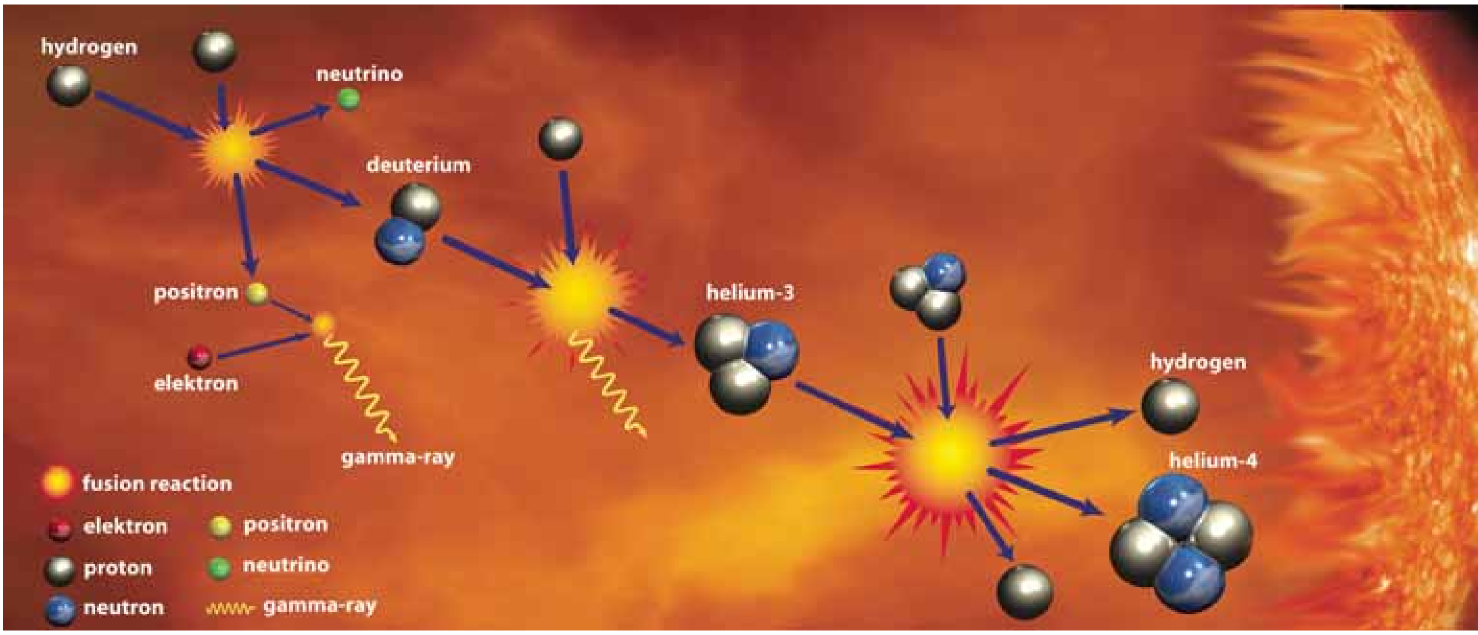
Fusion in the Universe: the power of the Sun



Mark Tiele Westra from the European Fusion Development Agreement (EFDA) in Garching, Germany, elucidates the source of power on Earth: the Sun.

Just over one hundred years ago, nobody had a clue how the Sun manages to produce the enormous amount of energy it radiates into space. Sure, there were thoughts and ideas, many of them very clever. Some scholars thought the Sun was a huge cloud of gas, collapsing under its own gravity, with the resulting friction and collisions causing it to heat up. Others thought that the Sun just hadn't had a chance to cool down since its creation. These ideas led to a similar conclusion: that the Sun couldn't be much older than a couple of tens of millions of years. Any older and it would have already cooled down.

But along came Darwin and his colleagues, studying the formation and erosion of rocks, and the slow, slow evolution of life. For their theories to make sense, they needed the Sun to be much older, at least hundreds of

Energy production in the Sun: two hydrogen nuclei fuse to form a deuterium nucleus, a positron and a neutrino. The positron quickly encounters an electron, they annihilate each other, and only energy remains. The deuterium nucleus goes on to fuse with another hydrogen nucleus to form helium-3. In the final step, two helium-3 nuclei fuse to form helium-4 and two hydrogen nuclei

millions of years, perhaps even a billion years, old. Controversy reigned.

It was not until the discovery of radioactivity, and the acceptance of the surprising notion that mass and energy are somehow interchangeable according to Einstein's $E=mc^2$, that a solution was in sight. Sir Arthur Eddington, a British astronomer, was the first to weigh up all the evidence, and boldly conjecture that it might be nuclear fusion, the process that creates heavier elements by fusing lighter ones, that was responsible for the Sun's copious energy production. In the meantime, we know that the Sun indeed burns hydrogen, the lightest gas in the universe, and turns it into helium. We even know how – see the figure above.

The details of this process are intriguing. First, a hydrogen nucleus (proton) in the Sun has to wait on average of five billion years before it

BACKGROUND

The discovery of helium

In the 17^{th} century, scientists studied the composition of light (the spectrum) by splitting it into its composite colours using a thin slit and a prism. From experiments with glowing gases, it was well known that elements, when heated, selectively emit certain precise colours of light, showing up as bright lines in the spectrum (think of a neon tube).

Looking at the spectrum of the Sun, people found dark lines that corresponded exactly to the place in the spectrum where bright lines appeared in glowing gases. People were quick to realise that the dark bands must be caused by the same element, which, instead of emitting light, *absorbs* it. In this way, the composition of the Sun could be analysed by carefully studying the spectrum of sunlight.

Most bands in the solar spectrum were known to belong to elements occurring on Earth, but there was a set in the solar spectrum that eluded scientists. In 1868, the British astronomer Norman Lockyer hypothesised that these dark bands were caused by a hitherto unknown element present in the Sun, which he dubbed "helium", after the Greek Sun god Helios. It was not until 25 years later that helium was first isolated on Earth.

takes the plunge, fusing with another hydrogen nucleus to form deuterium. This is actually good news for us: if it happened any faster, the Sun would have run out of fuel long ago, and we wouldn't be here. The second step, in which helium-3 is produced from deuterium and hydrogen, happens on average after 1.4 seconds, and the final step, the production of helium, takes 240 000 years. The energy released during the fusion process is turned into photons: light.

When the first excitement is over, and photons of light have been produced that could one day reach Earth, they still need some patience. A photon sets off on its journey to Earth at the speed of light, but almost immediately bumps into an electron, which scatters the incoming photon in a random direction, like the ball in a pinball machine. This happens again, and again and again. It takes the average photon over 20 000 years to make the 695 000 kilometre trip from the centre of the Sun to the Sun's surface, which translates into a rather pathetic four metres per hour.

After this long and erratic journey, the photon covers the remaining 149 *million* kilometres to Earth with the usual speed of light, and 8 minutes later finally arrives at its destination. And those are the lucky ones: there are also photons in the Sun that were formed five billion years ago, but have still not made it out. Imagine that for a maze...

In the fusion process, another odd particle is formed: the neutrino (see figure). A neutrino hardly interacts with matter, and can therefore escape from the Sun in an instant. Huge numbers of neutrinos are formed by the Sun: every second, 100 *billion* solar neutrinos fly through the tip of each of your fingers! Most neutrinos fly straight through the entire Earth, without being affected by it at all. In fact, a neutrino would fly through a light-year of lead, without being stopped!

When we think about the centre of the Sun, we image some fierce, fiery furnace, blasting out heat. With a density 150 times that of water (half a litre of Sun weighs as much as an average person), and a temperature of 15 000 000 degrees Celsius, it is a pretty daunting environment by any standards. But if you were to take a cubic metre from the centre of the Sun, you would find that it only produces about 30 Watt, hardly enough to power a light bulb. It is the sheer size of the Sun that ensures that we actually feel warm on Earth.

At the moment, the Sun burns 600 million tonnes of hydrogen each second, turning it into 596 million tonnes of helium. Where did the missing four million tonnes go? It has been completely transformed into energy. Applying $E=mc^2$ (with E the energy, m the mass, and c the speed of light), we find that 4 million tonnes of matter equate to 100 000 000 000 000 000 000 Kilowatt hours of energy, or roughly *one million* times the amount of energy that the entire world uses in a year. And that energy is released by the Sun every second. Now that's solar power!

So far, the Sun has burned up half of its hydrogen fuel supply. It has been burning for five billion years, and will burn for another five billion. What then? Then the party is over. The Sun will swell up to become a 'red giant', boiling away the atmosphere and all water and life on our home planet. We'd better get out before that time, but let's enjoy it while it lasts.

Resources

For a discussion of fusion as a future energy source, see:

Warrick C (2006) Fusion – ace in the energy pack? *Science in School* **1**: 52-55. www.scienceinschool.org/2006/issue1/fusion

REVIEW

In an age where non-renewable sources of energy are fast disappearing and efficient renewable sources of energy are frantically sought, fusion is often the subject of discussion in many scientific journals and newspapers. From a young age, students may be faced with such a term without understanding quite what it means.

Mark Tiele Westra from the European Fusion Development Agreement in Garching, Germany, gives us a very interesting and concise account of the fusion process occurring within the Sun. Although the article provides a theoretical treatment of the topic and is of interest to the science teacher just as it is, it comes with a very informative illustration, both of which can be easily adapted and used according to the students' abilities to explain fusion in the science classroom. For more advanced students, there is also some detailed information on the discovery of helium.

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