In the Beginning

Obviously, before we can have any geochemistry we need some elements to react with one another. The most commonly held scientific view for the origin of the universe is the "Big Bang" theory. This theory holds that the universe started out as an infinitely small object of infinitely high density and temperature. This object exploded and within the first few seconds matter (in the form of protons, neutrons and electrons) was formed. The protons and neutrons are actually made up of even smaller entities, but these needn't concern us here.

![Diagram of basic constituents of atoms]

Figure 1: The basic constituents of atoms

After about three minutes the temperature had cooled even further, so that neutrons were able to combine with $^1\text{H}$ to form $^2\text{H}$;

$$^1\text{H} + n \rightarrow ^2\text{H}$$
Shortly after this, temperatures cooled further in the expanding cloud, so that other reactions were able to take place:

\[ ^2H + n \rightarrow ^3H \]

However, \(^3H\) is not stable, so it undergoes radioactive decay to form an isotope of helium:

\[ ^3H \rightarrow ^3He + e^- \]

In this case, a neutron in the hydrogen nucleus is transformed into a proton and an electron is expelled from the nucleus.

\[ ^2H + ^1H \rightarrow ^3He + e^- \]
So what we are seeing is the addition of either a proton or a neutron to the nucleus of an atom to form a new atom with a higher mass. During all of these reactions gamma radiation is released and we can still see this gamma radiation as a background in the universe. However, we cannot easily make heavier atoms by this process as the next isotopes in the chain, $^5$He and $^5$Li, are very unstable and undergo radioactive decay before they can collide with another particle. So the Big Bang created a universe made up almost entirely of hydrogen and helium.

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**The Universe starts to pull itself together: Gravitational Instability**
After about 700,000 years the expanding cloud of gas had now expanded sufficiently that the temperature had fallen to 3000K and electrons were now bound to all the nuclei to form neutral gas atoms.

This cloud of atoms continued to expand for the next 500x10^6 years, during which time inhomogeneities started to form in the distribution of atoms. Gravitational attraction between these more closely grouped atoms led to their growth into dense patches. These denser areas developed larger gravitational fields that further fueled their growth.

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**Things get heavier: Nuclear Fusion**

Once this gravitational collapse proceeded to the point that the density in some regions reached 6g/cm^3 the temperature in these areas increased to 10-20x10^6K due to the increased number of atomic collisions and the release of gravitational energy. At this point the temperature was high enough for the initiation of hydrogen burning:

\[
\begin{align*}
^1H + ^1H & \rightarrow ^2H \\
^2H + ^1H & \rightarrow ^3He \\
^3He + ^3He & \rightarrow ^4He + 2^1H
\end{align*}
\]

This hydrogen burning is a form of nuclear fusion and is occurring in our sun at this time. Once the
hydrogen is exhausted in the core of a star (which will take about another $5 \times 10^9$ years in the case of the sun), the interior of the star collapses and the release of gravitational energy causes an increase in the star's temperature. The star expands to become a red giant (during this phase our sun will swell to the point that it reaches out to the present position of the earth) and if it is big enough for the core density to reach $10^4$ g/cm$^3$ and the temperature to reach $200 \times 10^6$ K, then He burning (otherwise known as He fusion) can occur.

$$^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be}$$

$$^4\text{He} + ^8\text{Be} \rightarrow ^{12}\text{C}$$

However, there is a problem here as $^8\text{Be}$ is very unstable and only has a half life of $10^{-16}$ seconds. So, if He fusion is to form $^{12}\text{C}$ then essentially three $^4\text{He}$ atoms have to collide simultaneously. This requires very high pressures as three body collisions are rare if the He atoms are widely dispersed. If you want to prove this to yourself, see how often three pool balls collide simultaneously once the balls have been spread around the table.

If the star is small, then after this step it will collapse to form a white dwarf, essentially the burnt out ember of nuclear synthesis.

However, if the star is big enough then fusion can continue in the form of carbon burning to form heavier atoms;
\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + ^{4}\text{He} \]
\[ ^{12}\text{C} + ^{4}\text{He} \rightarrow ^{16}\text{O} \]
\[ ^{12}\text{C} + ^{16}\text{O} \rightarrow ^{24}\text{Mg} + ^{4}\text{He} \]
\[ ^{16}\text{O} + ^{16}\text{O} \rightarrow ^{28}\text{Si} + ^{4}\text{He} \]

These reactions take place at temperatures of around \(800 \times 10^6\) K. If the star is sufficiently small and oxygen poor it will then collapse to form a blue giant.

If the star is massive enough it will move on to the next fusion stages of neon, silicon, and oxygen burning at temperatures of up to \(3000 \times 10^6\) K. This results in the formation of \(^{32}\text{S}, ^{36}\text{Ar}, ^{40}\text{Ca}, ^{44}\text{Ca}, ^{48}\text{Ti}, ^{52}\text{Cr},\) and \(^{56}\text{Fe},\) as well as lesser amounts of other isotopes, such as \(^{23}\text{Na}.\)

![Figure 7: The limits of fusion](image)

At this point the fusion stops producing heavier isotopes. The reason is that up to a mass of \(^{56}\text{Fe}\) fusion produces energy, but fusion to form isotopes with heavier masses requires an input of energy.
The star now resemble a giant onion, consisting of a series of layers of successively heavier nuclei and a core of iron. The temperature is greatest at the centre of the star, but the layers remain unmixed because each shell is denser than the one outside it.

**Adding to the mixture: The s-process**

One of the byproducts of the various stages of fusion is neutrons. These neutrons are captured by the nuclei of elements within the stars. Because the neutrons are released relatively slowly at this time, hence these reactions are known as the slow- or s-process. We can see how this process works by considering a starting point at $^{56}\text{Fe}$.

If we add a neutron to $^{56}\text{Fe}$ its mass increases by one to form $^{57}\text{Fe}$

$$^{56}\text{Fe} + n =^{57}\text{Fe}$$

Adding another neutron produces $^{58}\text{Fe}$

$$^{57}\text{Fe} + n =^{58}\text{Fe}$$

And on to $^{59}\text{Fe}$

$$^{58}\text{Fe} + n =^{59}\text{Fe}$$
However, $^{59}\text{Fe}$ is unstable and undergoes radioactive decay with a half life of 44.5 days. During this process a neutron within the nucleus will be converted to a proton and an electron will be ejected from the nucleus. As the number of protons in the nucleus has changed we now have a new element, in this case cobalt, but the mass number doesn't change. The radioactive decay can be written as:

$$^{59}\text{Fe} \rightarrow ^{59}\text{Co} + \text{e}^-$$

$^{59}\text{Co}$ is stable and if we add another neutron we form $^{60}\text{Co}$. Again, this isotope is unstable, so it undergoes radioactive decay.

$$^{60}\text{Co} \rightarrow ^{60}\text{Ni} + \text{e}^-$$

And so it goes on, with neutrons being successively added to the nuclei of atoms until they reach an unstable isotope. This then undergoes radioactive decay and a new element is formed.

**Supernovae: The r- and p-processes**

Once the core of a star has largely been converted to iron it is set for a spectacular end to its existence. The stellar core collapses from a diameter roughly equal to that of the earth to a diameter of only 100 km and has a density of $3 \times 10^{14} \text{g/cm}^3$. This collapse occurs in less than a second and sends out a massive shock wave which causes the star to explode.

During this explosion, which may be readily visible in the night sky for several weeks, massive amounts of neutrons are generated in a period of less than two minutes. This means that neutrons are added to unstable nuclei before they have a chance to decay. Hence, there is a large build up of radioactive isotopes that undergo decay after the flux of neutrons ceases. Some of these isotopes have very long half-lives and are still decaying today, where they form the basis of modern dating.
methods. This rapid release of neutrons gives its name to the r-process, which can be summarized thus;

As you should be able to see, the r-process tends to form the heaviest (neutron-rich) isotopes of an element.

The other process that occurs during supernovae is proton capture, the p-process. This process is responsible for formation of the lightest isotopes of an element, but is much less common than the r-process, as capture of a proton requires much higher energies to overcome the repulsion between the positively charged proton and the positively charged nucleus. Overall, the various processes combine to form the variety of elements.
The end result: The abundance of elements in the solar system

The various nucleosynthesis mechanisms outlined above result in the following distribution of elements in our solar system.
There are a number of things that you should take away from this diagram.

1. I mentioned earlier that our sun is only big enough to get as far as hydrogen fusion, so where do the other elements come from? The answer is that our solar system contains the products of many previous episodes of stellar nucleosynthesis and supernovae from elsewhere in our galaxy.

2. Hydrogen and helium are several orders of magnitude more abundant than all the other elements in the solar system. Overall, they account for more than 98% of the matter in the solar system.

3. There is a general decrease in abundance with increasing atomic number.

4. Elements with even atomic numbers are generally an order of magnitude more abundant than the elements either side of them. This reflects the greater stability of nuclei with this nuclear configuration.

5. Elements with masses up to iron that contain isotopes that are the products of fusion are the most abundant in the solar system (after hydrogen and helium).

6. Lithium, beryllium and boron have much lower abundances than the other light elements. This reflects their unusual origins, that were not discussed above. Basically, they are largely formed by the interaction of cosmic rays with other nuclei. This process (spallation) is far less efficient than the other nucleosynthetic pathways mentioned earlier.

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**What you should be able to understand at the end of this module**
1. You should be understand the basics of the four major nucleosynthetic pathways; fusion, s-process, r-process, p-process.
2. You should be able to look at a portion of the chart of the nuclides and work out which nucleosynthetic process was responsible for which isotope.
3. You should understand the basic reasons for why we observe the solar system abundance of the elements.

To test your understanding of this part of the course, please go to Module 1 test.

Additional reading for this course can be found in Chapter 10 of Gill.

These WWW pages were created by Martin Palmer