The role of supernovae in the origins of life

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This [Figure 1] is the Crab Nebula, the remnant of a supernova explosion that was observed in 1074 by Chinese astronomers. It is 6500 light years away from Earth. While being far away from the Earth, supernovae explosions are an essential part of the formation of life. This is because they have played a part in the formation and distribution of virtually every element that exists in the universe. Only hydrogen, some helium, and some lithium, formed 13.7 billion years ago in the Big Bang, were created independently of supernovae. So what are supernovae and how do they form large elements? The full answer is very complicated, but the simple one is through nuclear fusion.

Figure 1: Crab Nebula [Available from http://en.wikipedia.org/wiki/File:Crab_Nebula.jpg]

Nuclear Fusion

The sun is the closest star to Earth. All stars are driven through the process of nuclear fusion, a process by which atoms fuse together to produce new elements. An atom is mostly empty space; in the centre is the nucleus, which occupies a tiny proportion of the atom's space yet constitutes 99.9% of its mass. Electrons occupy specific energy levels around the nucleus and determine the chemical properties of an element. However nuclear fusion, as its name suggests, is a nuclear, not chemical, reaction. The nucleus is composed of two different subatomic particles, the proton and the neutron. The number of protons in the nucleus of an atom is what defines what element the atom is. In nuclear fusion, the protons and neutrons of two different nuclei combine to form a single nucleus.[1]

Fusion, however, is not quite so simple, for while neutrons are electrically neutral, protons have a relative charge of +1. Electrostatic repulsion between protons is a barrier called the coulomb barrier, which protons must overcome in order to fuse. This is achieved by the strong nuclear force. The strong nuclear force is 1032 times stronger than gravity, while electromagnetism is only 1018 times stronger. However, we rarely feel the strength of the strong force, because it only acts over a distance of $1\text{-}1.5 \times 10^{-15}$ m. If two particles come close enough together, the strong force will influence the particles and the electromagnetic Coulomb barrier is broken. But for this to take place, the particles require very high energies, in order to achieve the requisite velocity to come so close together.[2]

Fusion in Stars

In stars, there are two main different 'cycles' of nuclear fusion. These are called the proton-proton chain reaction (PP) and the Carbon-Nitrogen-Oxygen Cycle (CNO Cycle).[3] The PP chain is the reaction by which stars up to 1.3 times the mass of the sun fuse; its net results are the fusion of four protons to one alpha particle (a helium nucleus). Supernovae explosions can only result from stars that use the CNO Cycle[4] of fusion. The CNO cycle can only take place at temperatures of at least 13 $\times$ 10^6 K, hence its prominence in larger stars. In the CNO Cycle, four protons fuse, using carbon, nitrogen, and oxygen isotopes as a catalyst (the nuclei give fusion a platform on which to fuse and so lower the Coulomb barrier), to form an alpha particle, two positrons, and two electron neutrinos. The formation of another element by nuclear fusion is called nuclear synthesis.[5] Positrons are a form of antimatter (they are electrons with a positive charge), and so further energy is produced in the form of gamma rays when the positrons annihilate with electrons in the vicinity. The isotopes of carbon, nitrogen, and oxygen are essentially one single nucleus that is constantly recycled through the process. The nuclei either originate from the cosmic dust that the star formed from or a very small amount of fusing helium in a star's core. The cycle is shown in Figure 2; the equations for the stages are:

$612C+11H \rightarrow 713N+\gamma+1.95$ MeV
$713N \rightarrow 613C+e++\upsilon e+2.22$ MeV
$613C+11H \rightarrow 714N+\gamma+7.54$ MeV
$714N+815O \rightarrow 713N+\gamma+7.35$ MeV
$715N+11H \rightarrow 612N+24He+4.96$ MeV
$815O \rightarrow 715N+e++\upsilon e+2.75$ MeV

The energy produced by the cycle's fusion heats the star allowing fusion to carry on occurring until the star uses all of its hydrogen fuel. When a star has this equilibrium, it is said to be a 'main sequence star'. All stars eventually reach the stage at which their hydrogen fuel runs out and their main sequence ends. Practically all stars have a brief stage at the end of their lives during which the helium that has been produced by hydrogen fusion begins to fuse, because the force of gravity (which is now larger than the radiation pressure) induces such immense pressures on the helium nuclei that three can fuse, by a process called triple alpha burning, into a carbon nucleus, or sometimes an oxygen nucleus. The increased fusion in the star's core causes an expansion into an Asymptotic Giant Branch star, virtually always a red giant.

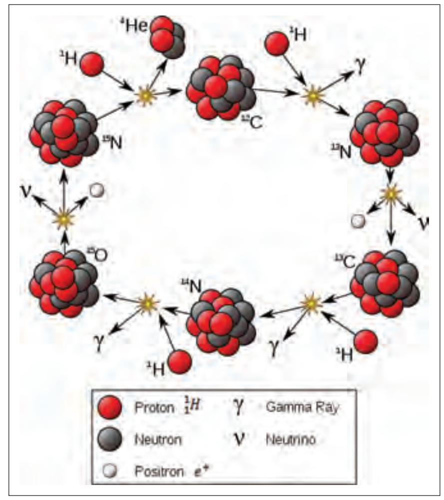

Figure 2: CNO Cycle [available from http://en.wikipedia.org/wiki/File: CNO_Cycle.svg]

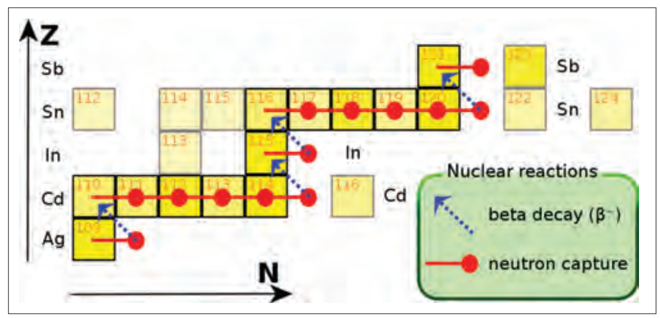

Figure 3: S-process [available from http://en.wikipedia.org/wiki/File: S-process-elem-Ag-to-Sb.svg]

Red giants play a role in producing new elements. During their lives a slow neutron capture system called the S-process [Figure 3] increases the mass of the helium and carbon nuclei in the star until about half of the elements heavier than iron are produced; the other half are formed in the supernova itself by the R-process[6] (see end of section on supernovae). The nuclei of atoms can capture neutrons, increasing their mass whilst doing so. Neutrons in neutron-heavy nuclei undergo beta-minus decay, in which, through the weak force, a neutron decays into a proton, electron and an anti-neutrino. The S-process is the combination of these processes over thousands of years to form new elements. Normally the heavy elements are only formed in stars large enough to go supernova; they are only released into space during the actual explosion.

Supernovae

There are two types of supernova; type I and type II.[7]

Ninety seven percent of all stars in the universe will collapse to form white dwarf stars at the end of their lives; most of the other 3% form type II supernova explosions.[8] As has been shown, a star's helium will typically fuse to form carbon at the end of its life, and then collapse into a white dwarf. Whereas, if a star has a mass more than nine times than that of our sun, then when the star collapses after the helium fusion, the force of gravity is so immense that the pressures produced are high enough for the carbon produced by helium fusion to also fuse. Because of the reignited fusion, the radiation pressure is once again high enough to make the star expand, and so the cycle of expansion-contraction is repeated [Figure 4]. The main products of the carbon fusion are neon, sodium, and magnesium. When the gravitational contraction occurs the neon nuclei begin to fuse, so that the cycle is repeated until a nickel ion is formed.[9] The cycle goes through this order [Figure 5], in which the element with an arrow coming from it is fusing.

The specific nickel nucleus produced is that of a nickel-56 ion. The most important thing that now occurs in relation to the supernova explosion is that the nickel nucleus undergoes several beta decays to produce an iron-56 nucleus. Iron has the highest binding per nucleon of any element. The binding energy of an element is the energy required to break the nucleus's components apart. Because of this, any fusion afterward is endothermic, not exothermic (i.e. takes in energy instead of giving it out). Therefore, an iron and nickel core accumulates in the centre of the star, with the other fusion products surrounding it in layers, so that the shown structure evolves. All of the elements lighter than nickel that exist in the universe, other than hydrogen, some helium and some lithium, were produced by this initial process.

So how do the elements heavier than iron and nickel get formed? As further fusion is impossible, the answer is in the actual supernova explosion itself. The core at the center of the star is under immense pressure from gravity, and because no

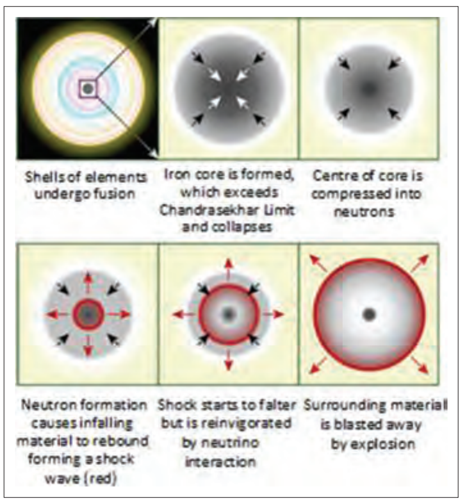

Figure 4: Core collapse [available from http://en.wikipedia.org/wiki/File: Core_collapse_scenario.png, edited by Ben Maybee]

H →	He →	C →	Ne →	O →	Si →	Ni
		O	Na	Mg	S	
			Mg		Ar	
			Al		Ca	

Figure 5: Order through elements - Ben Maybee

Figure 6: Galaxy NGC 4526 [available from http://hubblesite.org/gallery/album/pr1999019i/]

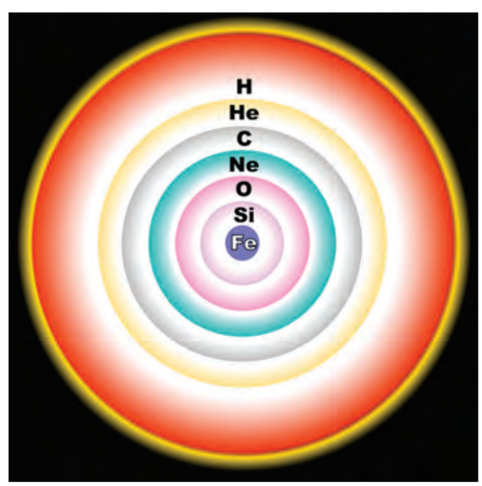

Figure 7: Star layers [available from http://en.wikipedia.org/wiki/File: Evolved_star_fusion_shells.svg]

fusion is occurring, the star is only supported by the degeneracy pressure of electrons in the core's atoms. By quantum mechanics, electrons occupy energy levels, or shells, around their central nucleus, and there are a finite number of spaces in each shell. Pauli's Exclusion Principle prevents two electrons from occupying the same space in a shell. It is this quantum exclusion that is the degeneracy pressure. However, if the iron core accumulates to more than 1.44 solar masses, a point called the Chandrasekhar Limit, the degeneracy pressure is no longer enough to repel gravity and the core collapses. The electrons and protons of atoms, if given enough energy, can combine to form neutrons, in the process releasing neutrinos as well. This is what the collapse causes, and the energy involved is so high that the outer layers of the core travel at 70000 kms^{-1}, almost a quarter of the speed of light. Because neutrinos rarely interact with matter they escape from the collapse, and in doing so, remove energy and further accelerate the collapse.

Eventually, contraction is halted by neutron interactions, mediated by the strong force. Because of the incredibly large gravitational energy that was held by the collapsing material, the collapsing matter rebounds, producing a huge shock wave that travels through the star. The newly produced neutron core has a temperature of about one hundred billion Kelvin at this point. Much of the excess thermal energy is lost by the release of more neutrinos, resulting in a ten second neutrino burst. These neutrinos carry a massive 10^{46} Joules of energy, but 10^{44} J is reabsorbed by the stalled shock wave, producing a massive explosion. This reinvigoration of the shock by interaction with the neutrino burst blasts away the layers that surrounded the core, leaving behind a neutron star, or if the star was more than 20 times larger than the sun, a black hole. The supernovae release so much energy and radiation that they can appear brighter than whole galaxies. Figure 6, taken from the Hubble Space Telescope demonstrates this; the bright dot in the left corner is one single supernova, 1994D in Galaxy NGC 4526.

During the explosion, about half of all of the other elements heavier than nickel are formed, by a process called the R-process. The R-process is caused by the massive amount of neutrons that exist in a supernova after the core collapses. Because of this, in the explosion, there is an incredibly high 'neutron flux', or the amount of neutrons that pass through an area per second increases; in this case, it is about 1×10^{22} per cm^2 per second. This high neutron flux is combined with a very high temperature. The R-process is dependent on exactly the same processes as the S-process, neutron capture and beta decay. However, due to the high temperature and neutron flux in a supernova, the R-process is much, much quicker and the rate of neutron capture is higher than the rate of beta decay. Because of this, nuclei produced before the explosion rapidly capture neutrons until they reach something called the neutron drip line. At this point, the nuclei are so neutron-heavy they must undergo beta decay before more neutrons can be captured. Both the atomic number and atomic mass of the nuclei increase very rapidly, as protons are being formed by alpha decay and the neutrons are then captured. This process forms very high-mass radioactive elements; the maximum possible mass is thought to be about 270 nucleons. Most of the high-mass elements then decay into heavy, but stable, neutron-rich nuclei. This process all happens very rapidly during the explosion, which blasts the nuclei into interstellar space along with those formed by the S-process in the original red dwarf.

Why are Supernovae Important for Life?

It is at this point that we should now consider the initial title: Why are supernovae important to life? The simple answer is that other than hydrogen, some helium, and some lithium (which were formed in the Big Bang); every element in the universe was produced by a star at the end of its life and expelled into space by a supernova explosion. Supernovae are thought to be solely responsible for the formation of half of all the elements heavier than iron, and also the formation of virtually every element in the mass range between helium and iron. Through all of this nucleosynthesis, supernovae are what produce the elements that not only are fundamental for all known life forms, such as carbon, oxygen, and nitrogen, but also the elements that form the planets on which life evolves and develops. Supernovae are responsible for the dispersion of heavy elements, produced by both the R and S-processes, all around the universe. Without the formation of an iron and nickel core [Figure 7] at the very end of a massive star's life, the core of our own planet could not possibly have formed. Without this core, our planet [Figure 8] would never have been able to form from the dust cloud that existed in the early years of our solar system. In fact, without the nucleosynthesis inside supernovae, explosions and the conditions that existed just before, as well as the dispersion of the heavy elements produced by red

Figure 8: The Earth [available from http://en.wikipedia.org/wiki/File:The_Earth_seen_from_Apollo_17.jpg]

giants, none of the planets, asteroids, comets, and heavy mass objects that we observe in the universe would exist. The universe would be completely lifeless, containing just stars and giant clouds of gas. Then, in short, as the old saying goes: "*We are all made of stardust*".

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About the Author

Ben Maybee is a 15 year old student at Haybridge High School and Sixth Form, Worcestershire, UK. He finds physics beyond the standard curriculum really fascinating because of the challenging ideas and way of understanding the universe that it presents us, and he thus has a particular interest in quantum and particle physics. Nuclear fusion and how it operates in stars is another area that intrigues Ben, because it incorporates many different fields of physics and it is the fundamental process by which most of the universe was built.