How Stars Make Energy and New Elements

Introduction:

Hydrogen and Helium were practically the only elements created in the Big Bang. All other atoms in your body, on Earth and in space - were created by stars by a process called *Nucleosynthesis* (this means "putting together an atomic nucleus"). Virtually every atom other than Hydrogen or Helium was created inside of a star. The way stars produce bigger atoms also creates a lot of energy. To learn about this, first we have to learn a bit about the nucleus of an atom.

The Atom, its Nucleus, and Protons and Neutrons.

At the center of every atom is a nucleus which contains Protons and Neutrons. The number of Protons determines what element it is (e.g. Hydrogen atoms have one Proton, Helium atoms have two Protons – the number of Protons equals the *Atomic Number* of the element). The number of Neutrons determines the isotope (variety) of the element; it affects how stable an atom is (i.e. how long until it falls apart). Generally, stable atoms have at least as many Neutrons as Protons in their nucleus. In other words atoms can have different numbers of Neutrons and still be the same type of element as long as the number of Protons is the same. For example: Hydrogen always has one Proton – it can have zero, one or two Neutrons.

To distinguish different varieties of Hydrogen (i.e. *isotopes*), we use little numbers like this: ^{1}H (this means Hydrogen-1, an atom with only one particle in its nucleus, which must be a Proton – since Hydrogen always has one Proton). We will, also, encounter this isotope: ^{2}H, (Hydrogen-2, with two particles in the nucleus: one Proton and one Neutron – this is sometimes called *Deuterium*)

Other common atoms we will see are ^{3}He and ^{4}He – which are Helium-3 and Helium-4, both with two Protons and with one and two Neutrons respectively (why?) Also we will encounter:

^{12}C (Carbon-12) an atom with 6 Protons and 6 Neutrons
^{13}C (Carbon-13) an atom with 6 Protons and 7Neutrons
^{13}N (Nitrogen-13) an atom with 7 Protons and 6 Neutrons
^{14}N (Nitrogen-14) an atom with 7 Protons and 7 Neutrons
^{15}N (Nitrogen-15) an atom with 7 Protons and 8 Neutrons
^{15}O (Oxygen-15) an atom with 8 Protons and 7 Neutrons

We will use these symbols as a shorthand to indicate how many Protons and Neutrons are found in a atom's nucleus. Remember the little number up and to the left equals the total of Protons and Neutrons in the nucleus. The number of Protons is determined by the type of element. Now that we understand what makes up the nucleus of an atom, we are ready to learn how Stars convert one type of atom into another and produce energy in the process.

Stars and E=mc^2

Everyone has seen the equation: E=mc^2, but what does it mean? It means that matter (**m**) can be converted into energy (**E**) and the conversion factor is the speed of light squared (**c^2**). A tiny bit of matter can be converted into a huge amount of energy. This is why nuclear bombs and nuclear reactors are so powerful – and dangerous. For instance, the amount of energy produced from the conversion of 10 grams of matter (about a penny) would equal that produced by burning 150,000 barrels of oil!

Inside stars, Hydrogen is converted into Helium, through nuclear fusion – and some matter is turned into energy in the process. Four Hydrogen nuclei are fused together to form one Helium nucleus. The question is: "How does this produce energy?"

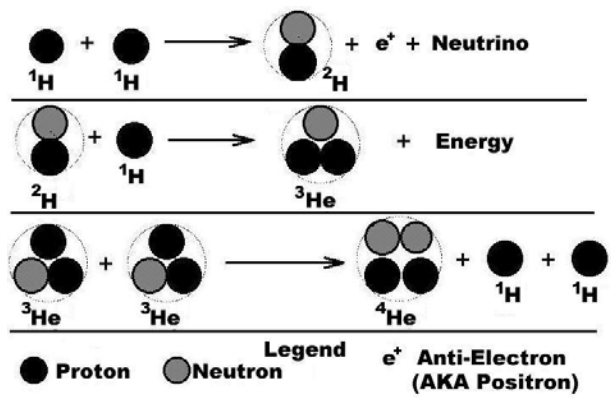
The answer comes from the fact that the weight of the final Helium nucleus is slightly less than the total weight of the four Hydrogen nuclei (about .71% less). Where did this mass go? It was converted to energy in an Einsteinesque manner (E=mc^2). Note: scientists are working to harness the energy of the stars on Earth. In principle, a virtually limitless supply of energy awaits us if we can make mini-stars in power plants on Earth. As you can imagine the technological issues are daunting. But back to our story …

The Sun converts 600 million tons of Hydrogen into Helium every second – this means that 4 million tons of matter turns into energy every second. The Sun loses 4 million tons of mass every second – don't worry, this is an infinitesimally small fraction of the mass of the Sun – even after 10 billion years it will hardly notice it! With this quantity of mass converted into energy each second, the Sun produces 4 x 10^{26} watts of energy – far more energy is released by the Sun in one second than humanity has used in its history!

We will look at two processes which occur inside of stars to convert Hydrogen into Helium. The method of converting Hydrogen into Helium does not affect the energy output. In every case 0.71% of the mass of the Hydrogen is converted into Helium.

The Proton-Proton Chain:

Most stars rely on this process to produce energy at some point. It is the main process occurring inside our Sun and other lower-mass stars (mass < 5 $M_{\odot}$). Helium nuclei are built by adding Protons to a Hydrogen nucleus.



The first step involves a collision between two Protons (^{1}H) to produce a Hydrogen-2 (^{2}H). One of the Protons turns into a Neutron, otherwise the two Protons would immediately fly apart. As the Proton turns into a Neutron, a Positron (e^+) is emitted. A Positron is a an anti-Electron, and it will immediately collide with an Electron. This wile annihilate both particles and produce pure energy in the form of Gamma Rays. Another particle produced in this reaction is the Neutrino – a very small, neutral particle which hardly interacts with matter at all.

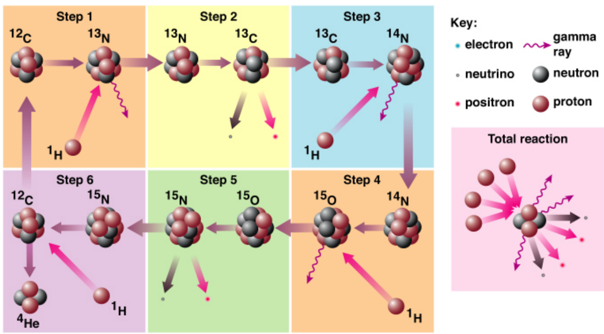
The second step adds another Proton (^{1}H) to the Hydrogen-2 nucleus (^{2}H) to produce Helium-3 (^{3}He) – which has one Neutron and two Protons. In the process some more mass is lost and another Gamma Ray is emitted. This isotope of Helium is not very stable, hence it is not the common variety we find: Helium-4 (^{4}He), which has two Protons and two Neutrons.

The final step combines two Helium-3 (^{3}He) nuclei to form one Helium-4 (^{4}He) nucleus with two left over Protons (^{1}H) which can then enter the reaction again.

The net effect is four Hydrogen nuclei (Protons) have been converted into one Helium nucleus, with a loss of 0.71% of the total mass.

The CNO Cycle

In hotter stars, the CNO cycle plays a more important role in converting Hydrogen into Helium (i.e. It does it quicker than the Proton-Proton chain). As seen in the figure below, the CNO cycle amounts to 'adding Protons to an atomic nucleus until a Helium nucleus splits off.



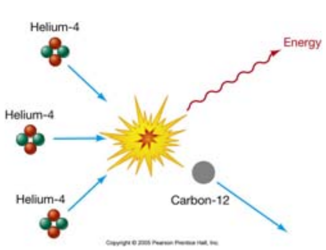
In step 1, a Proton is added to a Carbon-12 nucleus, converting it to Nitrogen-13. In step 2, the Nitrogen-13 decays into Carbon-13, by emitting a Positron. Step 3 has another Proton add to the Carbon-13 to make Nitrogen-14. In step 4, another Proton combines to make Oxygen-15; which decays into Nitrogen-15 in step 5. In the last step, a fourth Proton collides with the Nitrogen-15, which splits the nucleus into a Carbon-12 and a Helium-4 nucleus.

This can be thought of as building a Helium nucleus, using Carbon nucleus as a "workbench". Although the analogy is flawed it does illustrate that 4 Protons are added to a Carbon-12 nucleus, which results in a Helium-4 nucleus and another Carbon-12 nucleus. This also helps us understand why the most abundant elements in the Universe, after Hydrogen and Helium are: Oxygen, Carbon and Nitrogen (three elements which are very important to the chemistry of life).

The most important thing to remember here is that Carbon, Nitrogen and Oxygen are involved in the process of converting Hydrogen into Helium in hotter, more massive stars (i.e. stars whose mass is greater than 5 times the mass of our Sun)

The Triple Alpha Process

Another process which is important to explain the abundance of Carbon and Oxygen in the Universe is the Triple-Alpha process. It is so named because the Helium nucleus is also called an Alpha Particle (because often scientists name things before they understand them and once named it is awfully difficult to un-name something).



A simple comparison of Helium-4 and Carbon-12 would lead people to expect that if three Helium-4 nuclei were to collide at exactly the same moment they could produce one Carbon-12 nucleus. It turns out that it is far, far more complicated than that – and the odds of three Helium-4 nuclei colliding at the exact same time are almost zero! We definitely do not want to get into the nitty-gritty of the calculations here, however, the basic idea is correct: if three Helium-4 nuclei collide (almost) simultaneously, then they can result in one Carbon-12 nucleus.

Sometimes, an extra Helium combines and we get Oxygen-16. In fact, the two products of the Triple Alpha Process are: Carbon-12 and Oxygen-16. This goes partway toward explaining why Carbon-12 and Oxygen-16 are the third and fourth most abundant elements in the Universe.

Even though the chances of three particles hitting exactly at once are remarkably small, there are some mitigating circumstances which make 'near hits' more probable in the hearts of stars. There is much more to this than can be described in an introductory Astronomy course – but it is always helpful to let the student know when we have bigger truths to share in the future.

BTW: This strange coincidence has caused scientists (well, those who know of the Carbon-12 resonance) to speculate that the Universe was specifically designed for Carbon-12 to develop, and hence, intelligent life. Other scientists have replied "Well, if the Universe did not permit Carbon-12 to develop, and therefore intelligent life, thee would be no one to sit around asking these questions, right?" (Others point out that it is a remarkable coincidence that Earth-life is based on Hydrogen, Carbon, Oxygen and Nitrogen … four out of the five most abundant elements in the Universe – someone should write a book about this and blame in on the Da Vinci Code!)

Summary;
What do you really need to know about how stars make energy and make new elements?

1) Stars make energy by converting matter into energy as they make new elements by nuclear fusion – e.g. when 4 Hydrogen atoms are combined to make 1 Helium atom 0.71% of the mass is converted into energy. (and the Sun converts 4 million tons of matter into energy each second)

2) There are more ways than one to combine Hydrogen into Helium but it doesn't matter which process we use: the energy yield is the same! In the Sun and lower mass (i.e. cooler) stars the process is the Proton-Proton chain. In more massive (i.e. hotter) stars, the predominant process is the CNO cycle – although both processes occur.

3) After stars run out of Hydrogen, they combine Helium into heavier elements – and this is how many of the other elements are made (Like Carbon, Nitrogen, Oxygen, Silicon, Iron, Sulfur, etc). Many other elements are made by another process – but you have to take Astro 10B to find out about that.