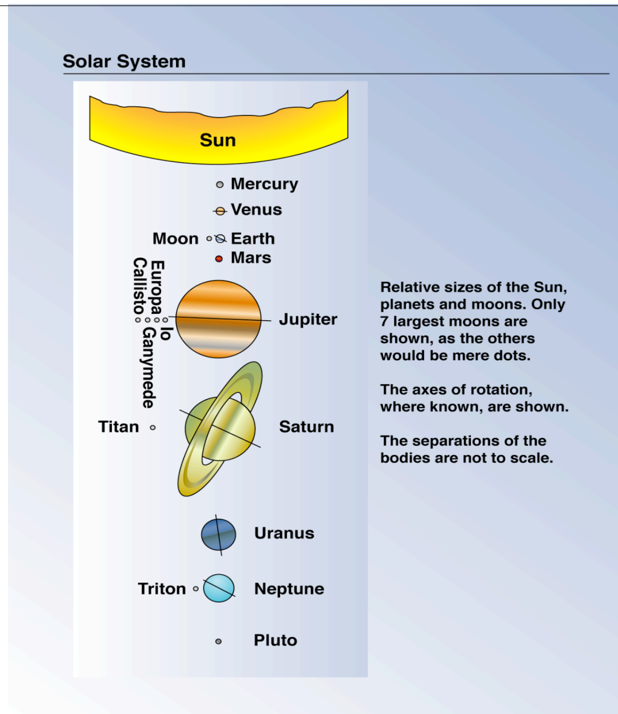
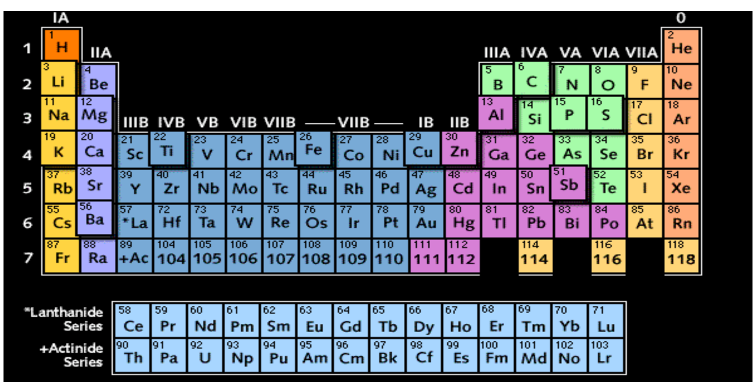
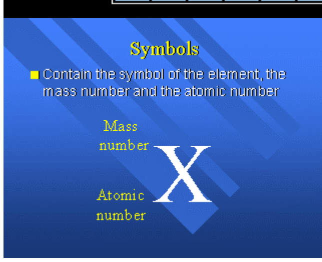


Periodic Table, Atomic & Mass Numbers



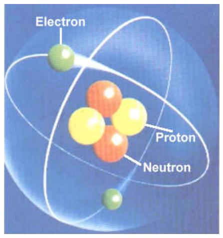


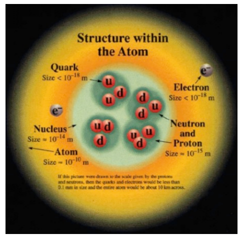
Atomic Number, Z = number of protons in the nucleus
(also = number of electrons in the neutral atom)

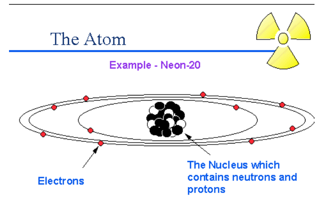
Mass Number, A = total number of protons plus neutrons in the nucleus

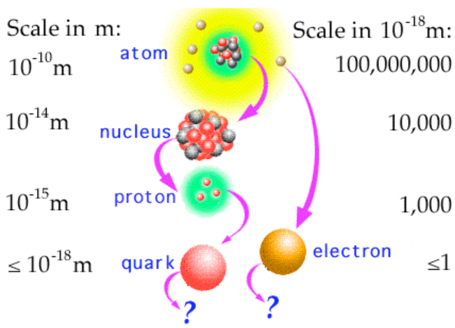
Therefore **A = Z + N**
(where N = number of neutrons = A - Z)

The General Atom





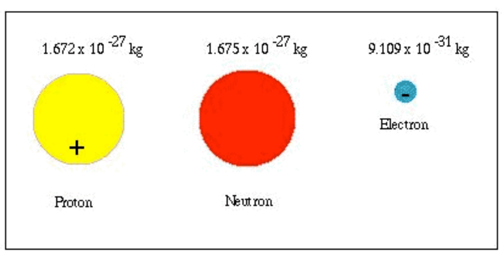




More than 200 subatomic particles have been discovered so far, all detected in sophisticated particle accelerators. Most of these are not fundamental and are actually composed of other simpler particles. Rutherford showed that the atom contained a nucleus and orbiting electrons. Later physicists showed that the nucleus was composed of neutrons and protons. Eventually it was shown that protons and neutrons are made up of quarks.

Fundamental Properties

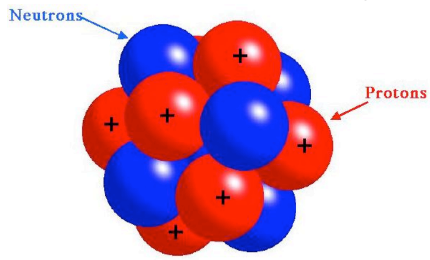
Mass (kg)



Charge (C)	$+1.6\times10^{-19}$	0	-1.6×10^{-19}
Mass (u, amu)	1.007276	1.008665	0.0005486

The nucleus consists of <u>neutrons</u> and <u>protons</u> that are collectively referred to as <u>nucleons</u>. We can represent the number of neutrons, protons and electrons in atoms using the well-known chemical symbols of the elements.

Nuclear stability: The Strong Force



The nucleus is approximately spherical with a radius given by:

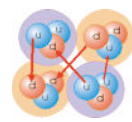
$$r \sim (1.2x10^{-15})\ A^{1/3}\ \ m$$

Although the mass of **different** nuclei is different, the **nuclear density** is similar. How can you prove this?

Why does the nucleus remain intact given the positive charged protons repel each other with a very strong repulsive electrostatic force ?

Why don't all nuclei burst apart?

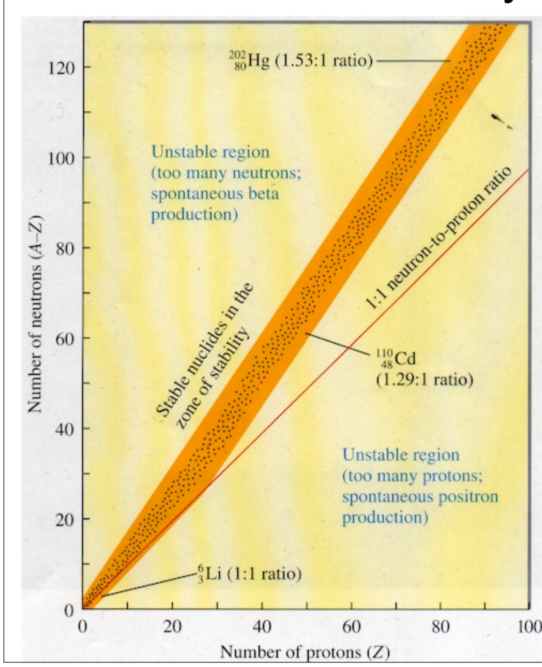
Because we know that nuclei do not (usually) disintegrate, we must infer there is a force that acts between neutrons and protons when these particles are extremely close together.



We call this THE STRONG FORCE.

It is very strong ONLY when the protons and neutrons are VERY CLOSE to each other (short range force, ~ 10^{-16} m).

Nuclear stability (continued)



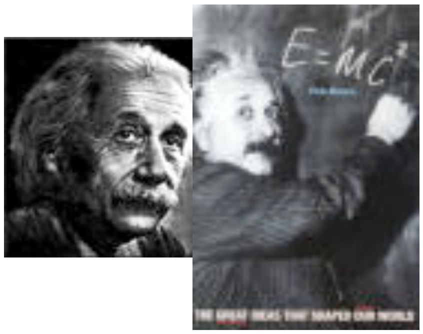
So, the Strong Force "glues" together neutrons and protons within the nucleus. **The electrostatic repulsive force is balanced by the Strong Force.**

As the number of protons (+ve charges repelling) increases, the number of neutrons must increase even more so as to "glue" all the nucleons together as a stable entity.

As Z becomes very high (> 83), this balance cannot be achieved and the nuclei are UNSTABLE. In this case, they spontaneously break apart or ***disintegrate*** – this process is called **RADIOACTIVITY**.

Mass Defect & Binding Energy

Because of the Strong Force, the nucleons inside the nucleus are held tightly together. Therefore ENERGY is required to separate the nucleus into its constituent protons and Neutrons. This energy is called the **BINDING ENERGY.**



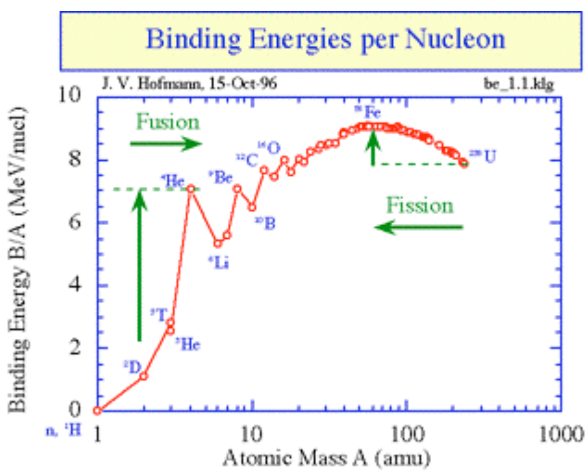
Einstein's Special Theory of Relativity shows that mass and energy are equivalent via his famous equation **$E = mc^2$**.

In our case, mass should really be written as a change in mass, Δm, which is referred to as a **MASS DEFECT**.

Binding Energy = $\Delta m\ c^2$

Where c = speed of light (3.0×10^8 ms^{-1})

Binding Energy Per Nucleus

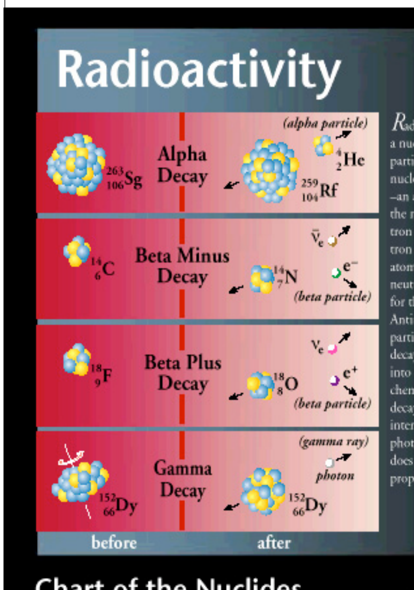


This plot shows the binding energy PER NUCLEON, i.e. the binding energy divided by the number of nucleons in the nucleus.

Above ~83, this value begins to decrease. There is less and less "glue" per nucleon as the atomic mass increases (beyond 83) and thus the nuclei become less and less stable.

Furthermore, when light elements fuse together, there is a release of energy, but when heavy elements fuse, energy is required.

Radioactivity & Radioactive Decay

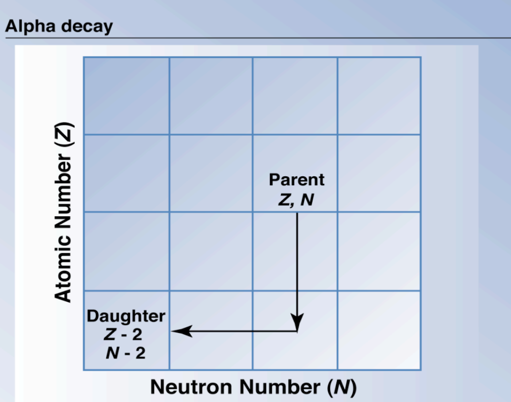


α Emission of a helium nucleus which is a particularly stable entity (2 protons + 2 neutrons)

β Transformation in the nucleus: either

1. a neutron transforms into a proton plus an electron (β- emission)
2. a proton transforms into a neutron plus a positron (β+ emission)

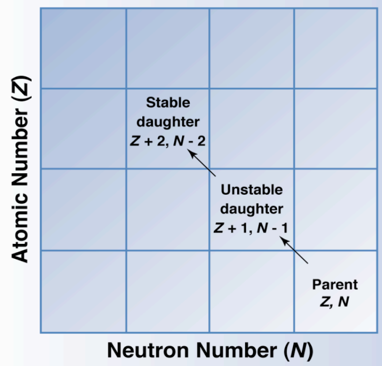
γ Relaxation of an excited nucleus with the emission of electromagnetic radiation.



Location of the daughter nuclide produced by alpha decay of its parent in coordinates of *Z* and *N*. Both the atomic number of the daughter are reduced by two, thus reducing its mass number by four. The daughter may itself be subject to further decay by either alpha emission, or beta emission, or both.

	Atomic Number	Neutron Number	Mass Number
Parent	Z	N	$Z + N = A$
Daughter	$Z - 2$	$N - 2$	$Z + N - 4 = A - 4$

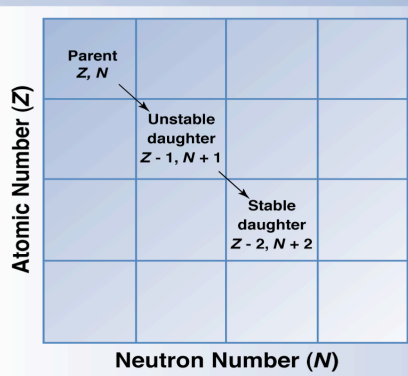
Beta (negatron) decay



Schematic representation of the location, on the chart of the nuclides, of the position of daughter atoms relative to their parents which is subject to beta (negatron) decay. The atomic number is increased by one while the neutron number is reduced by one. Consequently, parent and daughter have the same mass number, that is, they are isobars. If the daughter is itself radioactive and decays by beta emission, a second isobaric daughter is formed and so on, until at last a stable daughter is produced.

	Atomic Number	Neutron Number	Mass Number
Parent	Z	N	$Z + N = A$
Daughter	$Z + 1$	$N - 1$	$Z + 1 + N - 1 = A$

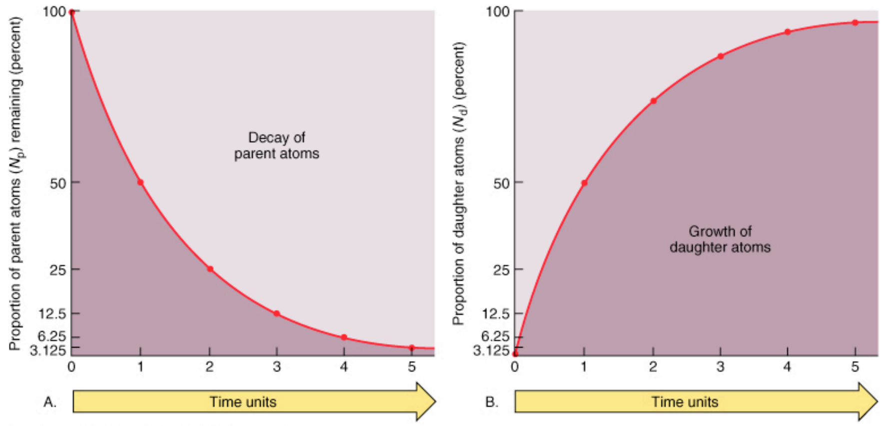
Positron emission



Schematic representation of the position, in the chart of the nuclides, of daughters produced by positron emission of the parent. Note that the atomic number (Z) decreases by one while the neutron number (N) increases. The daughters are isobars of their parent and are isotopes of different elements.

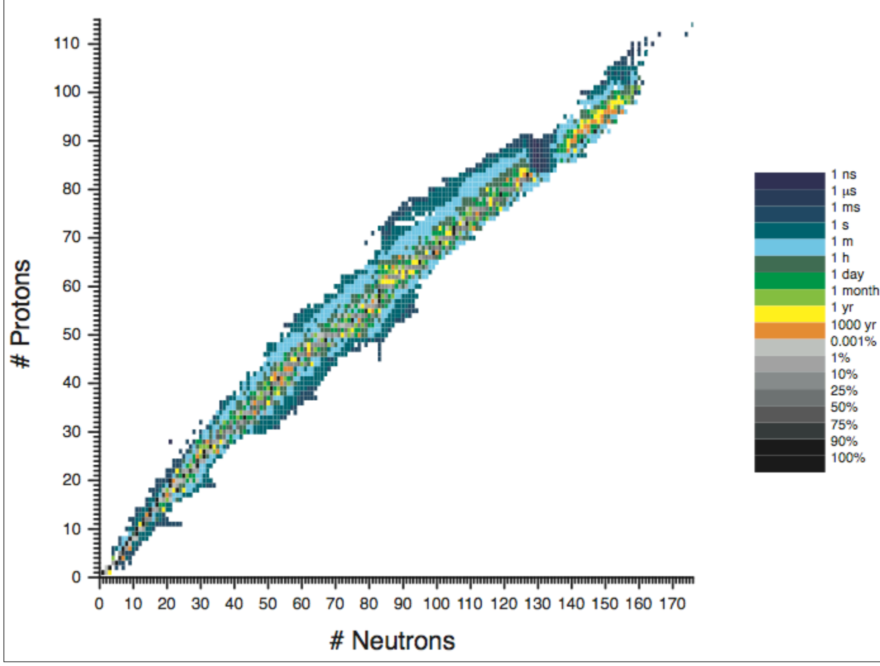
	Atomic Number	Neutron Number	Mass Number
Parent	Z	N	$Z + N = A$
Daughter	$Z - 1$	$N + 1$	$Z - 1 + N + 4 = A$

Radioactive Decay Law



$N = N_0 e^{-\lambda\tau}$ $\quad t_{1/2} = \frac{\ln 2}{\lambda}$

λ is the decay constant
$t_{1/2}$ is the half life

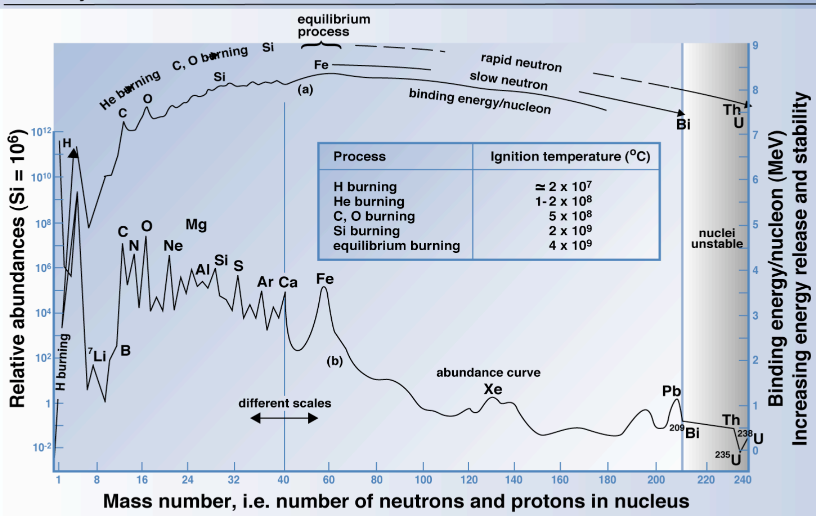


Nuclear Synthesis

- Elemental synthesis resulting from thermo-nuclear reactions in stars
- Starting material ^{1}H
- Postulated sequence of events related to stellar evolution

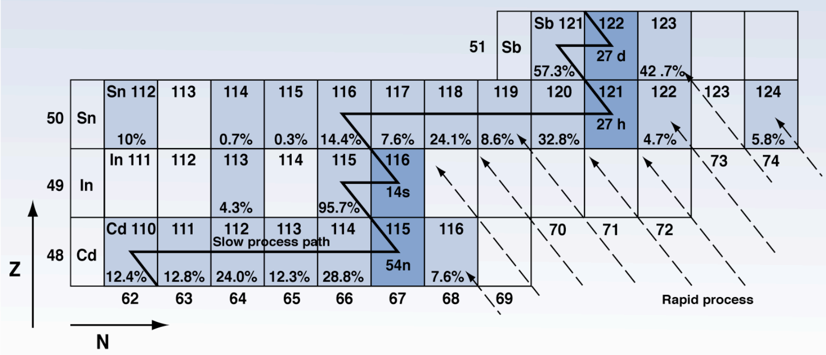
1) ^{1}H burning 2×10^{7} °C
   four P+ $\longrightarrow$ ^{4}He $+2\beta^{+}$
2) He burning $= 2 \times 10^{8}C$ $3\,^{4}He \longrightarrow {}^{12}C$
3) C, O burning $5 \times 10^{8}C$ combine to produce ^{28}Si
4) Si burning
   combinations of elements < ^{28}Si
5) e-process
   most stable nuclei/peak binding energy
6) s-process (slow neutron)
   neutrons added slowly
   n/p exceeds optimum
   β^{-} decay occurs n $p^{+} + \beta^{-} + \surd$
7) r-process
   neutrons added rapidly
   successive β^{-} decays

Nucleosynthesis and the abundance of elements



Nucleosynthesis and the abundance of the elements. (a) Binding energy per nucleon curve (upper curve): the higher up the curve that a nucleus is, the more stable it is, and, if a less stable nucleus is converted to a more stable one, energy is released, proportional to the vertical difference multiplied by the number of nucleons involved. The more important nuclear reactions are indicated. (b) Relative abundances (lower curve): these are derived from solar and meteoric abundances and are believed to represent the proportions in the Solar Nebula. Note that the superimposed on the overall trend of decreasing abundances are peaks corresponding to peaks or changes of slope on the curve above.

Roles of the s- and r- processes in the production of isotopes of Cd, In, Sn and Sb



Part of the chart of the nuclides used to show the roles of the s- and r- processes in the production of Cd, In, Sn and Sb. The s-process path is indicated by the continuous line. The r-process decay lines enter from the lower right. Dark shaded rectangles are naturally occurring stable isotopes; lighter shaded rectangles are isotopes which undergo β-decay, thereby terminating the s-process path for that particular atomic number.

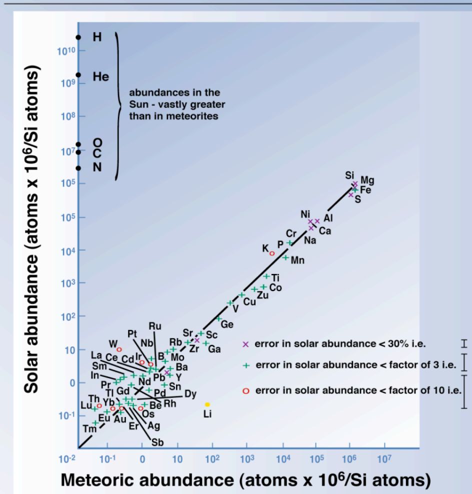
Composition of Earth

1) Earth Differentiated
2) Mass Balance
3) Composite and CI Models

CI Model

- Four classes of Meteorites (Irons, Stones”, Stony-irons, Chondrites)
- Irons, Stones”, Stony-irons are differentiated
- Chondrites are “more” Primitive
- CI’s most similar to Solar Photosphere

Solar and chondritic meteorite element abundances

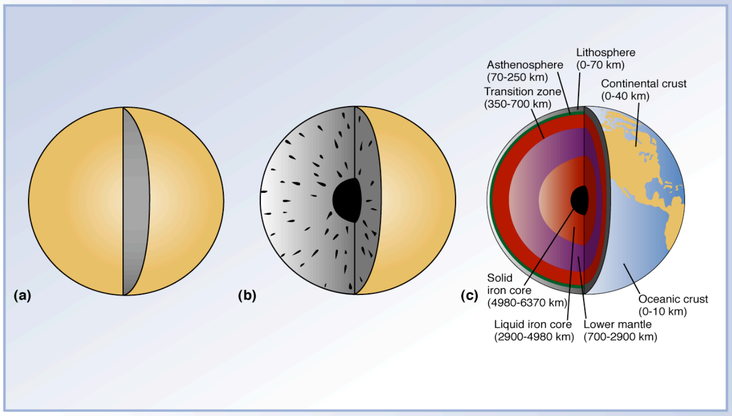


Comparison of solar and chondritic meteorite element abundances (silicon is set at 10^6). H, He, 0, C and N are not compared because they have largely been lost from meteorites, owing to their great volatility, but are shown on the solar abundance axis to demonstrate their preponderance in the Sun. The anomalous position of lithium (Li) is because it is produced as a spallation product(Data from Trimble 1975.)

Mass Balance

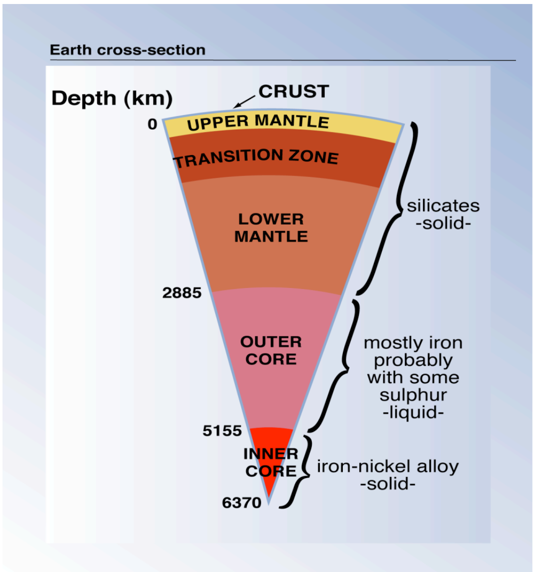
1) Total Earth= Core + BSE
2) BSE= Mantle + Crust

History of the Earth and Solar System



The early Earth **(a)** was probably a homogeneous mixture with no continents or oceans. In the process of differentiation, iron sank to the center and light material floated upward to form a crust **(b)**. As a result, the Earth is a zoned planet **(c)** with a dense iron core, a surficial crust of light rock, and, between them, a residual mantle. The upper mantle consists of two zones which are important in explaining many geologic phenomena: an outer solid, strong lithosphere underlain by a partially molten, weak asthenosphere.

Earth is Structured



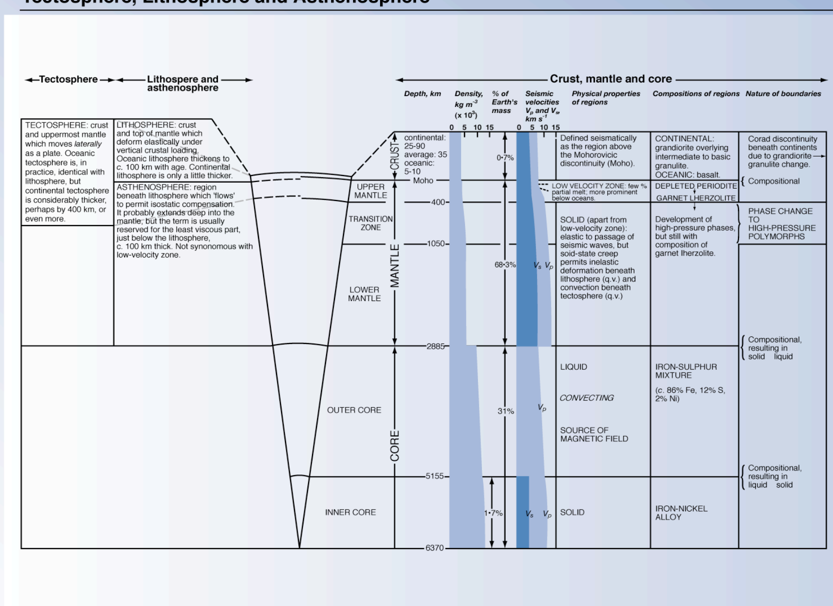
A) Metal Core and Silicate mantle and Crust

B) Deduced by:

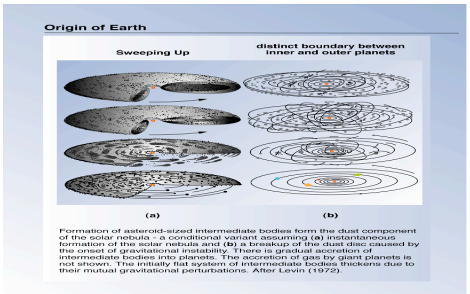
-Observation of crust and mantle derived rocks

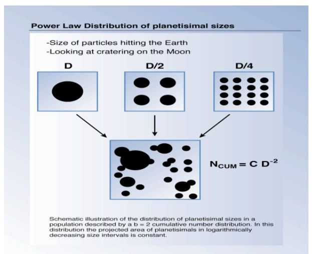
-Seismic structure (P and S waves)

-Knowledge of Earth mass deduced from its gravitational attraction and moment of inertia



How was this structuring created?





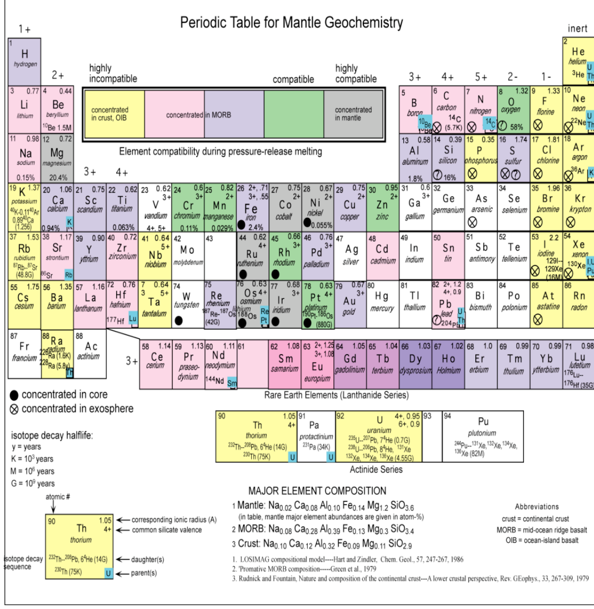
A) Primary feature of accretion or result of differentiation?

B) Two end-member models of planetary accretion and layering:

i. heterogeneous accretion (pre-accretion element segregation)

ii. homogeneous accretion (accreted uniformly and subsequently differentiated)

Primer on Element segregation



i. Element segregation occurs over many scales- condensation in the solar nebula, core formation, oceans (sandy beaches, carbonate reefs, shales…)

ii. Electronegativity (E) {Linus Pauling, 1959}; dimensionless number (E = 1-4) which describes the ability of an atom to gain an electron to become a negatively charged anion (highest for Halogens like F^- = 4.0, or O^{2-} = 3.5; and lowest for those elements which tend to lose electrons to form cations (see proceeding table)

Primer on Element segregation (contd)

Geochemical affinities and cation electronegativities

E< 1·6 Lithophilic			*1·6 < E < 2·0 Chalcophilic*		*2·0 < E < 2·4 Siderophilic*	
Cs^{+}	0·7		Zn^{2+}	1·6	As^{3+}	2·0
Rb^{+}	0·8		(U^{4+}	1·7)	(P^{5+}	2·1)
K^{+}	0·8		(W^{4+}	1·7)	Ru^{4+}	2·2
Ba^{2+}	0·9		(Si^{4+}	1·8)	Rh^{3+}	2·2
Na^{+}	0·9		(Ge^{4+}	1·8)	Pd^{2+}	2·2
Sr^{2+}	1·0		Fe^{2+}	1·8	Os^{4+}	2·2
Ca^{2+}	1·0		Co^{2+}	1·8	Ir^{4+}	2·2
Li^{+}	1·0		Ni^{2+}	1·8	Pt^{2+}	2·2
rare earths	1·0-1·2		Pb^{2+}	1·8	Au^{+}	2·4
Mg^{2+}	1·2		Mo^{4+}	1·8		
Sc^{3+}	1·3		Cu^{2+}	1·9		
Th^{4+}	1·3		Ag^{+}	1·9		
V^{3+}	1·4	Large or L.I.L.	Sn^{4+}	1·9		
Zr^{4+}	1·4		Hg^{3+}	1·9		
Mn^{2+}	1·5		Sb^{3+}	1·9		
Be^{2+}	1·5		Bi^{3+}	1·9		
Al^{3+}	1·5		Re^{3+}	1·9		
Ti^{4+}	1·5					
Cr^{3+}	1·6					

Bracketed elements are those that tend to be lithophilic because their small ionic size and large charge favors the formation of complex anions with oxygen - hence they are misclassified using simple element electronegativities. (After Pauling 1959.)

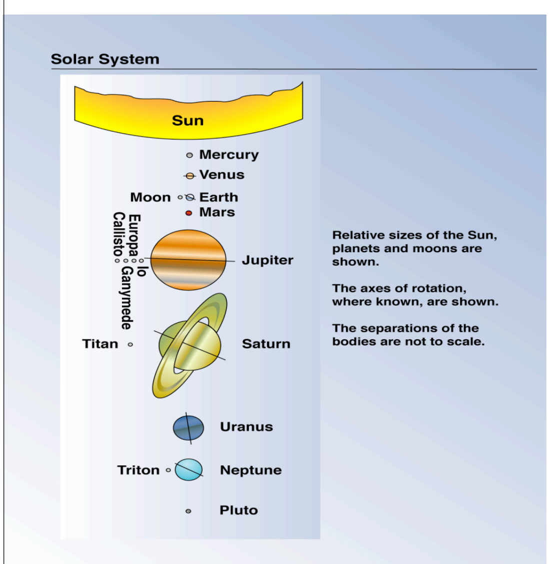
Three categories:

Lithophilic elements- tend to occur with oxygen in oxides; e.g. Rb, K, Ba, Mg etc.; E < 1.6 and have an affinity for ionic bonding in oxygen [Gr. lithos- stone]

Chalcophilic elements- tend to concentrate in sulfides; e.g. Cu, Pb, Zn, Sn, and Ag; 1.6 < E< 2.0; small differences in electronegativity between these elements and sulfur promote covalent bonding (electron sharing) [Gr. Khalkos, copper]

Siderophilic elements- tend to be metallic, e.g. Fe, Ni, As, Pt, Ir and Au; 2.0 < E < 2.4; metallic bonds [Gr. Sideros, iron]

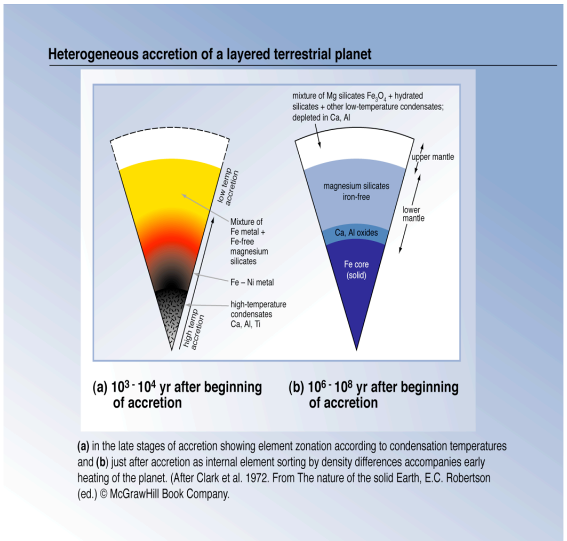
Pre-element segregation: heterogeneous accretion model



Inner terrestrial planets (M,V, E, M)/ outer major planets (J, S, U, N)

i. Outer planets less dense and much larger abundance of volatile elements (H, He, C and O)
ii. CAI: Ca, Al inclusions in C3 chondritic meterorite Allende- known to condense from high-T cloud

Pre-element segregation: heterogeneous accretion model



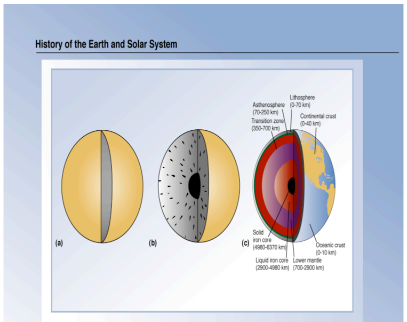
D) **Local temperature variations, so at any given distance from Sun, materials segregate progressively into solids in order of their condensation temperatures, resulting in the present layered planetary structures**

- Lower density outer planets: *silicate and Fe cores, followed by accretion of gaseous envelope*
- Rocky high density terrestrial planets:*high-T core rich in Ca and Al formed first, followed by metallic fe and then mantle silicates- forsorite, diopside, anorthite;* but it is then envisioned *that as the interior warms sufficiently for melting element segregation by density occurs* (untestable)

4Pre-element segregation: heterogeneous accretion model (contd)

Testable Prediction: Radial temperature gradients within the solar system are testable. With increasing distance from the sun-planets should contain larger portions of alkali feldspars, troilite… and Fe/Si should decrease (along with density)

5. Homogeneous planetary accretion with subsequent layering



The early Earth **(a)** was probably a homogeneous mixture with no continents or oceans. In the process of differentiation, iron sank to the center and light material floated upward to form a crust **(b)**. As a result, the Earth is a zoned planet **(c)** with a dense iron core, a surficial crust of light rock, and, between them, a residual mantle. The upper mantle consists of two zones which are important in explaining many geologic phenomena: an outer solid, strong lithosphere underlain by a partially molten, weak asthenosphere.

A) Accreting material condensed into grains (rocky planets @ < 100°C) prior to accretion

B) **Well Mixed**

C) C1 composition (for Chondritic Earth Model)

D) Subsequent reheating of the Earth

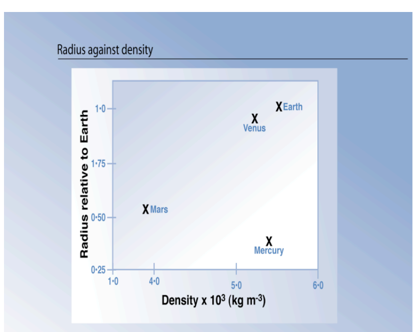
- **i. accretionary heating** (falling in of grains results in a loss of kinetic energy which increase with planet size)
- **ii. radioactive decay** of short lived isotopes (e.g. ^{244}Pu, ^{129}I, ^{26}Al)
- **iii. gravitational energy** with sinking material (see below)

E) Heating of condensed material leads to volatilization and loss of elements/compounds (e.g. H_2O, CO_2, SO_2, etc.) which are blown of into solar wind

F) Loss of oxygen rich compounds is accompanied by **chemical reduction** in remaining silicate material; this leads to an increase in the free metallic iron (with changing the Fe/Si ratio)

G) Density segregation with Fe sinking (core formation) and lighter silicate material floating and undergoing subsequent differentiation (crust formation) (Note constantly differentiating and remixing- mantle convection)

6. Synthesis- evidence for both heterogeneous and homogeneous accretion models



Plot of radius against density for the terrestrial planets, showing that density is an important function of size, hence internal compression, for Mars, Venus and the Earth.

xxix.

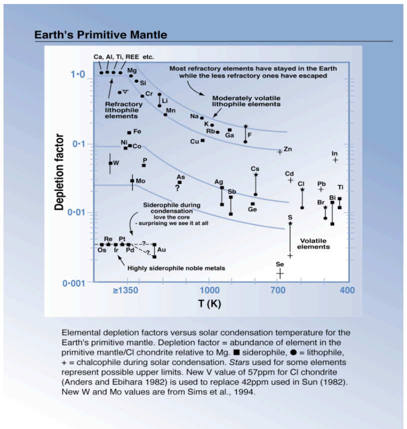
A) **Increase in mean density with size** for the planets Mars, Venus and Earth **(homogeneous accretion)**

i. Increasing state of thermal compression

ii. Volatile depletion

B) Mercury doesn't follow trend (heterogeneous accretion)

6. Synthesis- evidence for both heterogeneous and homogeneous accretion models



Elemental depletion factors versus solar condensation temperature for the Earth's primitive mantle. Depletion factor = abundance of element in the primitive mantle/CI chondrite relative to Mg. ■ siderophile, ● = lithophile, + = chalcophile during solar condensation. *Stars* used for some elements represent possible upper limits. New V value of 57ppm for CI chondrite (Anders and Ebihara 1982) is used to replace 42ppm used in Sun (1982). New W and Mo values are from Sims et al., 1994.

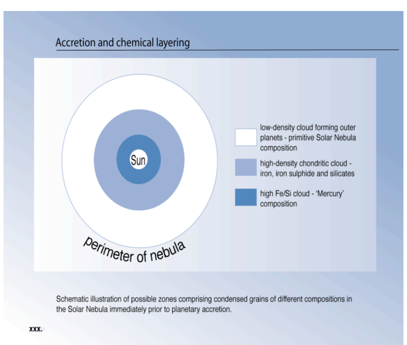
C) Earth compared to C1 composition (for Chondritic Earth Model) and it is speculated that Mars and the Moon also are "Chondritic" (Homogeneous accretion)

i.) volatile element depletion

ii.) siderophile element depletion

D) Variation between terrestrial inner planets compared to outer planets (heterogeneous accretion)

6. Synthesis- evidence for both heterogeneous and homogeneous accretion models



Schematic illustration of possible zones comprising condensed grains of different compositions in the Solar Nebula immediately prior to planetary accretion.

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- **Solar System Scale: Variation between terrestrial inner planets compared to outer planets (heterogeneous accretion)**
- **Local Scale: Heterogeneous Accretion**

Properties of terrestrial planetary accretion models

Features	*Heterogeneous accretion*	*Homogeneous accretion*
accretion temperatures	incandescent, above highest condensation temperatures and failing during accretion; incandescence due to heating during contraction of Solar Nebula under gravity	relatively cold, within the volatile condensation range of Table 5.1
cause of chemical difference between planets	selective condensation during nebular cooling: hence heterogeneous;. lower-temperature condensates are favored by greater distances from nebula center	volatilization during and after accretion due to planetary heating; accreting material for all planets is homogeneous; amount of volatilization increases with size of planet
reduction of iron to form core material	condenses directly as metal at temperatures greater than for silicates and sulphides of iron	reduction of silicates, etc., effected near the accreting planetary surface during initial heating and volatilization (Eqs 2.1 & 2.2)
timing of element segregation	pre-accretion followed by readjustments due to post-accretion melting and longer-term changes	post-accretion due to initial heating and melting followed by longer-term changes
cause of internal planetary heating	initially hot and cooling, but also reheated as in homogeneous model	release of kinetic energy during accretion, early short-lived radiogenic heat and long-term, long-lived radiogenic heat
planetary layering	selective condensation into a layered structure due to temperature gradient across the nebula and possible falling temperature during accretion	iron-rich core material becomes molten near the surface due to initial heating and sinks, leaving a solid silicate mantle
predicted chemical/density variations between planets, assuming chondritic starting materials	planets have progressively lower Fe/Si and refractory/volatile element ratios further away from the Sun; density therefore decreases in this direction	planets have similar total Fe/Si ratios but vary in volatiles and oxidation as a function of planetary size; small planets retain more volatiles, are more oxidized and have lower densities than larger ones

Both volatile loss and reduction processes (Eqs (2. 1) and (2.2)) become increasingly effective with growth of protoplanet size. Starting from the same material the most massive planets should have the least-oxidized compositions, having been most effectively heated by accretion. Because oxygen is one of the lightest elements in terrestrial planets, this model makes the specific prediction that the largest planets should have the highest densities and should contain the lowest concentrations of therelatively volitile alkali elements.

Chief properties for the Sun, the planets and the Moon

Property	*Sun*	Major planets *Jupiter*	*Saturn*	*Uranus*	*Neptune*	*Pluto*
distance from Sun (mean value) (units of 10^6km)	—	778	1427	2870	4497	5900
(Earth) = 1)	—	5•20	9•54	19•2	30•1	39•4
mass (Earth = 1)	343 000	318	95	14•6	17•2	c.0•002
mean density (water = 1)	1•4	1•3	0•7	1•2	1•7	<1•7
radius (km)	696 000	71 400	60 000	25 900	24 750	1900
year, i.e. period of revolution about axis Sun (Earth years	—	11•9	29•5	84•0	164	248
spin period, i.e. rotation about axis (days)	27	0•40	0•43	-0•89*	0•53	6•4
eccentricity of orbit	—	0•043	0•056	0•047	0•009	0•25
inclination of orbit, with respect to the Earth's (deg)	—	1•3	2•5	0•8	1•8	17•2
Inclination of axis, with respect to axis of Earth's orbit (deg)	7	3	27	82	29	?
number of moons known	—	14	10	5	2	1?
atmosphere, chief constituents	—	H_2, He	H_2, He	H_2, He, CH_4	H_2, He, CH_4	none?
magnetic field, dipole moment ‡ (Earth = 1)	3 x 10^6	1•9 x 10^{-4}	?	?	?	?

* Minus sign denotes rotation is retrograde, i.e. opposite to majority direction.
† That is orbit is in plane of Earth's equator.
‡ That is, strength of equivalent bar magnet (but some planetary fields are poorly represented by a dipole).