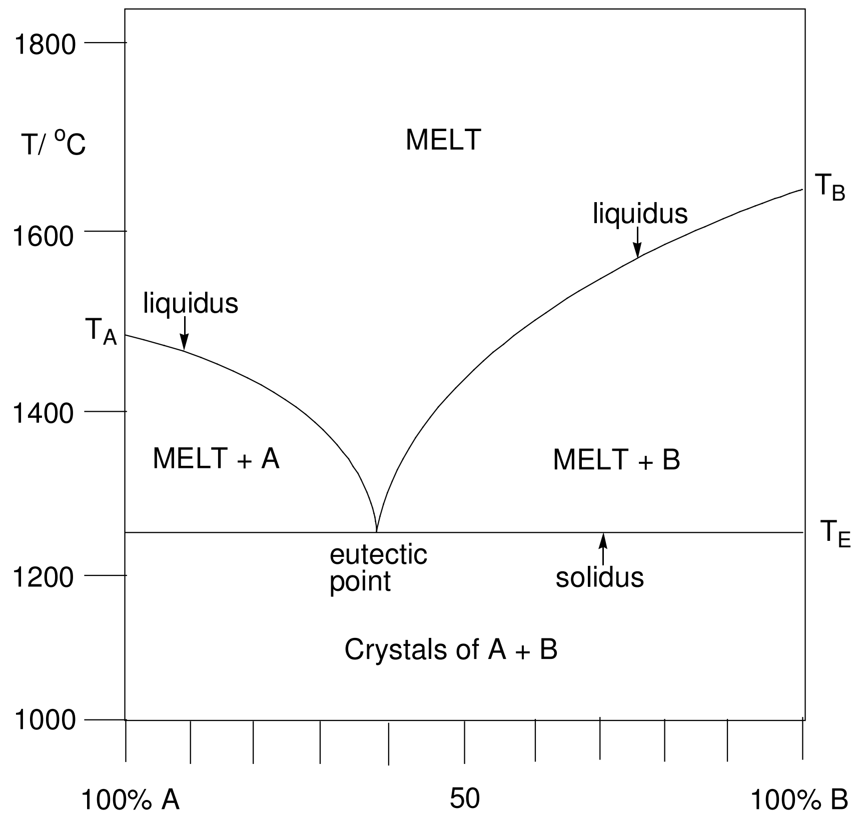
Mantle (solid) partially melts to form magma (liquid melt)
Magma rises and solidifies to form crust, eg in volcanic lava
Mantle enriched in Mg, crust enriched in Fe
Applies to other elements, as we will see in mineral formation. Original distribution of elements in earth has now changed significantly due to these differentiation processes.



Phase diagrams

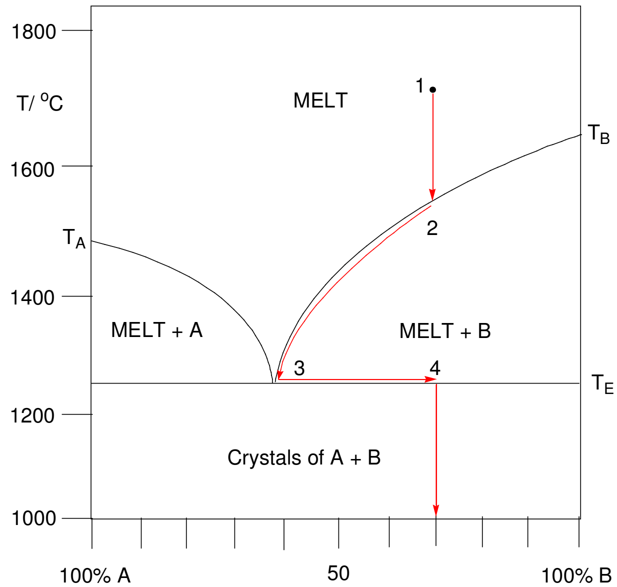
Phase diagrams depict the relationship between composition and usually temperature or pressure at thermodynamic equilibrium. They can be used to predict reactivity and behaviour of a single phase or mixture of phases. We will look at some simple interpretation. It can be useful to think of phase diagrams as chemical maps.

Case 1: Consider the following phase diagram containing two components A and B that as solids are not miscible (do not mix on the atomic scale).



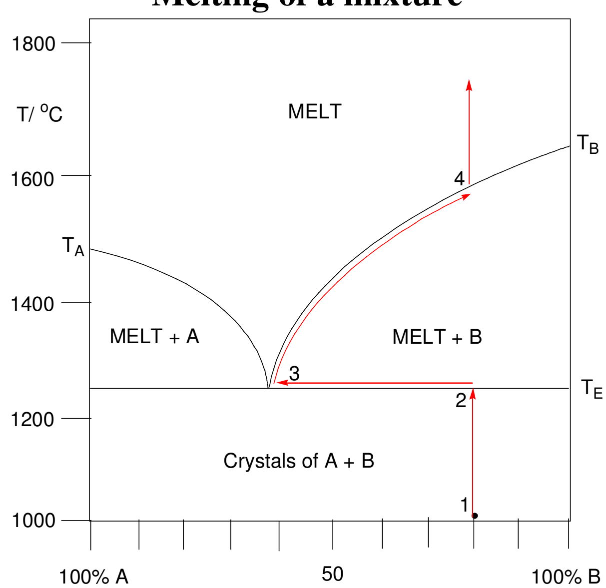
Liquidus- boundary between liquid and mixture of liquid + solid phases.
Solidus- boundary between all solid and liquid +solid phases.
Eutectic-the lowest temperature at which a composition can be liquid.
$T_{A(B)}$- melting point of pure A(B); T_E-melting point of eutectic mixture.
Below the solidus all compositions are solid and contain a mixture of crystals A and B.
Between liquidus and solidus compositions contain a mixture of melt and solid.
Above the liquidus all compositions are molten (a liquid).
At the eutectic point all three phases (solid A, solid B, and melt) exist simultaneously.

Equilibrium crystallisation from a eutectic melt



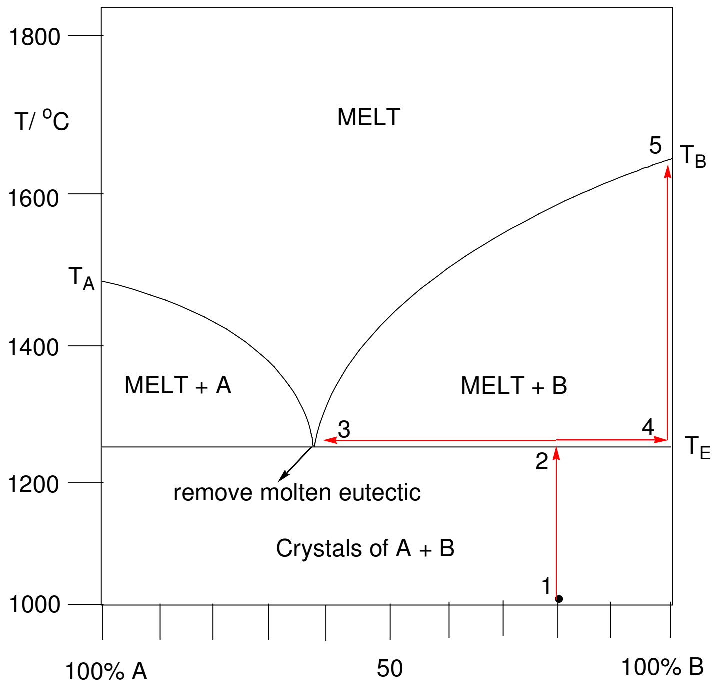
Consider an A:B 30:70 mixture at 1700 °C. It is a melt (point 1).
On cooling the melt begins to crystallise at the liquidus at ca. 1550 °C (point 2). Only pure B crystallises as A and B are immiscible and the composition is on the B rich side of the eutectic. As we continue to cool more B crystallises making the melt more rich in A until the melt reaches the eutectic mixture 60:40 (point 3). At the eutectic point A can begin to crystallise and crystals of A and B crystallise a 60:40 ratio (but the overall composition of all A and B remains at 30:70 (point4).

Melting of a mixture



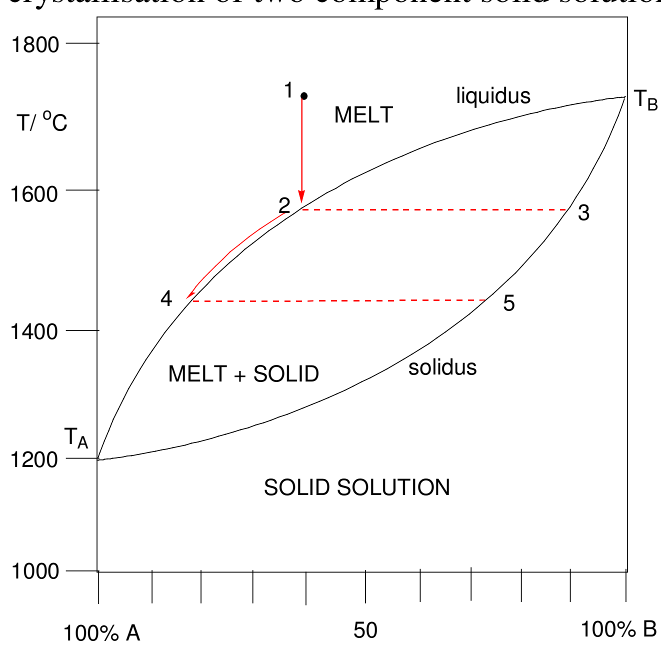
Consider an A:B 20:80 mixture at 1000 °C. It is a mixture of A and B crystals (point 1). On heating the mixture to the solidus at ca. 1250 °C (point 2) the mixture begins to melt. The composition of the melt is the eutectic 60:40 (point 3). The sample continues melting with a 60:40 ratio until all A is consumed giving a eutectic melt of 60:40 A:B and pure solid B. Continued heating causes some B to melt as we move along the liquidus from point 3 to 4 until all B is melted and we have a melt of composition 20:80.

Fractional melting/Crystallisation (non equilibrium process)



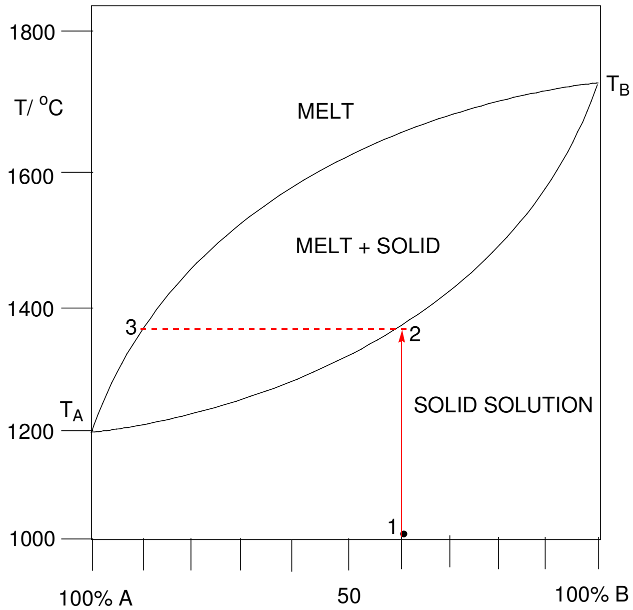
Imagine we removed the eutectic (point 3) during melting. Crystals of pure B would be separated from the eutectic (point 4). To melt everything, it is necessary to heat to the melting point of pure B (point 5). Non-equilibrium processes drive evolution of element distribution in the mantle and crust.

Case 2: Equilibrium crystallisation of two component solid solution.



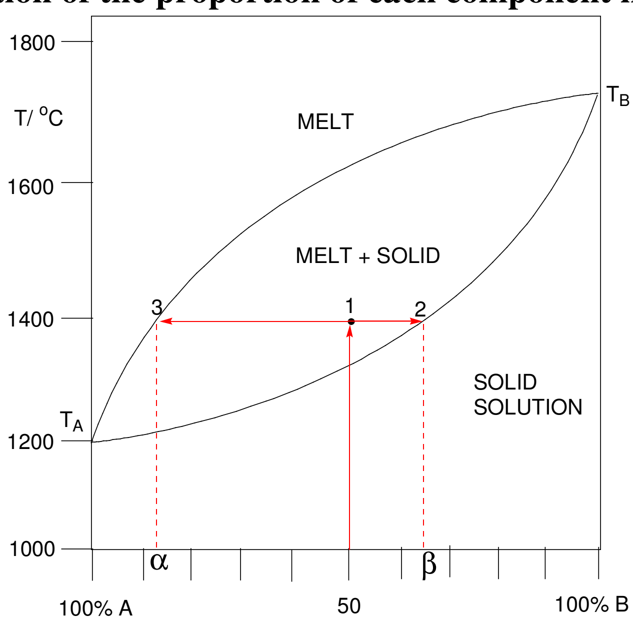
Consider a 60:40 mixture of A and B at 1700 °C. It is a melt (point 1).
On cooling the melt reaches the liquidus (point 2) and solid begins to crystallise. The composition of the solid is given by drawing a horizontal line to the solidus (point 3). In this case the melt is 60:40 A:B and the solid 10:90. The solid is an atomic mixture (solid solution) of A and B (A and B are miscible).
Further cooling establishes a different equilibrium e.g. point 4 and 5.

Fractional melting/crystallisation



A solid solution containing 40:60 A:B is heated to the solidus (point 2) and begins to melt. At equilibrium the composition of the molten phase (90:10) is determined by drawing a line to the liquidus at the same temperature (point 3).
Consider if the molten phase was removed at some point before equilibrium is reached. The solid would become increasingly rich in B.

Determination of the proportion of each component in a mixture



Consider a 50:50 A:B mixture heated to 1400 °C (point 1). The solid (β) contains 65:35 A:B (point 2) and the melt (α) 88:12. But how much of each are present?
The length of the lines 1,2 and 1,3 are proportional to the fractions present (Lever rule).
1,2 is proportional to the amount of α and 1,3 solid β. The lines 1,2 and 1,3 can be measured with a ruler or mathematically.

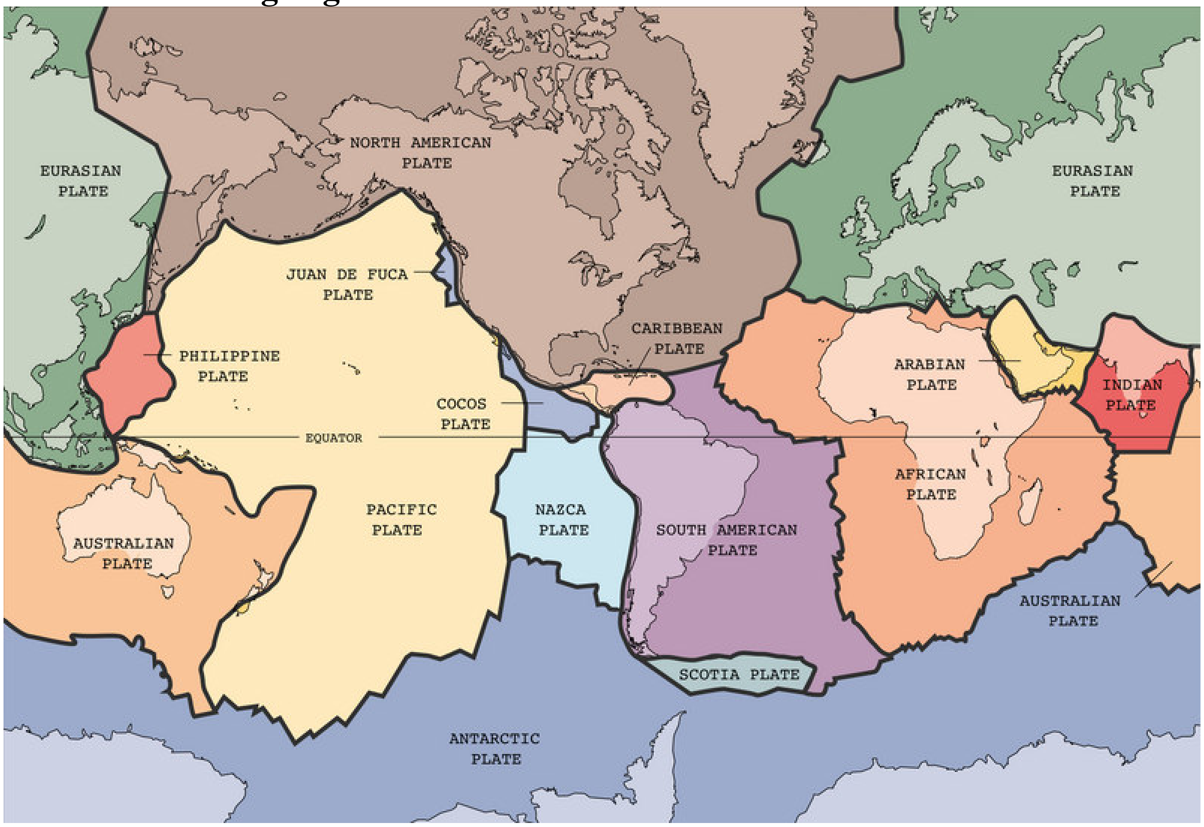
$$\text{amount of } \alpha = \frac{\text{line 1,2}}{\text{line 3,2}} = \frac{65\text{-}50}{65\text{-}12} \text{ or } \frac{50\text{-}35}{88\text{-}35} = 28\ \%$$

$\beta = 72\ \%$

How does crust interact with mantle?
Plate Tectonics

Lithosphere broken into 6 large plates, plates move (1-12 cm y^{-1})

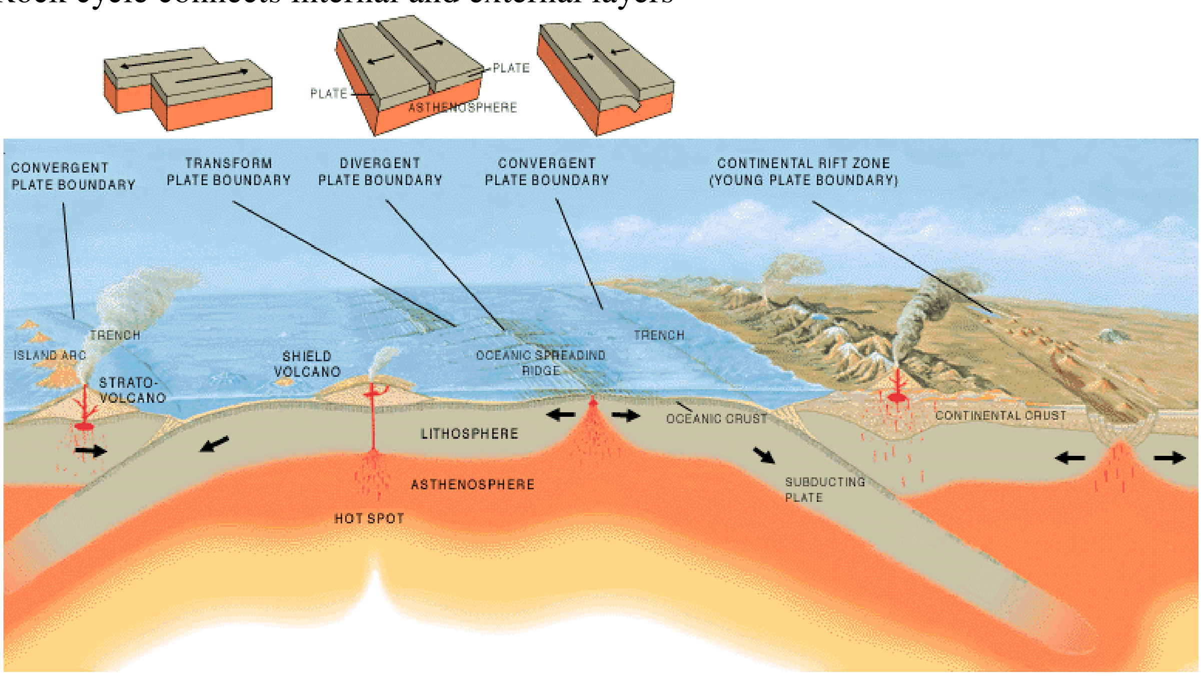
Interactions along edges.



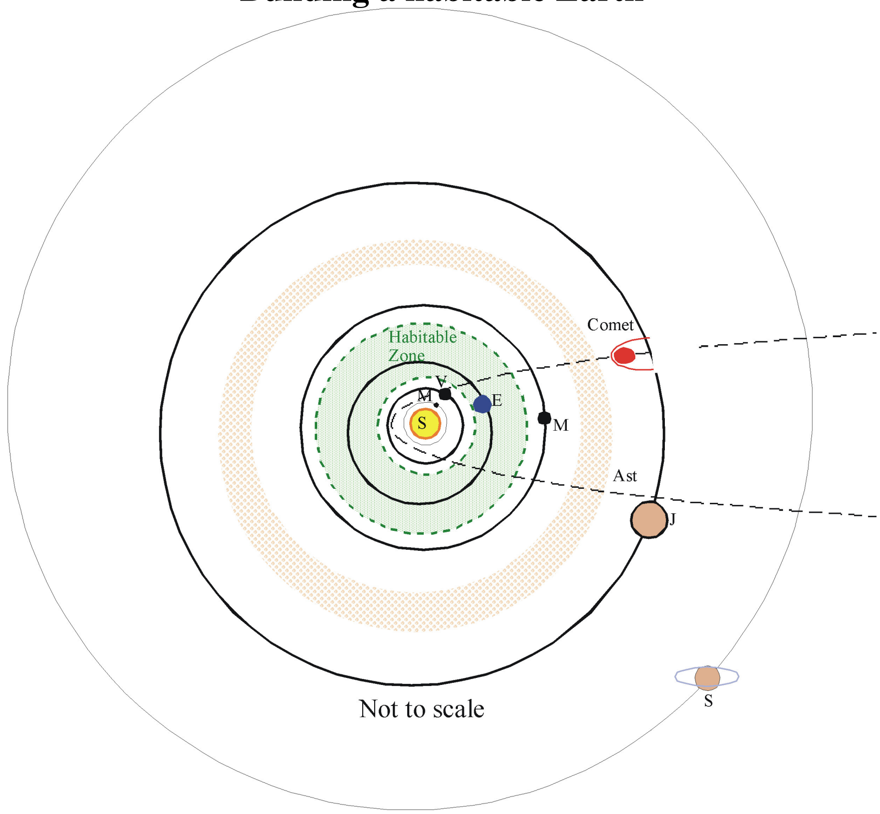
Oceanic plates: Created at spreading centres, destroyed at subduction zones

Continental plates: Accumulate material by volcanic action.

Rock cycle connects internal and external layers



Building a habitable Earth



Factors

Life on earth is dependent and many interdependent variables including:
Right distance from star - liquid water, tidal lock (day/night)
Right kind of star - mass: lifetime, UV - not first generation, ^{238}U
Right planetary mass - retain atm & ocean, heat for plate tectonics
Stable planetary orbits
Jupiter-like neighbour - clear out comets & asteriods, cross-talk
Plate tectonics - CO_2 - silicate balance, land mass, biotic diversity, magnetic field
Large moon - right distance, stabilize tilt
Right tilt - Seasons not too severe
Giant impacts - few, no global sterilizing after initial period
Right amount of H_2O - not too much, not too little, ocean
Right amount of C - enough for life, not enough for runaway greenhouse effect
Evolution of O - invention of photosynthesis, not too much or too little, right time
Right kind of galaxy - enough heavy elements, not small, elliptical or irregular
Right position in galaxy - not in centre, edge or halo

Arrival of “biogenic” elements

Temperature during accretion too high for abundant C, N or H_2O to be bound
Ice and C/N-rich solids accreted in asteroid belt.
Formation of Jupiter scattered volatile-rich planetesimals into inner solar system - “cross-talk”
First 600 x 10^6 y gave 100km diameter impacts that would sterilize Earth. No life possible
Currently 40,000 tons per year fall on Earth

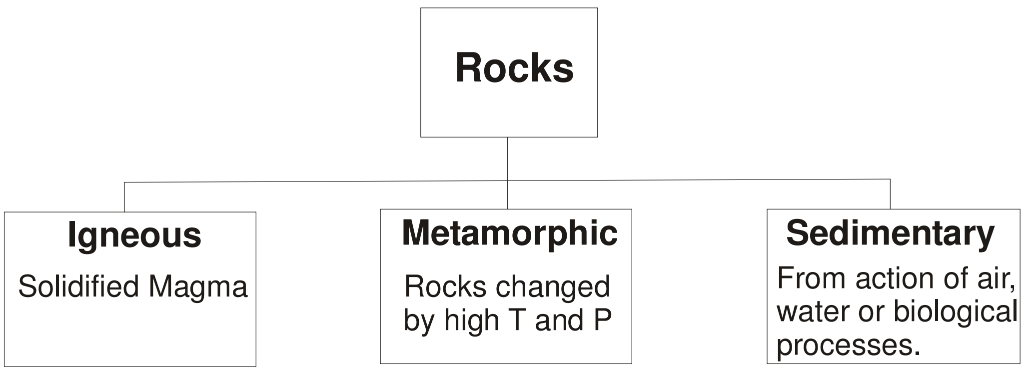
Minerals and Rocks

What is a mineral?
A mineral is a solid compound found in nature exhibiting a crystalline structure and a unique chemical composition. e.g. rock salt, NaCl > 4000 known.

What is a rock?
Essentially a mixture of minerals (3-4) with some glassy (amorphous) material with no unique chemical composition. E.g. granite

Mineralogy is the study of minerals. **Petrology** is the study of rocks.

The Earth's crust is formed of rocks, which are classified into three categories.



Classification is not always straightforward as rocks may have been through more than one process. All result in a change in the composition of the crust and chemical reactions that determine mineral formation.

Given composition of mantle and crust it is not surprising that most minerals contain Si and O (as silicates).

Major mineral classes are:
Silicates: 70% of crust Si and O, By far greatest mass of minerals are silicates.
Oxides: including many important ores e.g. Fe_2O_3 (hematite), magnetite (Fe_3O_4), rutile (TiO_2) and gemstones (Al_2O_3- ruby, sapphire), MgO.
Sulfides: e.g. HgS (cinnabar), FeS_2 (pyrite), MoS_2 (molybdonite)
Carbonates: e.g. $CaCO_3$ (calcite, aragonite)
Sulfates: $CaSO_4.2H_2O$ (gypsum)
Phosphates: e.g. $Ca_5(PO_4)_3OH$ (apatite-bone, teeth)
Halides: e.g. NaCl (halite), CaF_2 (fluorite)
Elements: e.g. gold, silver, carbon (graphite and diamond)

Minerals are also classified by crystal structure, habit (shape), density, colour, refractive index, cleavage, property e.g. fluorescence, magnetism, radioactivity.

Some important features of minerals (and solid state compounds in general)

1. On earth at T < 3000 K compounds must be neutral (no excess negative or positive charge)

2. The structure of solid state compounds can range from amorphous to crystalline (minerals are defined as crystalline).

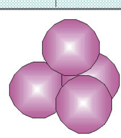
3. In the same way organic molecules have isomers for a single composition (e.g. C_4H_{10} has a linear and branched alkane) solid state compounds can exhibit different crystal structures for a single composition. These are called ***polymorphs*** e.g. $CaCO_3$ has at least two mineral polymorphs (calcite and aragonite).

4. Some solid state compounds are miscible and mix on an atomic scale to give ***solid solutions*** (e.g. Al_2O_3 and Cr_2O_3 to give $Al_{2-x}Cr_xO_3$). Compounds where the ratio of elements is not a whole number are known as ***non-stoichiometric***.

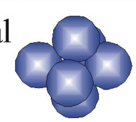
Silicate Minerals

	Ion	Continental crust abundance / % wt	Ionic radius / pm	Cation Coordiantion, n	Symmetry of cation site
ZO_4^{4-}	O^{2-}	45.28	140		
	Si^{4+}	27.28	26	4	Tetrahedral
	Al^{3+}	8.00	39/53	4/6	Tetrahedral/ octahedral
Inter-stitial cations	Fe^{3+} Fe^{2+}	5.8	65 77	6 6	Octahedral Octahedral
	Mg^{2+}	2.77	72	6	Octahedral
	Ti^{4+}	0.86	67	6	Octahedral
	Na^{+}	2.32	102/116	6 /8	Octahedral/ cubic
	Ca^{2+}	5.06	112	8	Cubic
	K^{+}	0.86	151/160	8/12	Cubic/ ccp

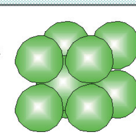
Tetrahedral



Octahedral



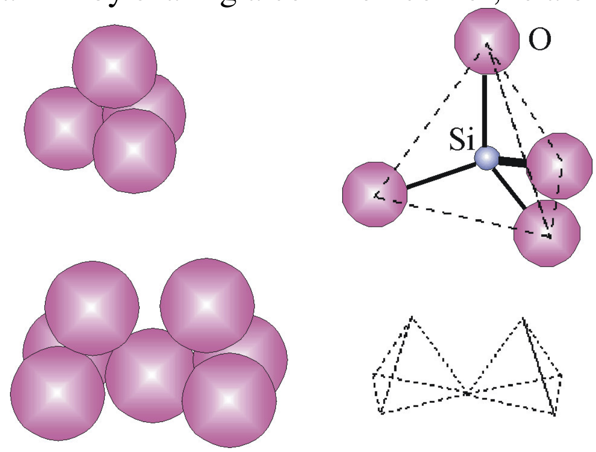
Cubic



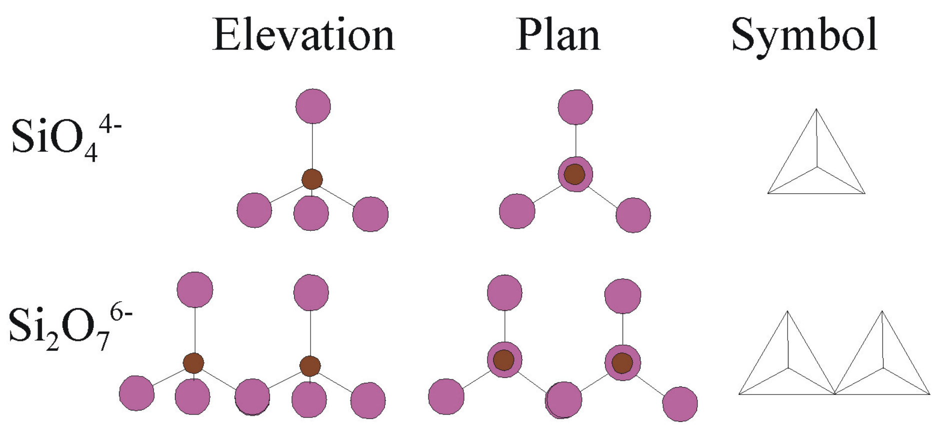
SiO_4^{4-} tetrahedral ion is the basic building block that can link together (polymerise) to form a range of structures. Si-O bond is strongest single bond involving O and is ~ 50% ionic. If Si-O skeleton is negatively charged cations are required for charge balance and occupy spaces (sites) in Si-O skeleton. The most important factors governing site occupation are

1) cation size (ionic radius)
2) chemistry (electronegativity, charge density)

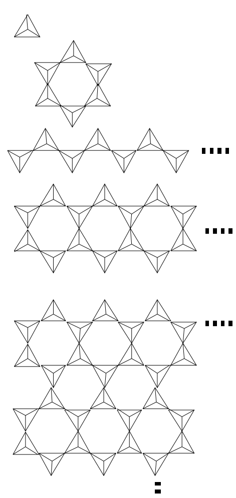
SiO_4 tetrahedra link by sharing a common corner, ie a bridging oxygen



Representation of tetrahedra



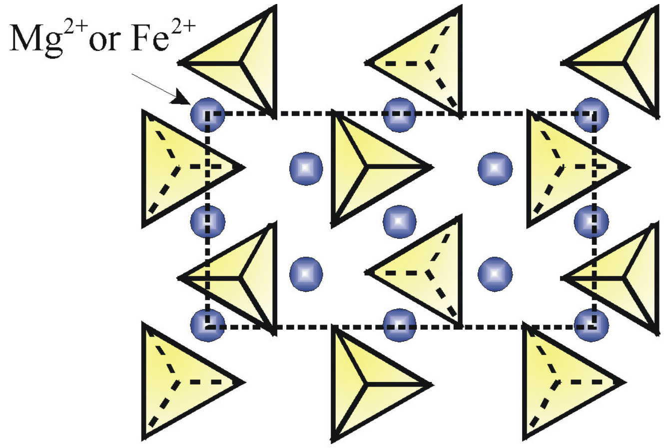
Polymerisation of tetrahedra

Geometry	Crust Abund	Diagram	Example Mineral
Isolated	3%		Olivines, garnet, sphene
Rings	<1%		Tourmaline
Single chains	} 16%		Pyroxenes
Double chains			Amphiboles, sillimanite
Sheets	5%		Micas, clays, chlorites
Frameworks	63%		Quartz, feldspars, cordierite

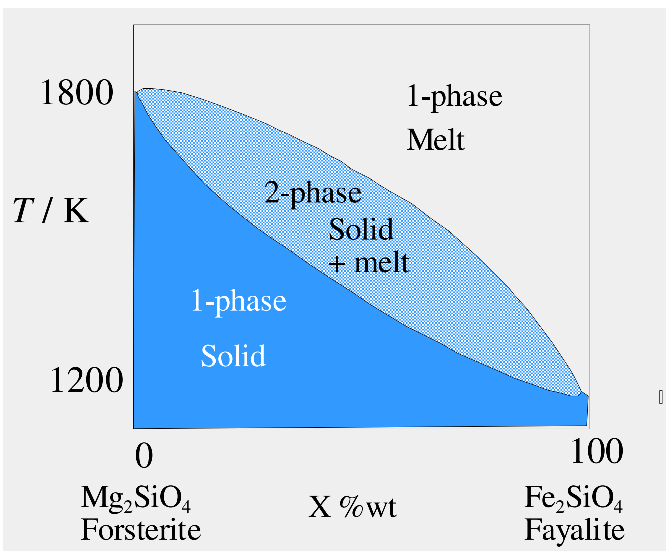
Isolated silicates

e.g. Olivines X_2SiO_4 ($X = Mg^{2+}$, Fe^{2+}): Mg_2SiO_4 (forsterite), Fe_2SiO_4 (fayalite). Very common in lower mantle, (~50 %).

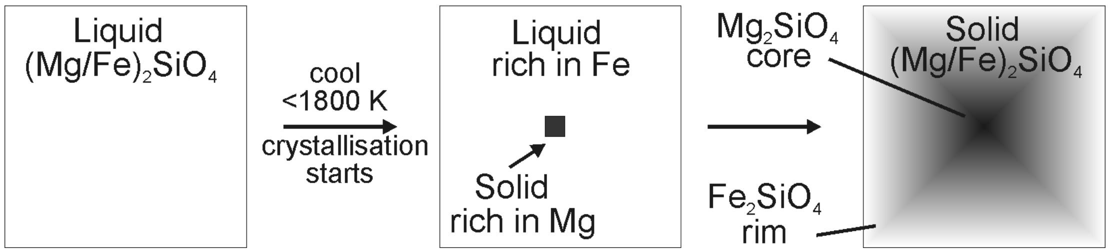
Structure



Olivine T vs X phase diagram



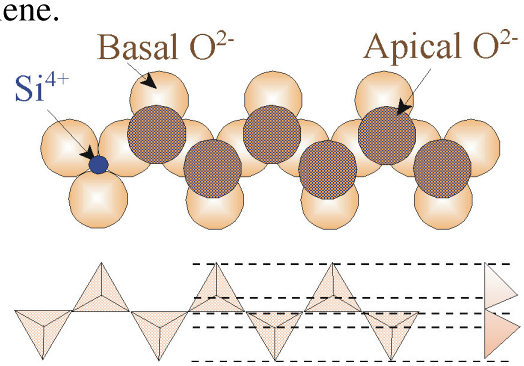
Olivines exhibit a solid solution between the two 'end members' forsterite and fayalite. Solid solution is possible because of similar size of Mg^{2+} and Fe^{2+} ions that can replace each other without causing strain in structure. From the phase diagram we can see that when the melt is cooled to a particular temperature between 1800 and 1200 K the crystallising solid will be Mg rich and the liquid Fe rich. This leads to zoning in crystals.



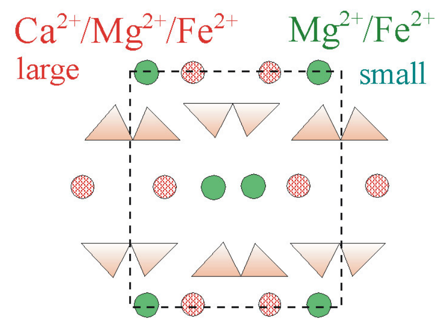
Zoning is common in minerals where solid solutions are present and depends on rate of cooling. Very slow cooling gives larger crystals of end-members. Zoning and crystal size give indication of geological process during crystallisation.

Chain silicates

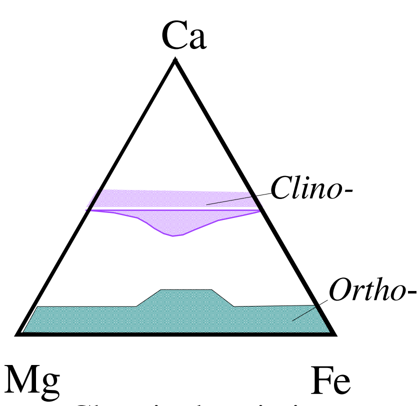
e.g. orthopyroxenes and clinopyroxenes (most have composition $XSiO_3$, X = Ca^{2+}, Mg^{2+}, Fe^{2+}). Very common in igneous and metamorphic rocks. Jadeite (jade) is a rare pyroxene.



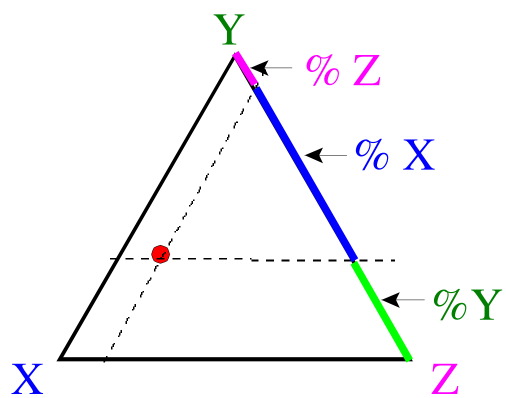
view parallel to chains



View perpendicular to chain



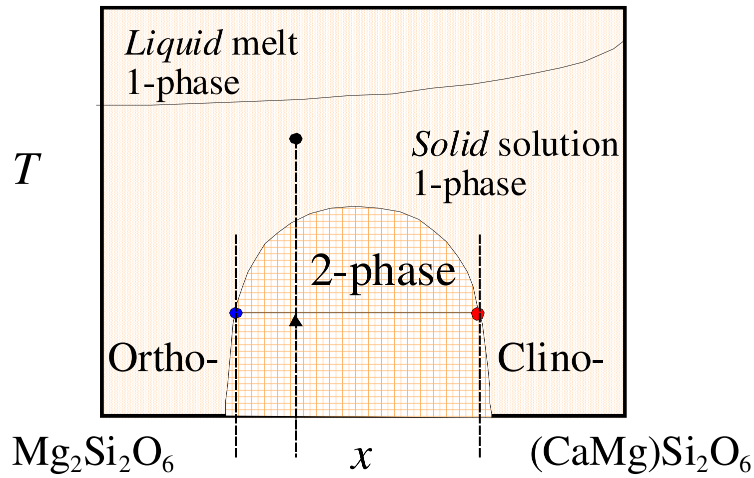
Chemical variation



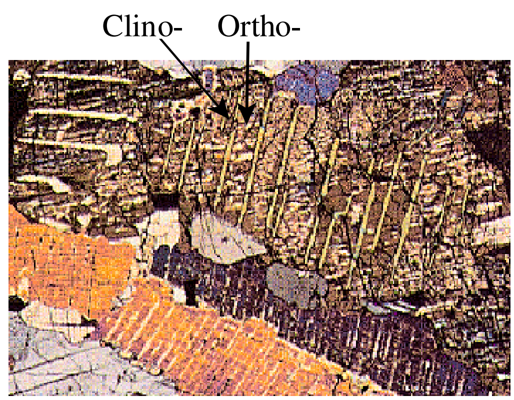
Ternary diagram

Composition varies according to ternary phase diagram.

Orthopyroxenes contain mainly Mg^{2+} and Fe^{2+}. Cations are similar size leading to solid solution.
Clinopyroxenes contain Ca^{2+} which is much bigger than Mg^{2+} and Fe^{2+}. The structure of clinopyroxenes is different to orthopyroxenes. Clino and ortho- pyroxenes often separate as 2 phases – intergrowths during rock formation from cooling magma. This can be shown on a phase diagram.



The 2-phase region is called an ***immiscibility dome***. In this region two phases are observed because at these temperatures a single silicate structure is not stable containing Ca^{2+} and Mg^{2+} ions. At temperatures or Ca/Mg compositions outside the dome a single solid solution phase (with either ortho- or clinopyroxene structure) is observed that is stable. This is because the 'size' of ions is a function of temperature due to ion vibrations. At high T ions vibrate more and are effectively 'bigger' which can stabilise a structure.

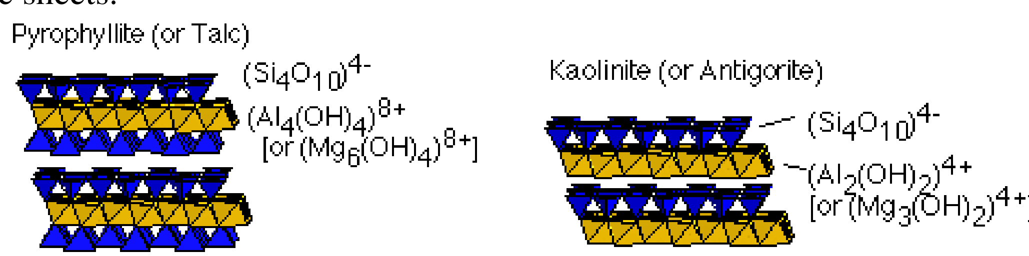


under cross polarised light intergrowths can be observed

Layered Silicates

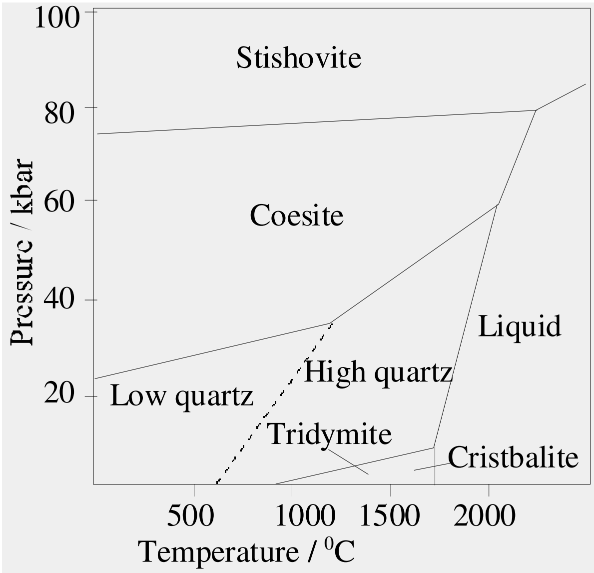
e.g. clays pyrophyllite ($Mg_3Si_4O_{10}(OH)_2$) (talc), kaolinite ($Al_2Si_2O_5(OH)_4$) (china clay) (used in ceramics, food, paper, cosmetics, medicine…)

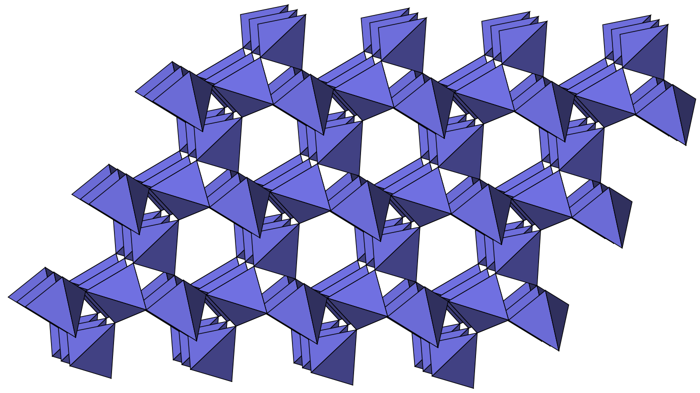
Formulas can be complex because lots of ions can fit between the layers and they contain variable water content. Structures can contain single, double or mixtures of silicate sheets.



Framework Silicates- Silicas

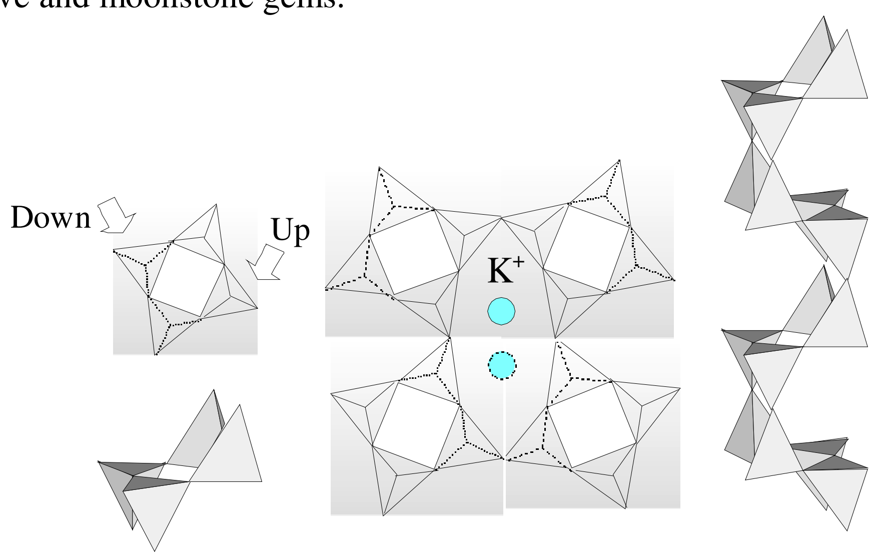
All corners of tetrahedra are shared.
SiO_2 silica has many polymorphs as shown on P vs T phase diagram.





Many uses and one of most common minerals. Goes under many different names, largely because of colours due to impurity ions. e.g. opal, amethyst and agate.

Related Feldspars are > 60 % of crust/upper mantle. E.g. $KAlSi_3O_8$ (orthoclase) used as an abrasive and moonstone gems.



Feldspars are constructed by substituting Al^{3+} into crystallographic sites occupied by Si^{4+} in silica. The silica skeleton is therefore negatively charged and to retain charge balance a cation is required e.g. Na^+ or K^+.

When large pore are present that can accommodate other molecules. e.g. H_2O these structures are referred to as zeolites. Zeolites have many industrial uses as catalysts and in ion exchange processes.

Gems

Gems have been prized for thousands of years for their beauty, but they also have many practical applications particularly derived from their optical (e.g. lasers), electronic (e.g. semiconductors) and mechanical properties (e.g. abrasives). We will consider three of the *precious stones*, diamond, ruby and sapphire and what causes their colour.

Defects

Defects are an important concept in solid state structural chemistry that are relevant to gems. You will learn more about this and related topics in year 3 materials chemistry. Defects influence optical, electromagnetic and mechanical properties.

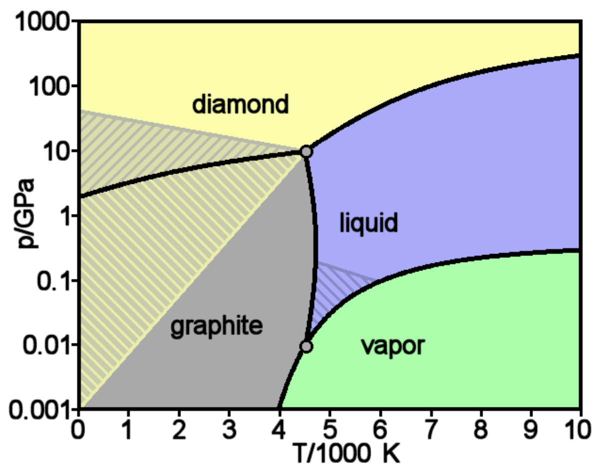
Extrinsic Defects: Foreign atoms are included in the structure either by addition or more commonly substitution.

Intrinsic Defects: Atoms are displaced from their ideal crystallographic position or missing from the structure (point defects). There are also other structural defects arising from relative displacement of planes of atoms (dislocations).

Note: In all cases charge balance must be maintained.

Diamond

carbon phase diagram



(hashed region is where one phase is metastable)

Note diamond is metastable at room temperature and pressure whereas graphite is thermodynamically stable.

Colours of diamond are caused by extrinsic and intrinsic defects (<1%).

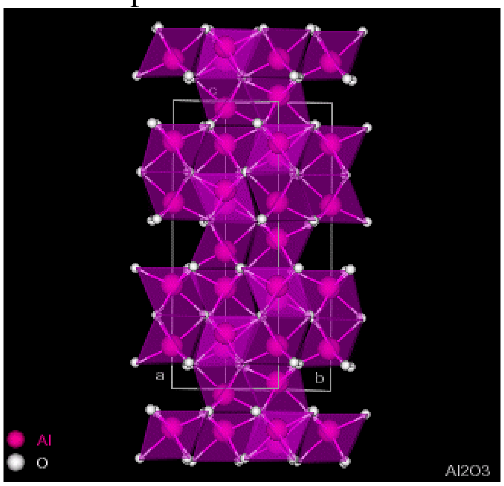
Extrinsic: Carbon atoms substituted by nitrogen (yellow), boron (blue). Colour due to extra (N) or absence (B) of an electron relative to carbon.

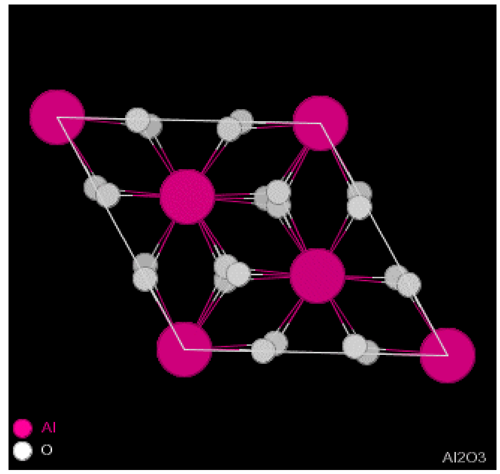
Intrinsic: Point defects and dislocations give other colours including brown, purple, green and pink.

Intrinsic defects caused by radiation or heat. Heat treatment can alter structural defects and change colour of many gems.

Ruby and Sapphire

Both are derived from the corundum polymorph of Al_2O_3. Pure corundum is a hard colourless transparent mineral.





Hexagonal close-packed oxygen atoms. 2/3 of octahedral interstitial sites are filled with aluminium atoms. Contains AlO_6 octahedra linked along vertices and faces.

Extrinsic defects most important
Substitution of Al^{3+} for Cr^{3+} (<1%) gives a red colouration (ruby).
All other colours are called sapphire. (including Ti = blue; V = purple; Fe = yellow-green and their mixtures for other colours). Different oxidation states give different colours.

Origin of Colour

All essentially arise from excitation of an electron (charge). The original location and final destination of the electron is dependent on the atomic composition and structure.

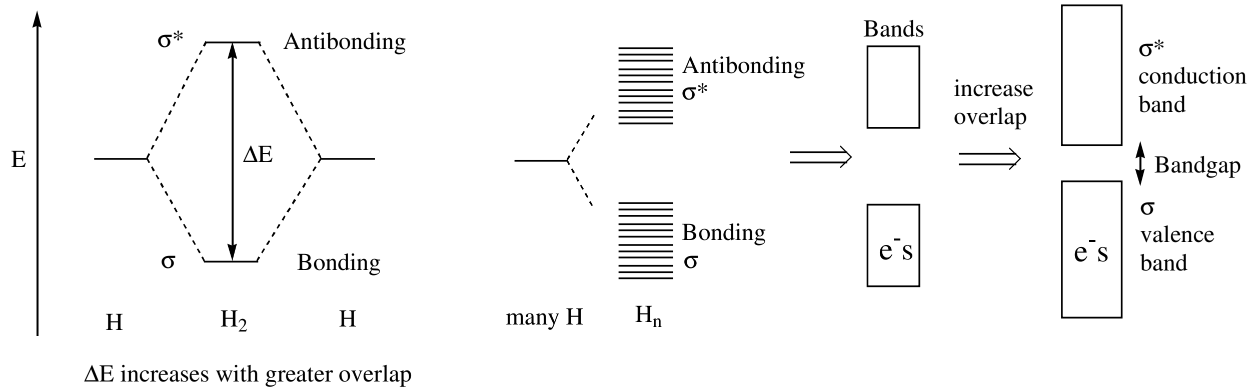
1. Extrinsic defects absorb light. The case for most transition metal impurities (d-d, metal-to-ligand (MLCT), ligand-to-metal charge transfer). In crystals containing two metals of different oxidation state charge transfer can also occur between them (intervalence charge transfer). All these phenomena are related to metal complex chemistry.

e.g. in some blue sapphires

$$Fe^{2+} + Ti^{4+} \xrightarrow{h\nu} Fe^{3+} + Ti^{3+}$$

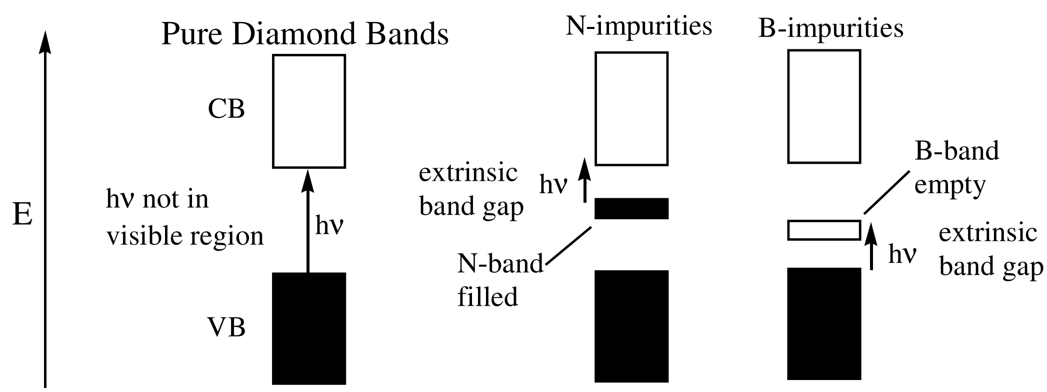
2. Excitation across a band gap.

In crystals containing billions of atoms molecular orbitals are represented collectively as bands.



The bandgap energy determines which frequencies are absorbed and hence the colour. In pure diamond the energy required to excite electrons across the band gap is higher than the visible region and no colour is observed. If there is no band gap all visible frequencies are absorbed and the material appears black. e.g. metals.

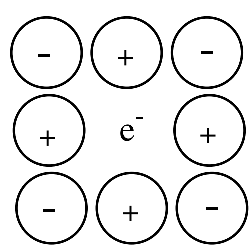
Extrinsic impurities can introduce an extra band.
In diamond, N impurities containing 'the extra electron' not used in bonding generate a filled band between the filled valence and empty conduction bands. B-impurities introduce a band of empty orbitals. Excitation across these extrinsic band gaps is in the visible region leading to colour.



3. Intrinsic point defects (colour centres)

Missing atoms or structural imperfections can lead to 'trapped' electrons that can be excited in the visible region (c.f. particle in a box). Usually caused by radiation or heat. e.g. NaCl irradiated with γ-rays is blue. Radiation, heat and sunlight can change intrinsic defects and hence colour.

e.g. If an anion is missing a 'free' electron must be present to conserve charge balance.



Glossary (Words in *italics* have separate entries in the Glossary)

Acid Rock A rock containing >65% SiO_2 by chemical analysis, e.g. *granite*. A potassium-rich feldspar $K[AlSi_3O_8]$ (Or)

Albite A sodium-rich *feldspar* $Na[AlSi_3O_8]$ (Ab)

Anisotropic Having different properties in different directions.

Anorthite A calcium-rich *feldspar* $Ca[Al_2Si_3O_8]$ (An)

Antimatter Matter composed of antiproton, antineutron, positrons, etc.. Each kind of particle has a corresponding antiparticle. For a few particles (necessarily neutral), e.g. the photon, the particle is its own antiparticle. Antiparticles are often denoted by a bar over the particle's symbol. Pair annihilation occurs when a particle and its antiparticle collide. Both particles disappear and two (or three) photons appear: decay onto a single photon is impossible because energy and momentum must be conserved.

Atmophile Elements found preferentially in the materials of the Earth's atmosphere.

Basic Rock A rock containing < 50% SiO_2 by chemical analysis, e.g. *basalt*

Big Bang An explosion of all space that took place about 15 billion years ago and from which the *Universe* emerged.

Birefringence see *double refraction*.

Black Hole An object whose gravity is so strong that the escape speed exceeds that of light

Blackbody A hypothetical perfect radiator that absorbs and reemits all radiation falling on it. It emits blackbody radiation.

Carbonaceous Chondrite A type of *meteorite* that has a high abundance of carbon and volatile compounds.

Clay A rock compose of fine-grained minerals, which is generally plastic at appropriate water content but hardens when dried. Clay minerals are *layer silicates*.

Cleavage Tendency of minerals to break along a preferred plane defined by the crystal structure.

CNO Cycle A series of nuclear reactions in which ^{12}C is used as a catalyst to convert ^{1}H to ^{4}He.

Cosmic Rays Particles that continually bombard the Earth from sources both within and beyond our *galaxy*, consisting of *neutrino*s, protons and heavier nuclei, with energies ranging from 1MeV to 10^{20} eV.

Cosmology The study of the structure and evolution of the *Universe*

Crab Nebula Example of *supernova* remnant 1054 AD. 6500 light years from Earth. Has a *pulsar* at its centre. In the Taurus constellation.

Crossed-polars The usual set-up for a petrological polarizing microscope (XPL) that reveals the *birefringence* of the *minerals* in the thin section. Polarizing directions of the analyzer and polarizer are at right angles so that the field of view is dark in the absence of birefringent grains.

Crust The outermost layer of the *lithosphere*, consisting of relatively light, low-melting temperature materials. Continental crust consists largely of *granite*, oceanic crust of basalt.

Double Refraction (*birefringence*) The phenomenon where an *anisotropic* crystal splits a ray of light into two rays (ordinary and extraordinary) that travel at different speeds and are polarized at right-angles to each other. Crystals either have one (uniaxial) or two (biaxial) directions along which light is not doubly refracted.

Extinction The position of the thin section of a *birefringent mineral* viewed under XPL for which the grain appears black.

Feldspar A group of *tectosilicate* minerals whose composition can be expressed in terms of the system: *orthclase* (Or), *albite* (Ab) and *anorthite* (An). Those with compositions between Or and Ab are alkali *feldspars*, between Ab and An plagioclase feldspars.

Framework Silicate	A large class of minerals in which all corners of the SiO_4 tetrahedra are shared. Comprise about 64% of crustal rocks. Includes the groups: SiO_2 polymorphs, *feldspars*, feldspathoids, scapolites and zeolites.
Galaxy	A large assemblage of *stars*, *nebulae* and interstellar gas and dust
Garnet	A common mineral in metamorphic rocks. $Mg^{2+}{}_3Al^{3+}{}_2[SiO_4]^{4-}{}_3$ (Pyrope), $Fe^{2+}{}_3Al^{3+}{}_2[SiO_4]^{4-}{}_3$ (Almandine)
Glass	A solid with short-range, but no long-range order, non-crystalline, a super-cooled liquid. (See *obsidian* and *pumice*)
Granite	A *felsic*, coarse-grained, *intrusive igneous* rock of *acid* chemical composition, composed of K-*feldspar*, *plagioclase* and *quartz*, with small amounts of *mafic* minerals, e.g. *biotite*.
Helium Burning	The thermonuclear fusion of ^4He to produce ^{12}C and ^{16}O. Convert *main sequence stars* into *red giants*.
Hertzsprung-russell Diagram	H-R diagram is a plot of the *luminosity* of stars against their surface temperature (or *spectral class*).
Igneous Rock	A rock formed by cooling and crystallization of *magma*.
Intermediate Rock	A rock containing 50-65 % SiO_2 by chemical analysis, e.g andesite
Isotropic	Having identical properties in different directions.
Kaolinite	A 1:1 layer silicate. A *clay* mineral.
Large Magellanic Cloud	(LMC) Companion *galaxy* to the *Milky Way*. The *supernova* SN1987 occurred in this galaxy. 165,00 light years from Earth
Lava	*Magma* that reaches the Earth's surface.
Layer Silicate	(*phyllosilicate*) An important group of minerals having a *platy* or flaky habit and one prominent *cleavage*. 3 main types: 1:1 , 2:1 and 2:1:1. Main groups: serpentines, *clays*, *micas,* chlorites
Lithophile	Elements found preferentially in the materials of the Earth's mantle.
Lithosphere	The outer rigid shell of the earth containing the *crust*, upper mantle, the continents and the plates.
Luminosity	Rate at which *radiation* is emitted from a *star* or other object.
Mafic	A *mineral* e.g. *olivine* and *pyroxene*, or *rock*, e.g. *basalt*, rich in Fe and Mg silicates.
Magma	Molten *rock*, generally a silicate melt with suspended crystals and dissolved gases.
Main Sequence	A grouping of stars on a *Hertzsprung-Russell diagram* extending diagonally across the graph from hot, luminous *stars* to cool, dim stars.
Matter	Everything in the *Universe* is either *radiation* or matter. Matter is contained in such luminous objects as *stars*, planets, *galaxies* as well as nonluminous dark matter. Matter consists of 6 leptons (electron, muon, tau and their *neutrino*s) and 6 quarks from which the hadrons (mesons and baryons, including protons and neutrons) are made.
Metamorphic Rock	Any *rock* formed from preexisting rocks by solid state reactions/recrystallization driven by changes in temperature, pressure and by chemical reaction with fluids.
Metamorphism	Alteration of the *minerals* and *textures* of a rock by changes in temperature, pressure and by chemical reaction with fluids.
Meteorite	A fragment of a meteoroid (a small rock in interplanetary space) that has survived passage through the Earth's atmosphere.

Mica A group of *layer silicates* with interlayer cations and no exchangeable water: muscovite (white) *biotite* (black).

Milky Way Our *Galaxy*. The band of faint stars seen from Earth in the plane of our Galaxy's disk.

Mineral A naturally occurring homogeneous crystalline (i.e. excluding amorphous *glasses*) solid with a definite (generally not fixed but varying between fixed limits) chemical composition. It is usually formed by inorganic processes. This definition includes the calcium carbonate (aragonite) of mollusc shells, but excludes petroleum and coal, which have neither a definite chemical composition or a crystalline structure.

Mineralogy The study of *minerals*.

Nebula A cloud of interstellar gas and dust.

Neutrino Elementary particle with no charge and little or no mass. Neutrinos are emitted in radioactive β^- decay, by *H-burning* in the Sun and other stars. If the neutrino has even a small mass the total mass of neutrinos in the *Universe* remaining now after the *Big Bang* could outweigh everything else. Neutrinos are almost impossible to detect, requiring enormous detectors made up of millions of kg of water, collisions produce flashes of light detected by photomultipliers.

Neutron Star A very compact, dense star composed almost entirely of neutrons. A type of stellar corpse, remnants of *supernovae*, smaller and more compact than a *white dwarf.* Rotate rapidly and possess a powerful magnetic field. (See *pulsar*)

Nova (New star) A star that experiences a sudden outburst of radiant energy, temporarily increasing its luminosity by about $\times 10^3$.

Nucleosynthesis The process of building up nuclei, e.g. deuterium and helium from protons and neutrons.

Obsidian A glassy extrusive rock with a chemical composition equivalent to *granite*.

Olivine Family of island silicates, including forsterite and fayalite X_2SiO_4, $X=Mg^{2+}$, Fe^{2+}, common in *basic* and ultrabasic igneous rocks

Orthoclase A potassium-rich *feldspar* $K[AlSi_3O_8]$ (Or)

Pegmatite A vein, or pocket, of very coarse grained *granite*, often containing economic amounts of rare minerals.

Petrology The study of *rocks*.

Phyllosilicate see *layer silicate mineral*.

Plane-polarized When a thin section of rock is viewed the microscope in this arrangement (PPL) the *birefringent* properties of the minerals are not differentiated, but the natural colour, refractive index differences and *cleavage* are more easily seen. Only one polarizing filter is in the light path.

Pleochroism The property of a mineral in thin section when viewed under PPL. The change of colour as the orientation of the grain changes with respect to the plane of polarization (i.e. as the stage is rotated).

PPI Chain A sequence of thermonuclear fusion reactions involving ^1H, ^2H,^3He that converts ^1H into ^4He. One of the main energy producing mechanisms of *nucleosynthesis* (hydrogen burning) for *main sequence* stars, like the Sun.

Pulsar Pulsating (period ~ milliseconds) radio source, associated with the rapid precession of rotating, magnetic neutron stars. Beams of charged particles emerging from the magnetic poles sweep across the sky. One is located at the centre of the *Crab Nebula*. http://pulsar.princeton.edu/

Pumice A volcanic glass, usually of *felsic* composition. Frothy - filled with hole. (See *obsidian*)

Pyroclast Fragmental rock produced by *volcanic* explosions.

Pyroxene A family of single-chain silicate minerals. $X^{2+}[SiO_3]^{2-}$, $X \equiv Ca$, Mg, Fe, common in *basic* igneous rocks, e.g. *basalt*.

Quartz A low-pressure, low-temperature polymorphs (different crystal structures) of silica.

Quartzite A hard, non-foliated white metamorphic rock formed from sandstones rich in *quartz* sand grains.

Quasar A star-like object with a very large *redshift*. Extremely *luminous* as bright as 10^{10} Sun. Distant *galaxies* 10^9 light years from Earth. Common in the very early life of the *Universe*.

Radiation Everything in the *Universe* is either radiation or *matter*. Electromagnetic radiation has both wave-like and particle-like (photons) properties. The electromagnetic interaction is mediated by photons. The transition between a radiation-dominated and a matter-dominated *Universe* happened about 2500 year after the *Big Bang*.

Red Giant A large, cool *star* of high *luminosity*.

Redshift The shifting to longer wavelengths of the light of distant *galaxies* and *quasars*. It is caused by an effect that is explained by the general theory of relativity and is not a Doppler shift.

Refraction The change in direction of a ray of light as it passes from one medium to another medium in which it has a different velocity (and refractive index).

Rock An aggregate of *minerals* that forms an appreciable part of the *lithosphere*.

Sandstone A clastic *sedimentary* rock composed of fragments ranging in diameter from 0.0625 to 2 mm, usually *quartz* and *feldspar*, cemented together by *quartz*, carbonate or other minerals or by a *clay* matrix.

Sedimentary Rock Rock formed by the accumulation and compaction of sediment.

Seismology The study of earthquakes.

Siderophile Elements found preferentially in the materials of the Earth's outer core.

Spectral Class Classification of *stars* according to their spectral properties.

Star Any self-luminous, gaseous, spheroidal heavenly body, seen as a fixed point of light in the night sky.

Supergiant A very large, very *luminous star*.

Supernova A *star* that experiences a sudden outburst of radiant energy, temporarily increasing its luminosity by about $\times 10^6$.

Tectonics The branch of geology that deals with regional or global structures and deformational features of the Earth.

Texture The size, shape and arrangement of *mineral* grains that make up a *rock*.

Twinning A symmetrical intergrowth of two (or more) crystals of the same mineral. The symmetry operation (reflection, rotation or inversion) that relates a crystal to its twinned counterpart is not one possessed by a single (untwinned) crystal. *Feldspars* commonly show various types of twinning.

Ultramafic An igneous rock composed almost entirely of *mafic* minerals, e.g. peridotite

Universe The totality of all things that exist; the cosmos. The whole of space and all of the *matter* and *radiation* contained within it.

Vesicle A small hole formed in a *volcanic* rock by a gas bubble that became trapped as the *lava* solidified.

Volcanism The processes by which *magma* and gases are transferred from the Earth's interior to its surface.

White Dwarf A low mass star that has exhausted all its thermonuclear fuel and contracted to a size roughly equal to the size of the Earth. A type of stellar corpse. (See *neutron star*)

Zoned Crystal A single crystal of one mineral which has a different chemical composition in its inner and outer parts: formed in *minerals* that can have variation in abundance of some elements and caused by the changing concentration of elements in a cooling *magma*.