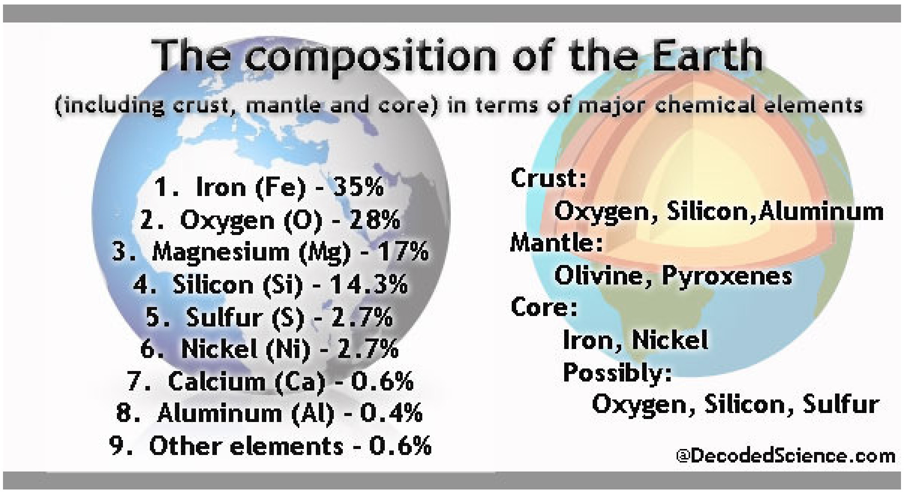
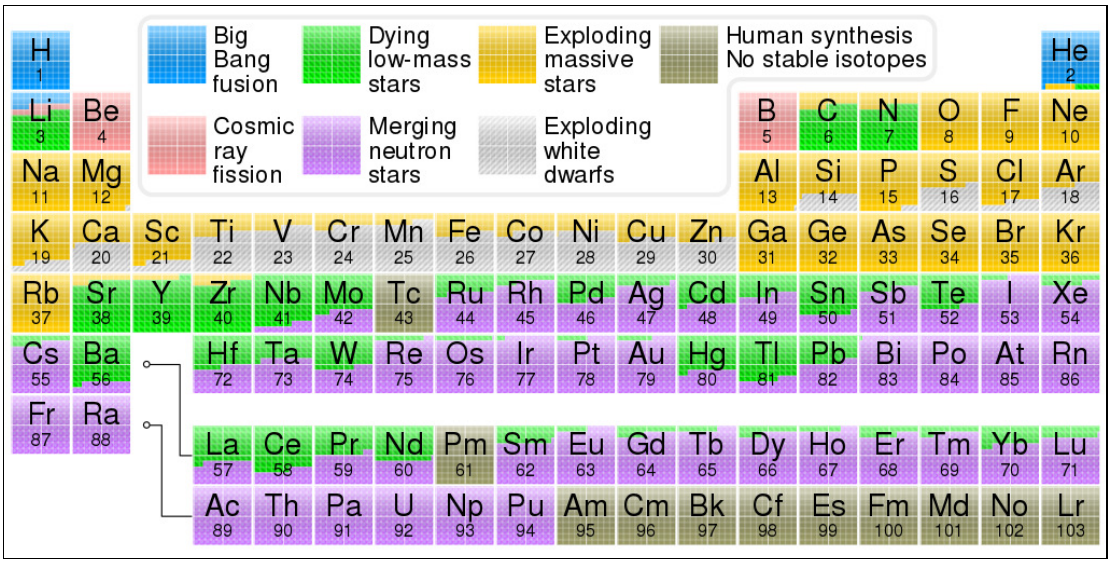
Notes for Discussion : Where do all the Elements come from?

In the beginning there was just Hydrogen. Then came Helium and Lithium followed by the rest of the elements. So, how did we get from the beginning to the earth?

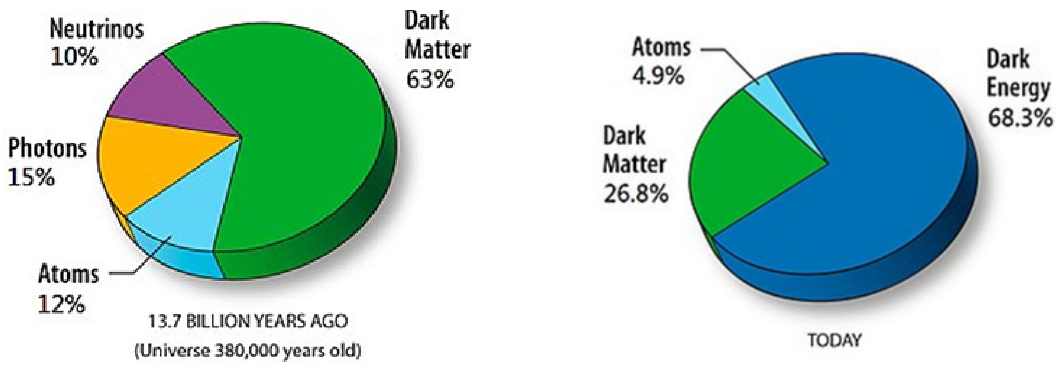


Below is the periodic table of elements illustrating the current theory of element sources.



Periodic table showing origin of elements in the Solar System, by CMG Lee based on http://www.astronomy.ohio-state.edu/~jaj/nucleo/by Jennifer Johnson.

Of course, it all started with the birth of the Universe some 13.8 billion years ago. Along the way we have had the Big Bang, Inflation, Nucleosynthesis and then the universe becoming transparent at the CMB (cosmic microwave background). We have also hypothesised Dark Matter and Dark Energy to try and explain what we see and measure today.



In the beginning

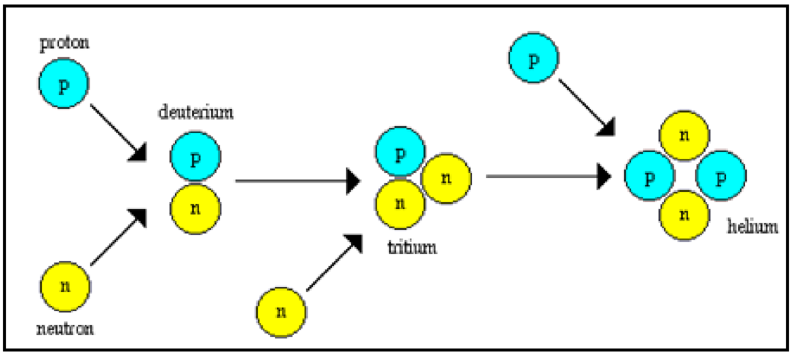
When the Universe was very young all that existed was an extremely hot and dense “soup” of fundamental particles and forces, ie quarks (the constituents of neutrons and protons), leptons (electrons and neutrinos) and bosons (photons, gluons, z and w forces).

When the density and temperature had cooled enough to allow the quarks to stick together neutron and protons were formed. The so called *Hadron Transition*.

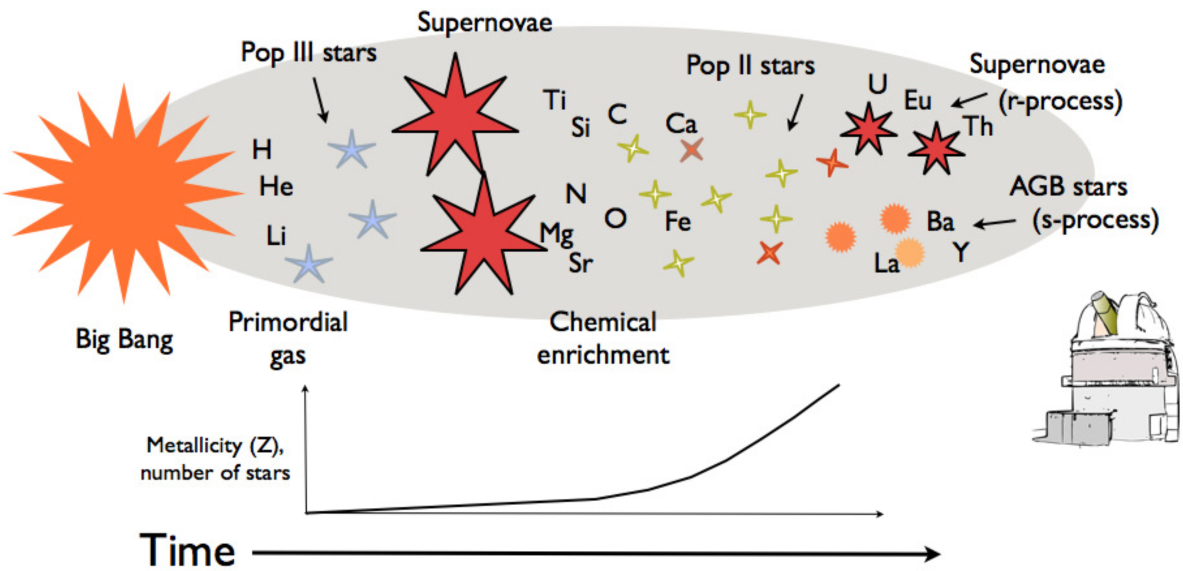
The first element, **Hydrogen** a proton consisting of 3 quarks, was now formed. At the same time neutrons, also 3 quarks, were formed. However, free neutrons decay to protons, half life approx 10 mins.

When, with continuing expansion, the temperature of the universe had dropped to less than 4.4 x 10^{12} K (ie 4,400,000,000,000 degrees), the formation of protons and neutrons stopped.

As expansion continued some 3 minutes later the density and temperature had again dropped allowing **Protons** and **Neutrons** to stick together. Then Helium and Lithium could be synthesised by fusion.



Since the CMB



Observational nuclear astrophysics: neutron-capture element abundances in old, metal-poor stars - Jacobson, Heather R. *et al.* J.Phys. G41 (2014) 044001 arXiv:1309.0037 [astro-ph.GA

Condensation of the early chemical soup of H/He/Li would have formed proto-stars. As gravitational forces continue to act the proto-star would contract and the central temperature would increase.

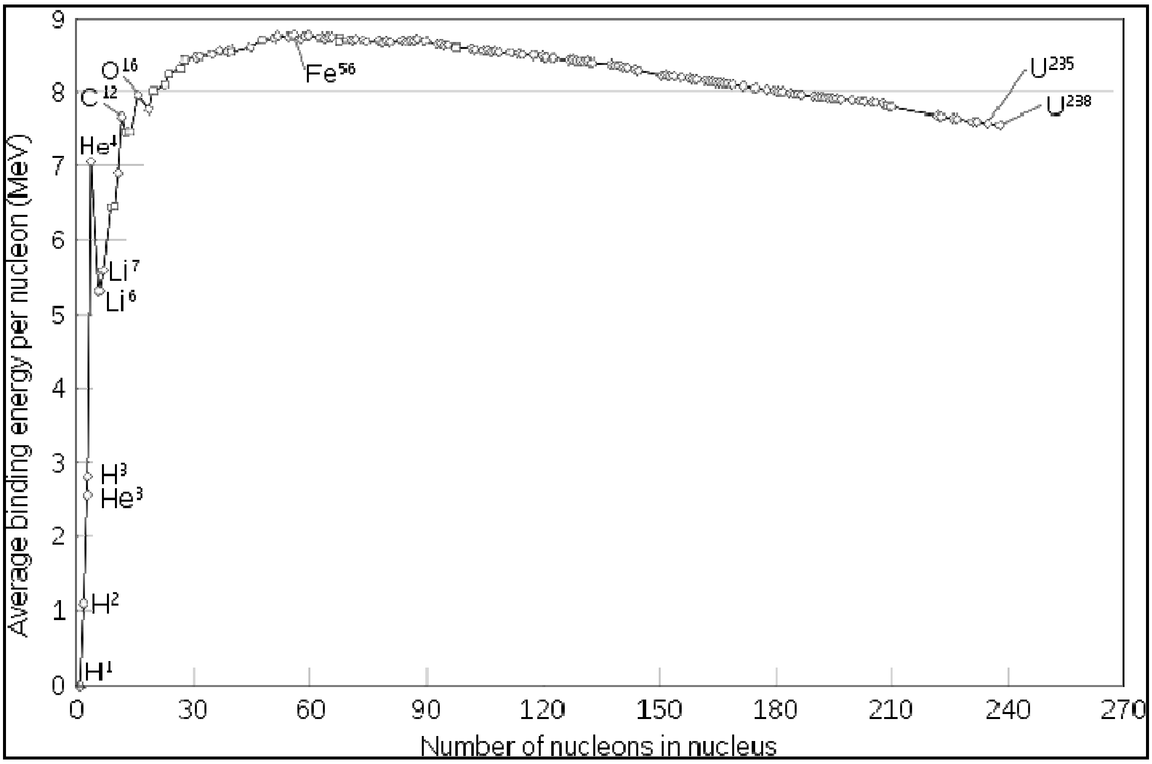
When the temperature is high enough H will start to fuse into He and further contraction will be difficult.

These first stars would have been massive, estimated to be 20 to 130 or even 1000 solar masses. This process then continues as the star consumes the H fuel producing He. As the mass of the products is less than the mass of the reactants large amounts of energy are produced. This is the process that is triggered in a Hydrogen Bomb.

Energy released is calculated from the equation : $\mathbf{e = mc^2}$

At different stages of the stars life these processes will continue to produce heavier elements. This can continue up to Nickel, which then quickly decays back to Iron.

The nuclear binding energy curve.



The formation of nuclei with masses up to Iron-56 releases energy, while forming those that are heavier requires energy input. This is because the nuclei below Iron-56 have high binding energies, while the heavier ones have lower binding energies, as illustrated above.

Beyond Iron

To make elements that are heavier than iron we have to look to star explosions.

When the star explodes the heavier elements are then distributed into the molecular clouds which will form the next generation of stars and planets. Supernova are the major source of elements that are heavier than Nitrogen.

The elements above iron are produced by neutron capture. It is estimated that rapid neutron captutre, the r-process, produces half of the elements beyond iron including plutonium and uranium.

Finally we have kilonova which result from neutron star collisions, or neutron star-black hole collisions, such as the one detected in October 2017 by the LIGO-VIRGO gravitational wave detectors. At the press conference announcing the find one speaker estimated that the amount of gold, platinum and other heavy elements was 16,000 times the mass of the earth.

References:-

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Cooking up the first light elements	http://www.einstein-online.info/en/spotlights/BBN/index.html
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Stellar nucleosynthesis	https://en.wikipedia.org/wiki/Stellar_nucleosynthesis
Stellar Population	https://en.wikipedia.org/wiki/Stellar_population
Chemical comp of stars & universe	http://spiff.rit.edu/classes/phys240/lectures/elements/elements.html
Supernova	https://en.wikipedia.org/wiki/Supernova
Kilonova	https://en.wikipedia.org/wiki/Kilonova
Nuclear binding energy	https://en.wikipedia.org/wiki/Nuclear_binding_energy
Rapid neutron capture	https://en.wikipedia.org/wiki/R-process

Note: These are my thoughts and notes. If there are mistakes or you disagree please let me know.