

9. Cosmic furnaces

The stars and the birth of elements

Life on Earth depends entirely upon the Sun. So vital is its light and warmth that, from ancient times, it has often been worshipped. More recently, we have come to understand that not only do we rely on our local star to sustain us, but that we actually exist because of other, long dead, stars. The Earth, and almost everything on it, is made from the ashes of giant stars that lived their lives and then exploded billions of years ago. The Solar System itself, to which the Sun, planets and humans belong, came into being around 4.5 billion years ago, condensing out of the gas and dust ejected by an earlier generation of stars in their death throes. There is an abundance of carbon, oxygen and iron, all vital to life, because carbon, oxygen and iron nuclei were produced and expelled as those early stars died.

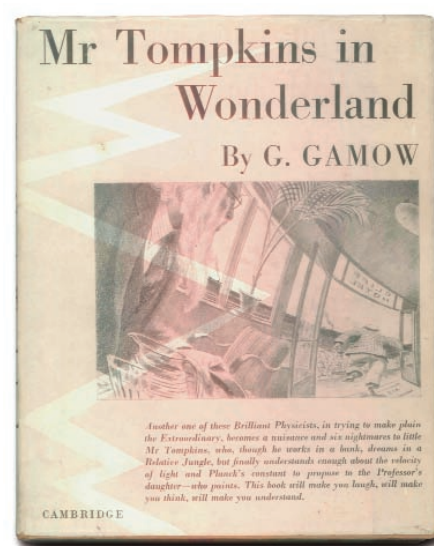
How stars shine and how the elements were produced, are two stories linked by nuclear physics experiments. Nuclear processes in stars can be understood by studying them on Earth; we can even attempt to tap the same source of energy which powers the Sun.

Apart from the fact that we depend on the Sun, the points made above are far from obvious. For example, in the 1830s the philosopher Auguste Comte claimed that the composition of the stars was an example of something that would always be beyond human knowledge. This statement was quite acceptable before the birth of spectroscopy.

More than two millennia before Comte, Aristotle made a proclamation which soon became dogma: "Everything in the heavens," he said, "is made of perfect, unchanging and incorruptible 'quintessence'." One reason Galileo Galilei was unpopular with the authorities was that some of his discoveries challenged this view. The idea that experiments on Earth might mimic processes in stars contradicted what people had believed for two thousand years. Such experiments are now carried out; stars are not made of 'quintessence' – essentially, they are composed of the same basic material as us.

A great physicist of the Victorian era, Lord Kelvin, proclaimed that the Sun could not be more than 100 million years old – a correct deduction based on the sources of energy known at that time. Geologists and biologists had strong reasons to believe that the Earth was much older, and in 1903 Rutherford pointed out the apparently continuous energy flowing out of radioactive nuclei showed "the maintenance of solar energy no longer presented a fundamental problem."

Finally, the nuclear physics pioneer, George Gamow, believed all the elements were produced in the Big Bang. This was a sensible deduction based on scientific knowledge of the 1940s, but Nature is an inexhaustible source of surprises and one of these was the discovery of technetium in certain red giant stars. This short-lived element could not have been made in the Big Bang so some elements, at least, must be produced in stars. There is now a great deal of evidence that this is so.



When George Gamow showed how alpha particles tunnel out of nuclei with the help of quantum theory, he had at the same time revealed how pairs of nuclei could tunnel inwards and fuse together. This opened the door to understanding how energy is produced in stars and how heavy elements are made from lighter elements, ultimately from hydrogen. He was also the father of Big Bang cosmology and the author of a much-loved series of popular physics books, still in print. (Courtesy Cambridge University Press.)



The Orion Nebula is found just below the belt in the constellation of Orion. It may be seen as a hazy patch in binoculars, or even with the naked eye from dark locations. Within it is a region of a thousand young stars crowded into a space less than the distance from our Sun to its nearest neighbouring stars. This is a stellar nursery where a new generation of stars is being born. This false colour image, taken in the infrared region of the electromagnetic spectrum, allows us to look deep into the region. (Courtesy European Southern Observatories.)

The abundance of the elements

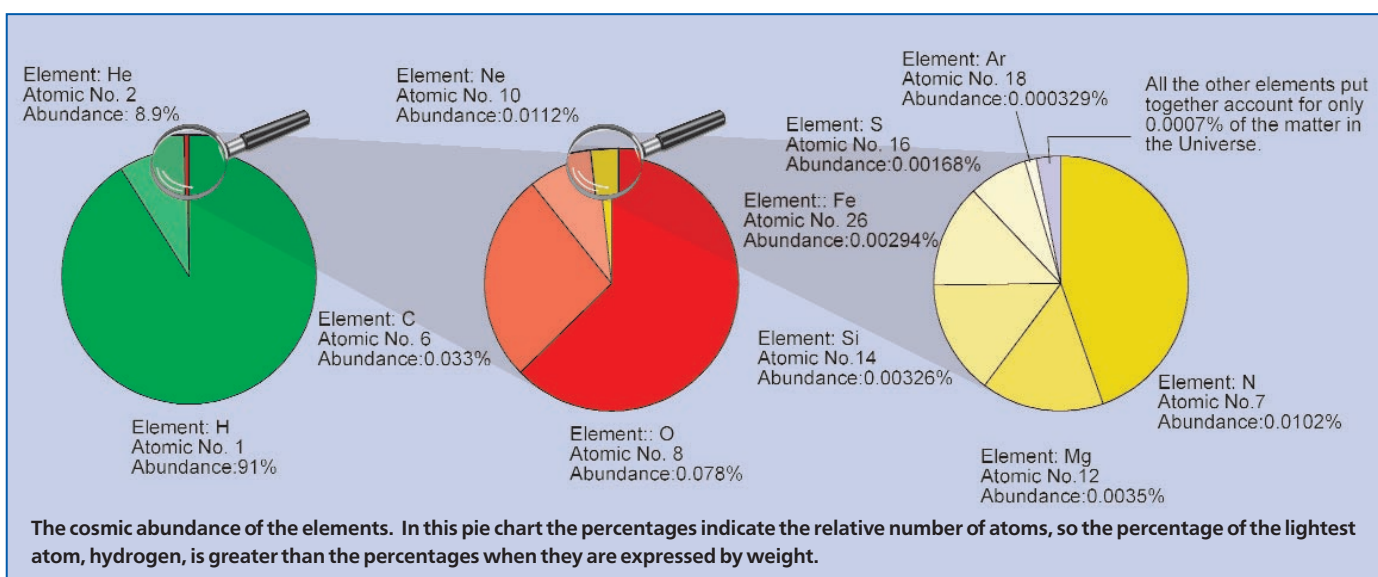
Gamow was not entirely wrong. At present, the Universe is roughly 70% hydrogen, 28% helium and only about 2% everything else. (These percentages are by mass, not by number of atoms.) The hydrogen and most of the helium, together with some lithium (element 3) were produced in the Big Bang, but every other element has been produced in stars. The 2% that Gamow was wrong about includes the carbon, oxygen, nitrogen, iron and all the other elements.

It is not a trivial job to determine the cosmic abundances of the elements, that is what proportion of each element, or what proportion of each kind of atomic nucleus exists in the Universe. Many places are untypical in that they will contain a higher concentration of certain species than elsewhere – for example a jeweller's shop would not be a suitable place to estimate the cosmic abundance of gold.

Meteorites and the spectra of stars are two important sources of information about the cosmic abundance of elements. Certain kinds of meteorites are known to date back to the formation of the Solar System, and these reveal a consistent pattern of element proportions (the Solar System abundances) which are in fair agreement with that found in typical stars. The composition of each star depends upon the star's history, but an overall pattern emerges.



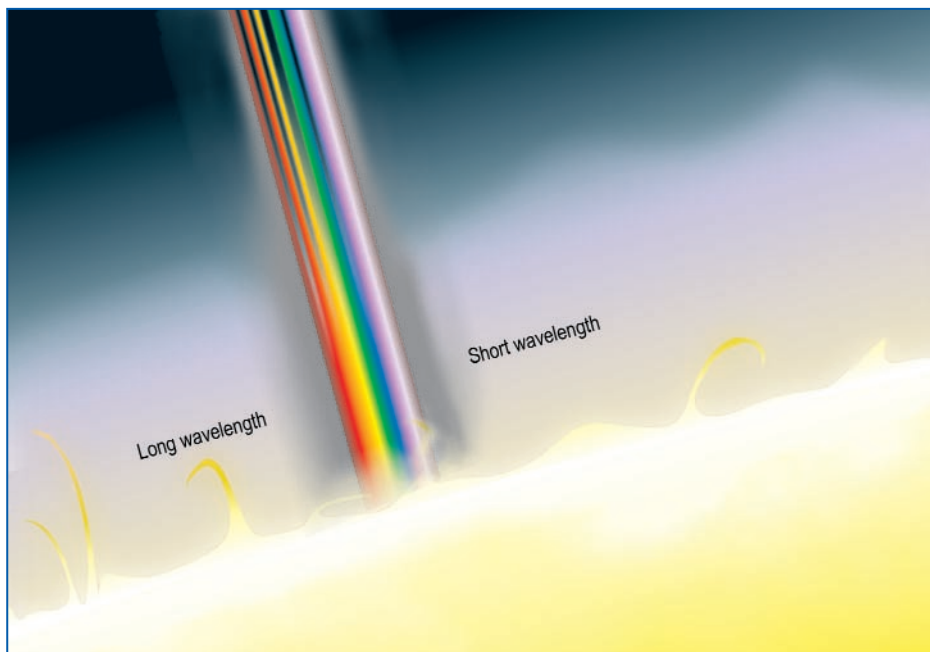
A messenger from space. The light-coloured 'chondrules' visible in this meteorite, Adrar 303, have elements in the same proportion as the gas and dust from which the Solar System condensed. The proportion of different nuclei is remarkably close to what is found in many stars, representing the cosmic nuclear abundance. (Courtesy Ian Franchi, The Open University.)



There are vast differences in the proportions of each element. Clearly there is some influence from the energy valley, with elements located beyond iron and nickel being much less abundant than the lighter elements. Magic number elements tend to be more common.

By and large, the lightest elements are the most common. Somehow, the elements must come from a series of nuclear processes that start with hydrogen and build progressively heavier nuclei. There is a lot of carbon and oxygen because, in many stars, the sequence of nucleus building can only reach as far as these elements.

As light streams up from the hot surface of the Sun certain colours are absorbed by the atoms in the Sun's atmosphere. This process is symbolized by showing how progressively darker bands appear in the spectrum of white light as the light penetrates outwards through the Sun's atmosphere. When light is analysed on Earth, it shows the fully developed black absorption lines due to the entire thickness of solar atmosphere.



From hydrogen to helium

Almost all the energy we receive from the Sun comes from a series of reactions in which protons (hydrogen nuclei) interact to make helium nuclei. These reactions are also the first step towards the production of all the other elements. The process begins when two protons are attracted to each other and make a new nucleus, but there are two factors which work against this happening. The first is that although the nuclear force is strong and attractive when the protons are close, it is actually very hard for the protons to get near enough to each other for the force to be felt. This is because of the other force between protons, the electrostatic repulsion, keeping the two like-charged protons apart. The second problem is that the nuclear force is not quite strong enough to bind two protons; a nucleus consisting of two protons, ${}^2\text{He}$, does not exist.

Neither of these problems exist if we begin with binding a proton and a neutron together. Since the neutron carries no electrical charge, there is no electrostatic repulsion acting against this pairing, and protons and neutrons do form a 'bound state': the deuteron (the nucleus of the isotope of hydrogen ${}^2\text{H}$). While this would have happened during the Big Bang when there were free neutrons around, all those that did not pair up with protons will have undergone beta decay long ago. Free neutrons cannot survive longer than a few minutes before turning into protons. With none of these free neutrons remaining today, we are restricted to the fusion of two protons.

The electrostatic repulsion between two protons can be overcome in stars by a combination of quantum mechanics and high temperatures. The same rule of quantum mechanics which allows alpha particles to tunnel out of certain nuclei, enables protons with sufficient energy to tunnel through the force barrier between them. Protons at room temperature would certainly not have sufficient energy, but the temperature at the centre of the Sun is about 15 million degrees Kelvin. Consequently, a few protons do have enough energy to surmount the electrostatic barrier.

Having surmounted the barrier, the second problem of two protons not sticking together to form a nucleus is overcome by one of the protons turning into a neutron via beta decay, emitting a positron and a neutrino.

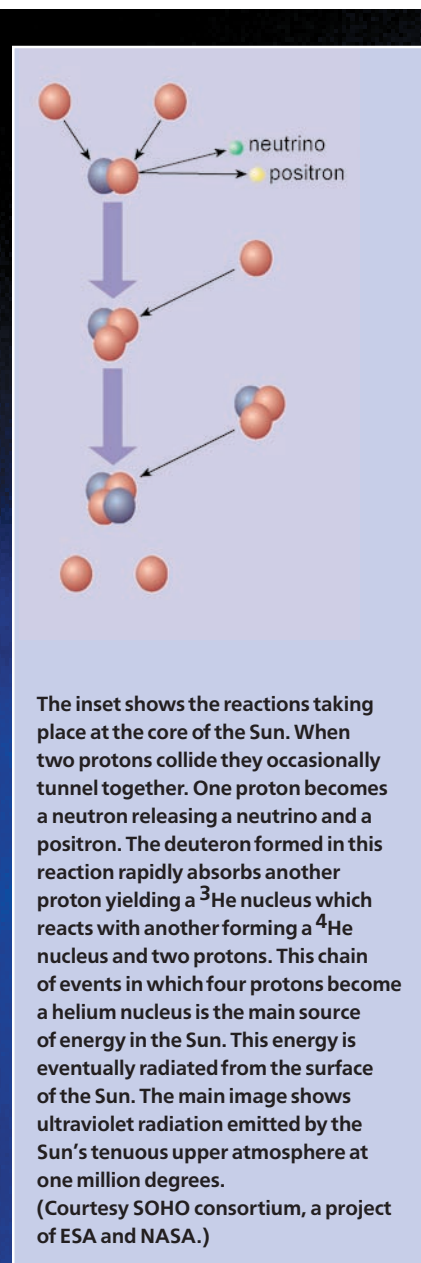
This complete process requires three of the four forces of Nature acting in coordination against the fourth. The gravitational force first compresses the hydrogen gas, raising its temperature and giving the protons the necessary energy to tunnel together. Next, the strong nuclear force keeps them close together while the weak nuclear force causes one of them to turn into a neutron, allowing the formation of the deuteron. During the process, the electromagnetic force acts to keep the two protons apart.

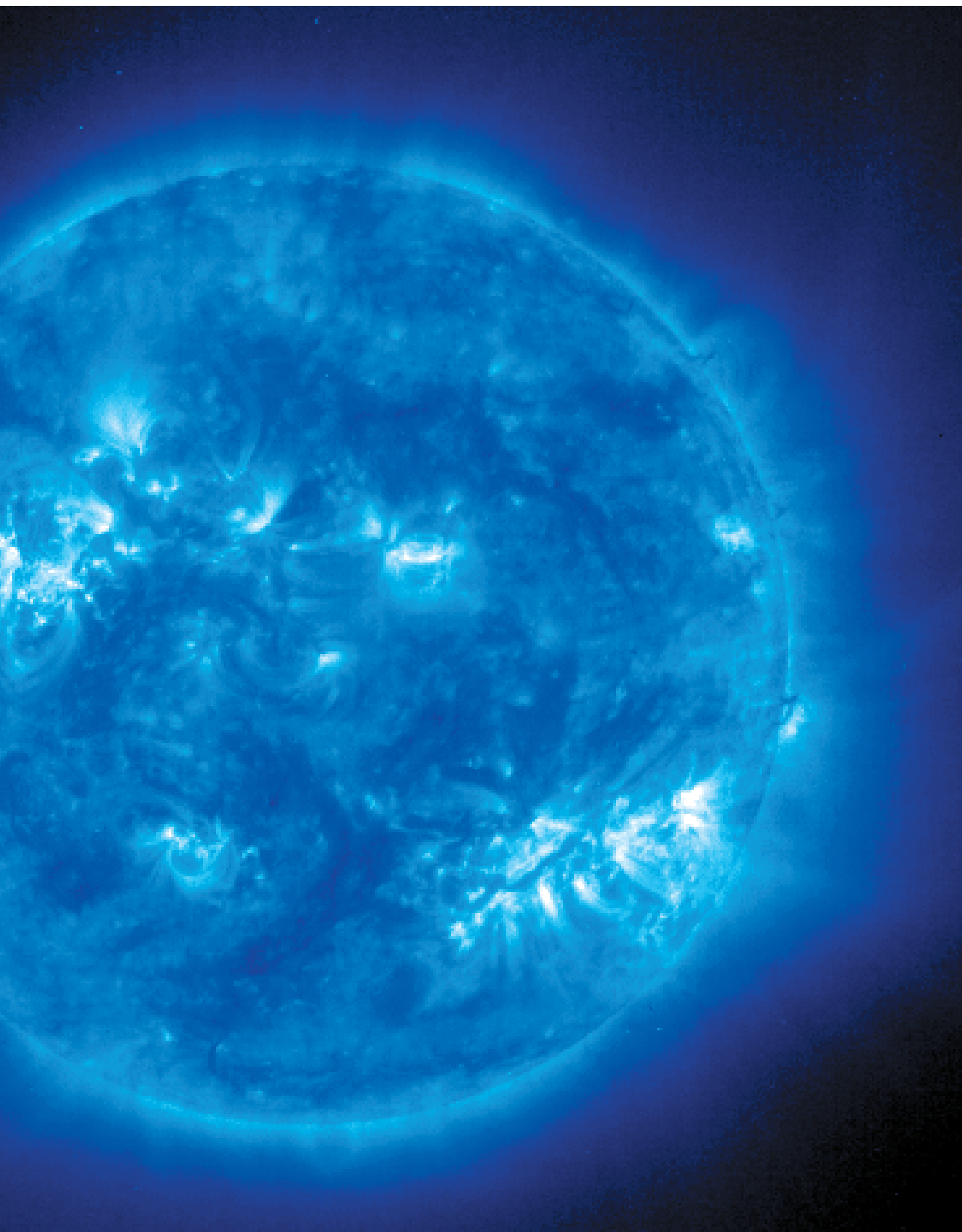
On average, it takes billions of years for protons in the Sun to join up to become deuterons because the transformation of a proton into a neutron happens very slowly. Once the deuteron is formed, the next step is much more rapid. Within seconds of being produced, a deuteron and another proton will tunnel together through the barrier between them to form the isotope of helium, ^3He .

The ^3He nuclei last somewhat longer than the deuterons, but they too will quickly disappear. Being positively charged, two ^3He nuclei will repel one another, but if they have enough energy they have a chance of fusing. If they do this, not all six nucleons will stick together, but a ^4He nucleus (alpha particle) will be formed and the two redundant protons will be emitted. The overall effect of this series of reactions is for six protons to form an alpha particle, with two protons left over, a process known as the 'pp chain'.

The first step, the fusion of two protons, is the bottleneck of the pp chain. It takes place too slowly for it ever to be observed on Earth, but the reaction between two ^3He nuclei can be measured. These very difficult measurements, first made in a tunnel deep beneath the Gran Sasso Mountains in Italy, help provide a firm basis for the detailed models of the internal workings of the Sun and other stars which are such a major part of modern astrophysics.

For most of its life, the Sun is, in effect, a factory for turning hydrogen into helium. Eventually, this process must end as the hydrogen at the centre of the Sun, where it is hot enough for fusion to take place, becomes exhausted. The core starts to contract and becomes even hotter, reaching the region of 100 million degrees. This is hot enough for the common isotope of carbon, ^{12}C , to be produced via the 'triple-alpha process'. While this is happening, the Sun's surface expands and the Sun becomes a red giant, eventually ejecting some of its outer layers into space. Some of this material will find its way into the next generation of stars and possible planetary systems.







The Crab Nebula, M1, in the constellation of Taurus is the remnant of a supernova explosion at a distance of about 6000 light-years. First observed almost 1000 years ago, such explosions are the source of the heavy elements which we find on Earth. The green light is predominantly hydrogen emission from material ejected by the exploding star. The blue light is emitted by very high energy (relativistic) electrons spiralling in the large-scale magnetic field (synchrotron emission). (Courtesy European Southern Observatories.)

The triple-alpha process – a very delicate balance.

Like all carbon-based creatures, we depend on the production of carbon in stars. The natural way for ^{12}C to be produced would be for two ^4He nuclei to tunnel through the repulsive barrier between them to form a nucleus of the beryllium isotope ^8Be . Another ^4He nucleus would then tunnel in to make a nucleus of ^{12}C . Unfortunately, the ^8Be nucleus is not quite bound, and almost as soon as it forms it splits back into two alphas. It has the unimaginably small lifetime of about 10^{-16} seconds which gives very little opportunity for another alpha particle to join up with it to form carbon.

The situation is saved by ‘resonance’. A resonance allows a radio to be tuned so that it is millions of times more sensitive to radio waves of a certain frequency than signals of all other frequencies. Similarly, nuclei have certain energies at which they are very much more likely to be formed in a reaction. ^{12}C has a resonance at exactly the right energy to allow alpha particles to exploit the extremely short-lived ^8Be nuclei in stars for carbon to be produced. Without this resonance at just the right energy, carbon-based life would not exist. It has been estimated that if the strength of the nuclear force were to be changed by one part in 200, then the production of ^{12}C nuclei would be thirty times less. The Universe is extraordinarily finely tuned!

Elements and energy in more massive stars

The Sun, along with other stars of the same mass or less, will never produce substantial amounts of nuclei heavier than ^{12}C , but such nuclei must have existed in the cloud from which the Solar System condensed.

The Sun is a star of about average mass. The stars that are much more massive produce the heavy elements. The more massive the star, the hotter it is and the more rapidly it passes through all the stages of its existence. The heaviest stars have quite short lifetimes and often end their lives in catastrophic supernova explosions. Such explosions are the source of much of the oxygen in our bodies and all of the uranium in our rocks and seas.

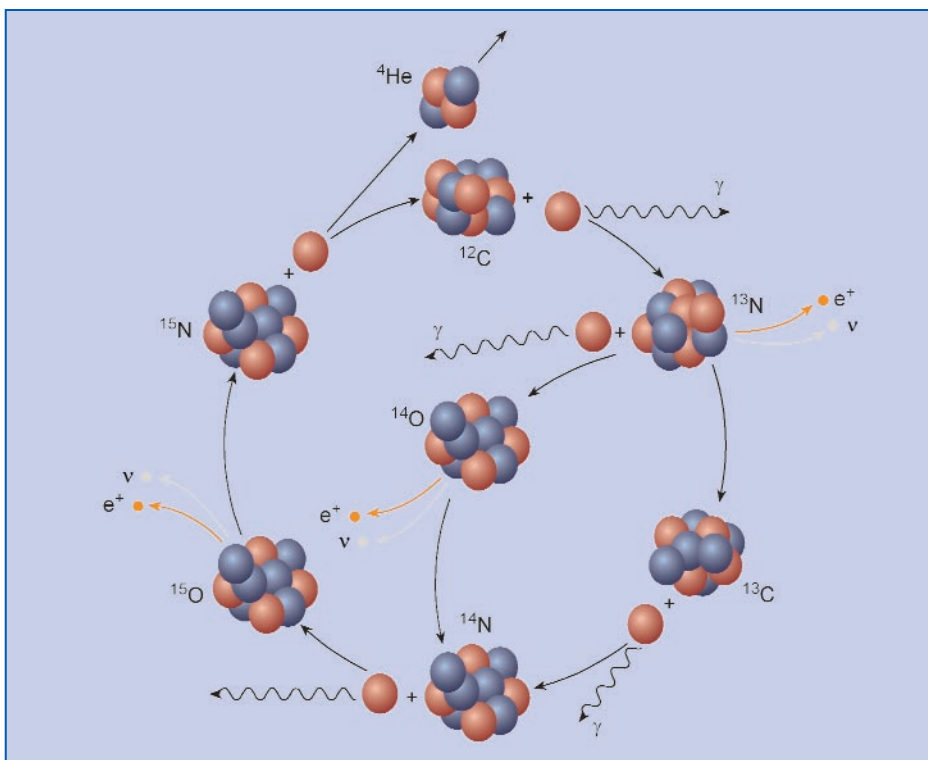
Temperature is the key to making heavy elements. All nuclei, being positively charged, repel each other. The greater the charge, the stronger this repulsive energy between them. The rate at which quantum mechanics allows them to tunnel through this energy barrier is very sensitive to how much energy they have due to their motion (kinetic energy) compared to the height of the barrier. A higher barrier means the nuclei need more energy to get through at a given rate. The energy of a nucleus within a star increases with the temperature of its location. The hottest part of a star is its core, at the centre. Since heat travels from hotter to cooler regions, the energy flows out from the core to the cooler outer regions of the star from where it is radiated into space.

At present the centre of the Sun is hot enough for hydrogen to fuse to make helium, but not hot enough for the triple-alpha process, and certainly not hot enough for the fusion of heavier nuclei. The temperature of the core will rise dramatically when it collapses after its hydrogen runs out. The triple-alpha fusion reaction ignites at about 100 million degrees. For stars more massive than the Sun, changes of this kind increase the core temperature even more, allowing much heavier nuclei to form.

Using carbon to make helium

In stars more massive than the Sun, there is an alternative to the pp chain method of producing helium from hydrogen. This is the CNO (carbon–nitrogen–oxygen) cycle, first proposed by Nobel prize winner Hans Bethe in the late 1930s. This process requires a star to have at least a trace of ^{12}C mixed in with the hydrogen. In this event, a ^{12}C nucleus can absorb a proton to produce a nucleus of the nitrogen isotope ^{13}N . Within a few minutes, the ^{13}N nucleus undergoes beta decay, turning into the carbon isotope ^{13}C , which is stable. Another proton will then tunnel through the ^{13}C barrier to produce ^{14}N . This nucleus is also stable and will eventually absorb another proton to become ^{15}O , a radioactive nucleus lasting just a couple of minutes before beta decaying to ^{15}N . The cycle finishes when ^{15}N absorbs a proton and an alpha particle is emitted leaving a ^{12}C nucleus, the starting point of the cycle.

The net effect of the CNO cycle is the same as the pp chain. Four protons, ordinary hydrogen nuclei, combine to produce a ^4He nucleus plus two positrons, two neutrinos and energy. In the CNO cycle, ^{12}C acts as a catalyst: it enables the process to take place, but is still there at the end. The CNO cycle certainly powers many of the stars shining today, but it would not have taken place in the very earliest stars that condensed out of the material produced in the Big Bang as that matter contained no carbon.



The CNO cycle takes place in hot stars. Four protons become an alpha particle (^4He nucleus) plus two electrons and two anti-neutrinos, indicated by the Greek letter nu (ν). Energy is released, partly as gamma rays (γ). The CNO cycle requires the presence of carbon nuclei ^{12}C , and the cycle starts when these absorb protons.

Using up the hydrogen

Towards the end of their lives, as the hydrogen in their cores becomes depleted, stars expand and become red giants. The Sun will enter its red giant phase in about five billion years and its outer atmosphere will extend to completely envelop the inner planets. Stars which are more massive than the Sun go through their red giant phase sooner in their lives, achieving particularly high temperatures deep within them as they do so. This enables a range of element-producing reactions to occur. Material ejected from the outer layers of red giant stars is believed to be the main source of the carbon and nitrogen upon which life depends.

Once ^4He and ^{12}C nuclei are created, a common process occurs by which they fuse to make ^{16}O ; this requires a temperature of about 500 million degrees. At higher temperatures still, tunnelling between nuclei becomes easier and so a great many different reactions take place. For example, pairs of ^{12}C nuclei or ^{16}O nuclei can fuse together. Although there are many other reactions taking place, including those involving the absorption of protons, it is the occurrence of these processes which partly explains why nuclei which are multiples of the alpha particle, such as those of carbon and oxygen, are abundant on Earth.

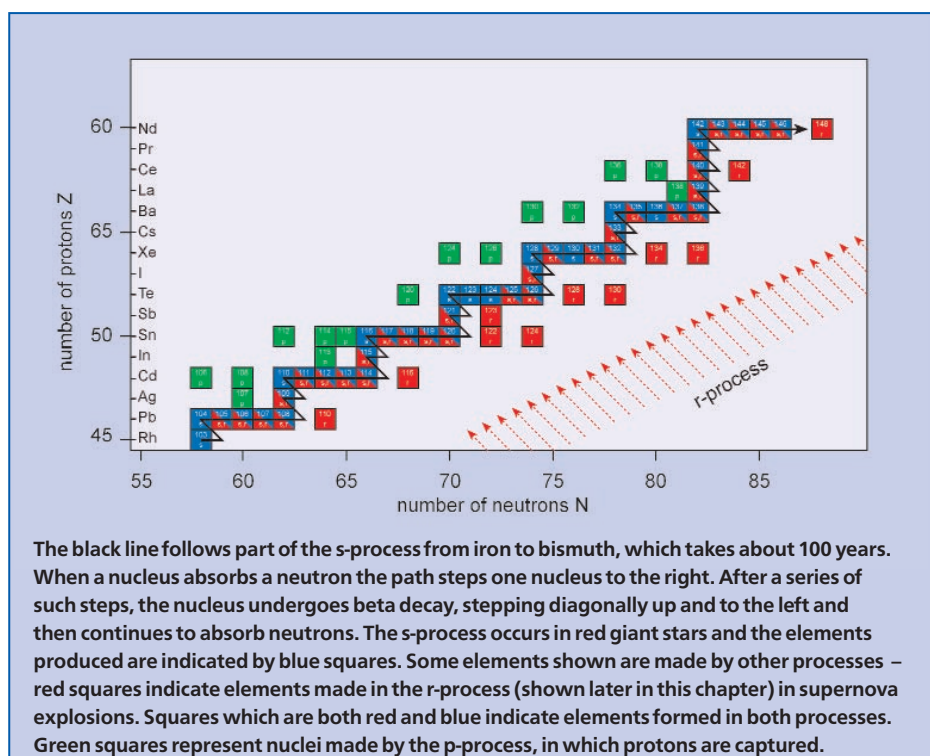
Another reason for this abundance is that these nuclei are particularly stable. At temperatures around a billion degrees, there exists a huge flux of gamma ray photons that can break up nuclei, especially the less stable ones.

At the centre of stars much heavier than the Sun, there eventually comes a rather brief period when temperatures reach around 4 billion degrees. At this temperature ^4He can fuse with the isotope of silicon, ^{28}Si , and heavier nuclei. Nuclei of elements all the way up to iron are thus both created and destroyed, until there is an equilibrium and the most stable nuclei are synthesized. Some of these will be ejected into space. The shape of the energy valley means that very few of the elements lying much past iron and nickel are made in this process.

The lead in your car battery

There is no problem with producing elements with up to 26 or 28 protons: iron and nickel. Beyond these, all the way up to lead (with 82 protons), ways have to be found to make them.

Some red giants generate large amounts of neutrons. When a neutron strikes a nucleus it may go straight through, but often it will be absorbed. If the new nucleus is stable, it will simply shake off any excess energy as gamma rays and wait for the next neutron. On other occasions, the extra neutron places the nucleus too far up the neutron-rich side of the energy valley; the nucleus now has too many



neutrons, causing the nucleus to undergo beta decay. The neutron will become a proton and the Z of the nucleus will increase.

In these neutron-rich stars, the nucleus will continue to be bathed in neutrons and another neutron will be absorbed. The effect is that the nucleus works its way along the floor of the energy valley towards heavier and heavier nuclei. If the nucleus gets too high up the neutron-rich side, it will slide back down by emitting the electrons and anti-neutrinos of beta decay. This process, known as the 'slow process' or 's-process', produces many of the isotopes of elements heavier than iron and nickel.

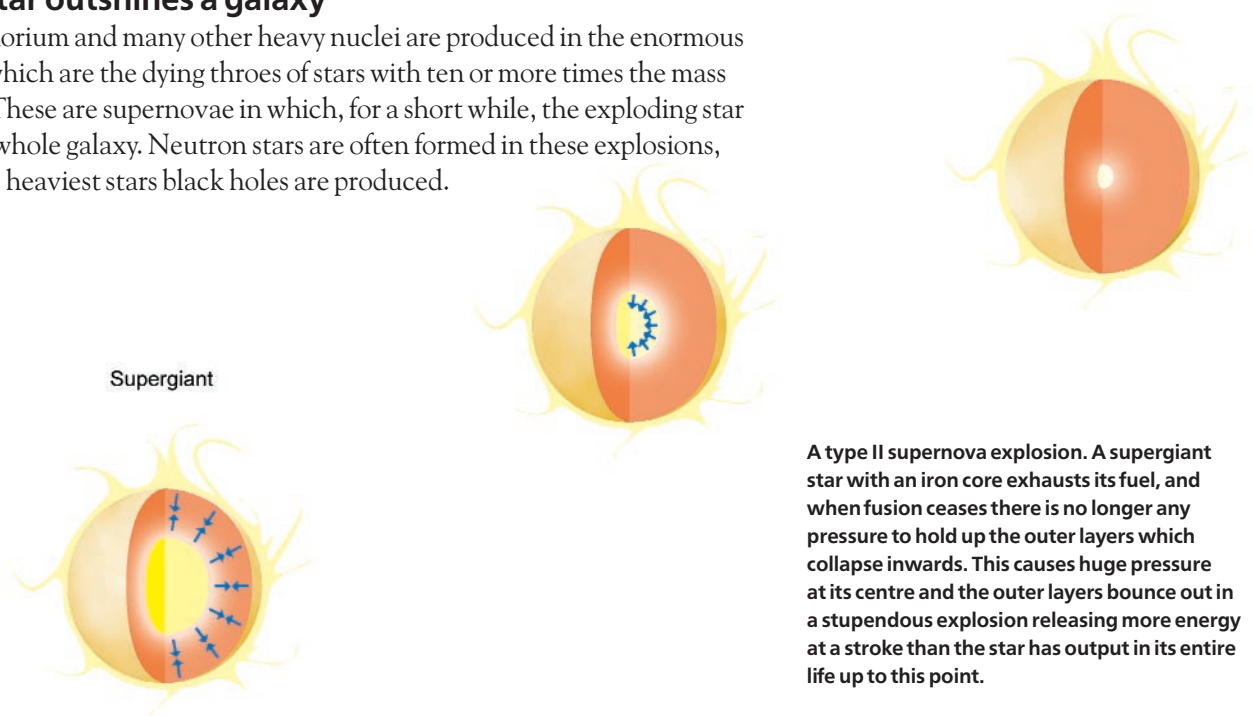
The s-process cannot be the whole story. Not all isotopes of the heavy elements are made in the s-process. The gullies crossing the energy valley tend to stop the s-process happening. The gullies represent nuclei with certain numbers of neutrons which are particularly stable and have lower energies than their neighbours. Such nuclei with closed neutron shells do not readily pick up additional neutrons, so the path to new elements is halted.

The s-process can make lead, and is a major source of iodine, essential for life. Another element made in this way is short-lived technetium. The observation of the spectroscopic signature of technetium in stars is strong evidence for the s-process occurring within them since the half-life of technetium is a great deal shorter than the ages of the stars.

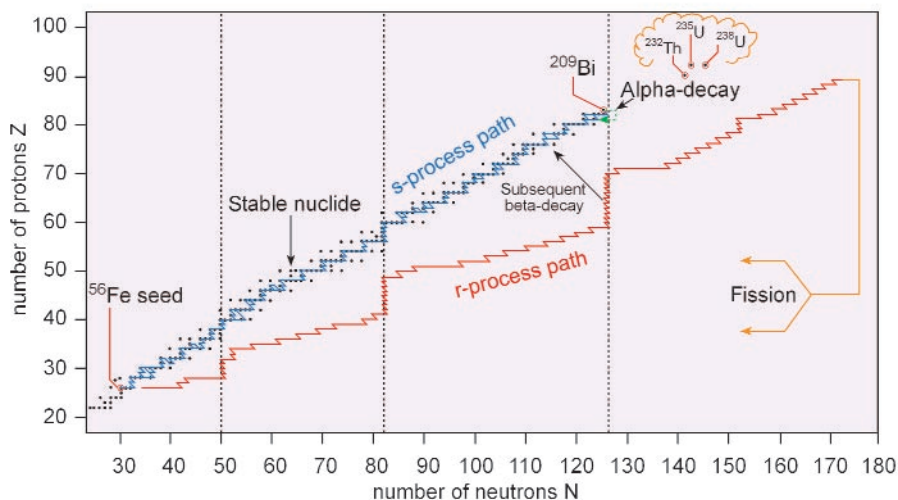
About half of the stable isotopes that are heavier than iron, including all the isotopes of uranium and thorium, cannot be made in the s-process. The existence on Earth of these elements is proof that there must be another process taking place. In addition, many elements have quite a few stable isotopes a short way up the neutron-rich side of the energy valley, and these are generally not made by the s-process.

When a star outshines a galaxy

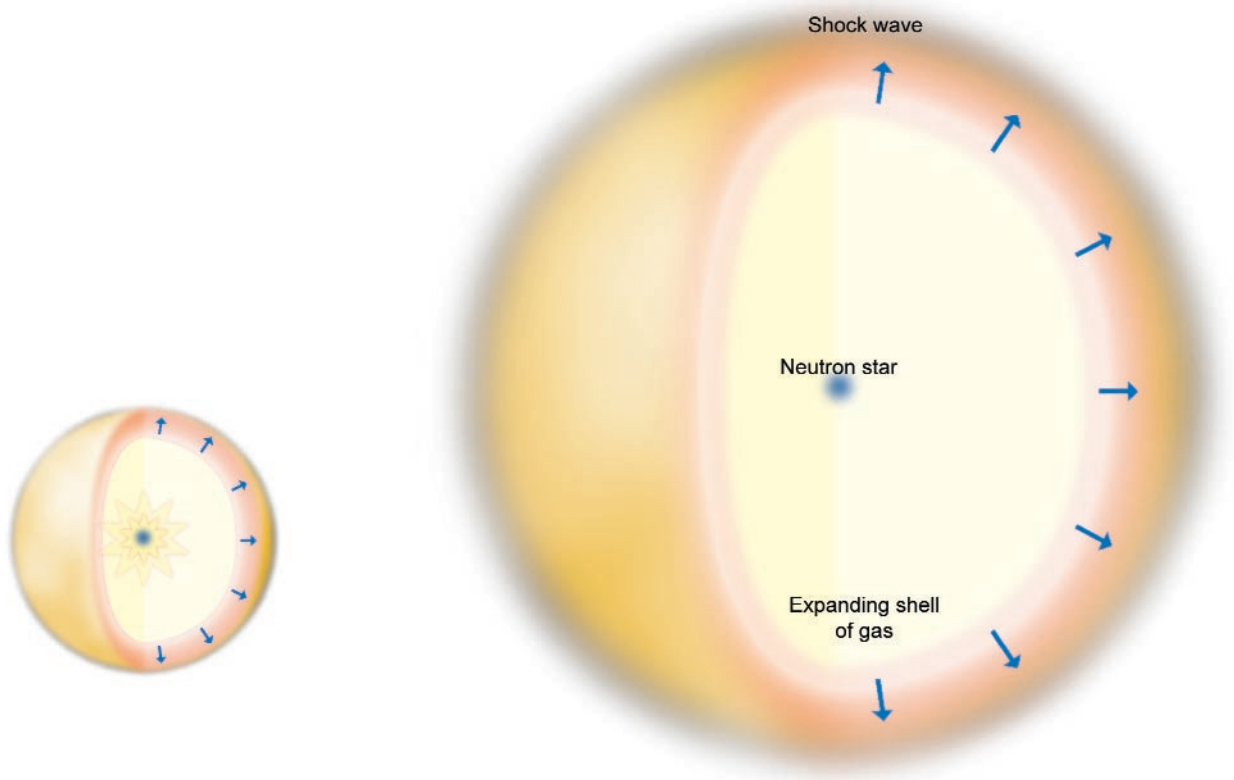
Uranium, thorium and many other heavy nuclei are produced in the enormous explosions which are the dying throes of stars with ten or more times the mass of the Sun. These are supernovae in which, for a short while, the exploding star outshines a whole galaxy. Neutron stars are often formed in these explosions, while for the heaviest stars black holes are produced.



A type II supernova explosion. A supergiant star with an iron core exhausts its fuel, and when fusion ceases there is no longer any pressure to hold up the outer layers which collapse inwards. This causes huge pressure at its centre and the outer layers bounce out in a stupendous explosion releasing more energy at a stroke than the star has output in its entire life up to this point.



The huge flux of neutrons from a supernova leads to the r-process in which very short-lived nuclei are produced far up the neutron-rich side of the energy valley. These subsequently beta decay down towards the floor of the valley. All the uranium and thorium on Earth was produced by the r-process.



The high pressures cause electrons and protons to combine to form neutrons and an immense pulse of neutrinos producing a shock wave which ejects the outer layers into space, leaving behind a neutron star. If the original star is sufficiently massive, the result will be a black hole. The flux of neutrons leads to the production of new elements which are dispersed in space.

The element-making process associated with supernovae is known as the ‘rapid’ or ‘r-process’. Certain (type II) supernovae release a vast flood of neutrons, far more than were present during the s-process. Exposed to such an intense flux, a nucleus can absorb a greater number of neutrons before it undergoes beta decay. As a result, the nucleus finds itself some distance up the neutron-rich side of the energy valley. Eventually, the nucleus becomes so unstable that it tumbles down the valley in a cascade of electrons and neutrinos. In this way, the r-process produces some nuclei that the s-process does not, uranium being an example.

Many nuclei on the r-process paths lie so far from the valley floor that they have never been made or studied on Earth. This has spurred intense activity to study nuclei out towards the neutron dripline. One goal is to get the nuclear information needed for a full understanding both of supernovae and the origin of the elements.

Fusion power on Earth

It has been a dream of scientists for half a century to reproduce and harness the fusion reactions that power the Sun. If successful, this process could provide a clean and inexhaustible supply of energy to help meet ever-expanding world demand.

The fusion of two hydrogen nuclei to produce helium is accompanied by the release of energy, but it is necessary to have enormous temperatures before the two hydrogen nuclei are energetic enough to fuse. Scientists face the problem of maintaining and containing such temperatures. In addition, the reaction employed cannot be that of two protons fusing together as it occurs far too slowly. Most practical schemes would have to involve the fusion of heavier isotopes of hydrogen such as deuterium and tritium. Fusion researchers use a machine called a Tokamak as a kind of test-bed for proving the principles of confined and controlled nuclear fusion on Earth, but while progress is being made, it will be many years before such an energy source is developed.

The big picture

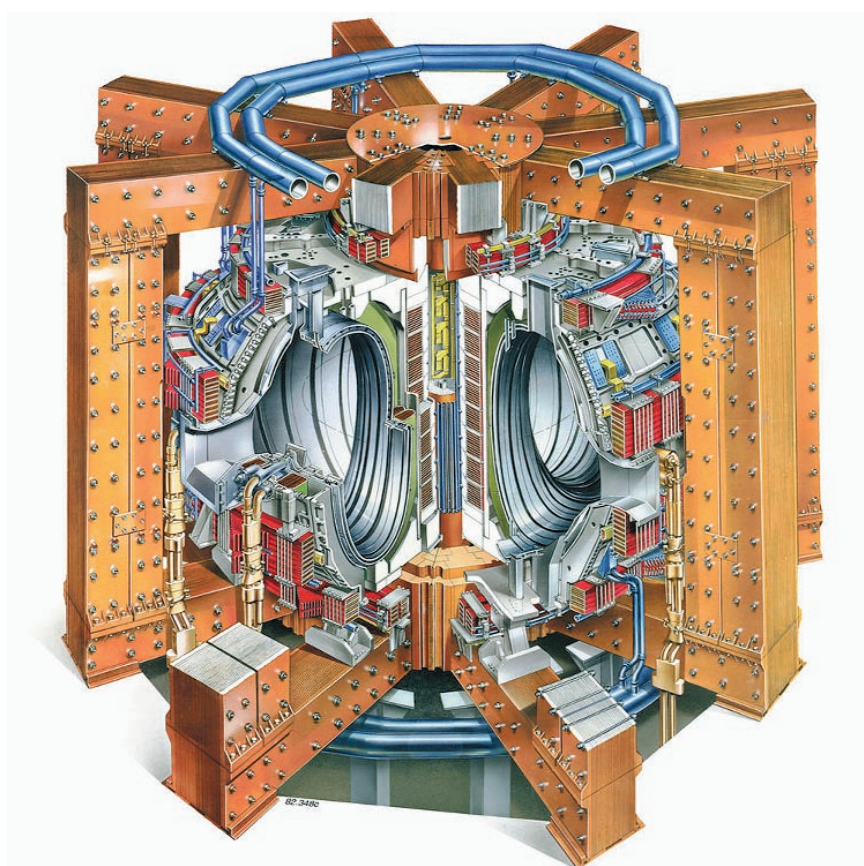
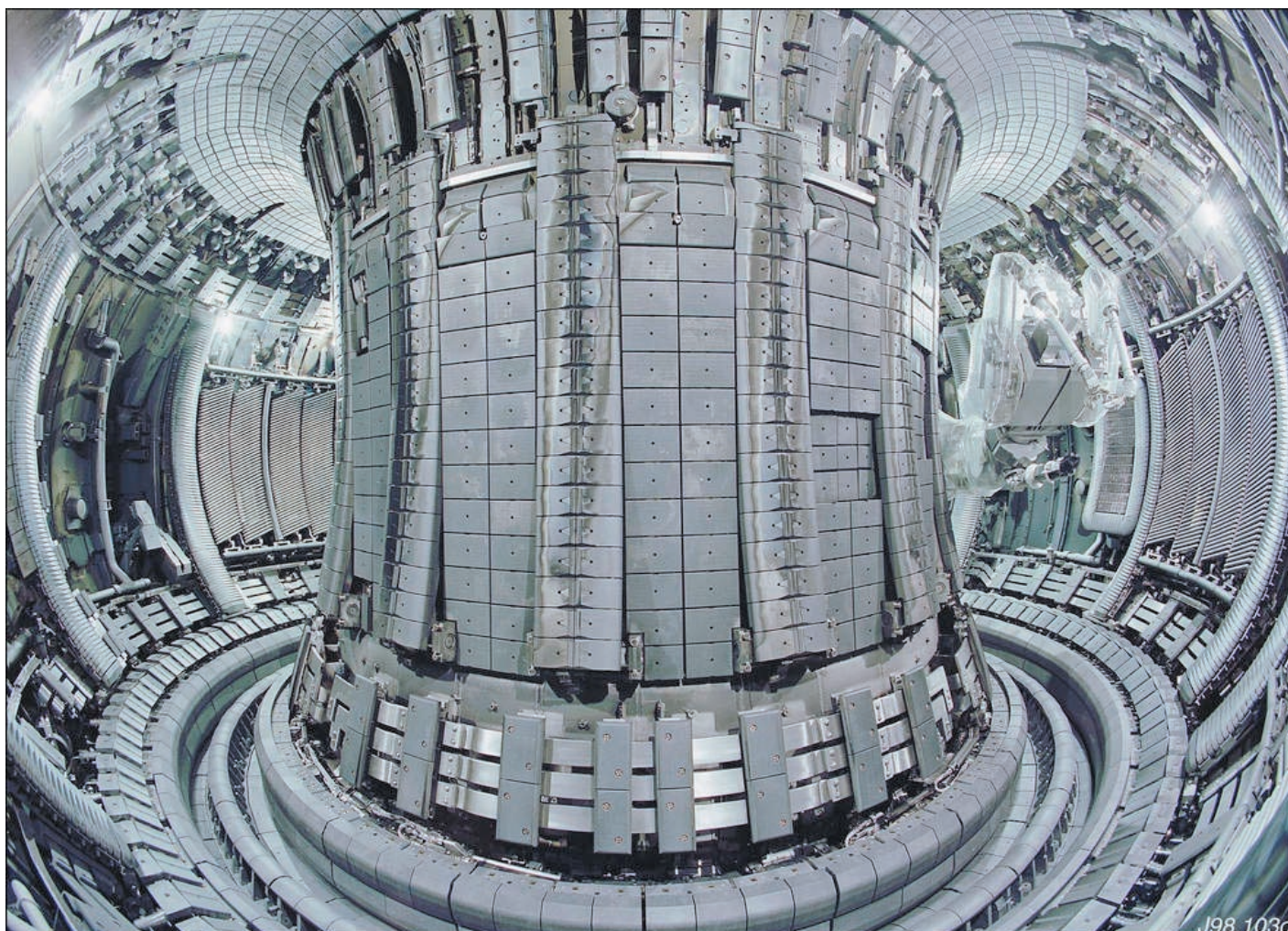
We have now met most of the ways that nuclei are made in stars. The initial hydrogen from the Big Bang fuses within the hot cores of stars, producing helium, which adds to the helium already produced just after the Big Bang. When the hydrogen in a star has been consumed, a succession of changes begins. The details of these changes depend on the mass of the star. In the heaviest stars, quite large amounts of elements up to iron are produced. Beyond that there is a precipitous drop in production, but significant amounts of copper and zinc (elements 29 and 30) are produced. These elements are essential for life, but only a few beyond them are, such as selenium (34), molybdenum (42) and iodine (53).

For elements such as these, the stable isotopes with the largest neutron numbers tend to be made in the r-process, whereas the stable isotopes at the very bottom of the energy valley tend to be made by the s-process.

There are also other processes at work. For example, certain supernovae, known as type Ia, appear to produce huge fluxes of protons instead of neutrons. These give rise to the ‘rapid proton’ or ‘rp-process’. This is similar to the r-process except that it operates on the proton-rich side of the energy valley. A nucleus absorbs several protons before it has a chance to undergo beta decay. The rp-process produces certain proton-rich isotopes that could not otherwise be made.

Another remarkable feature of these supernovae is the production of huge amounts of the unstable isotope of nickel, ^{56}Ni . This nucleus has 28 protons and 28 neutrons and is therefore a double closed shell nucleus. It is presumably formed by the successive fusion of 14 alpha particles, but a nucleus as far as ^{56}Ni from the floor of the energy valley cannot be stable even if it does have closed shells of both protons and neutrons. A ^{56}Ni nucleus has a considerable excess of energy, which it releases by beta decaying first to ^{56}Co (cobalt) and then to ^{56}Fe . When the star explodes, the energy released by these beta decays heats up the ejected material, contributing to the spectacular visible displays made by these supernovae.

Yet another process is responsible for producing certain light nuclei such as the lithium isotope ^6Li . Although a small amount of another lithium isotope, ^7Li , was made in the Big Bang, ^6Li was not. In addition, it is not made in stars – on the contrary, stars destroy it. The isotope ^6Li , along with the beryllium isotope ^9Be , are

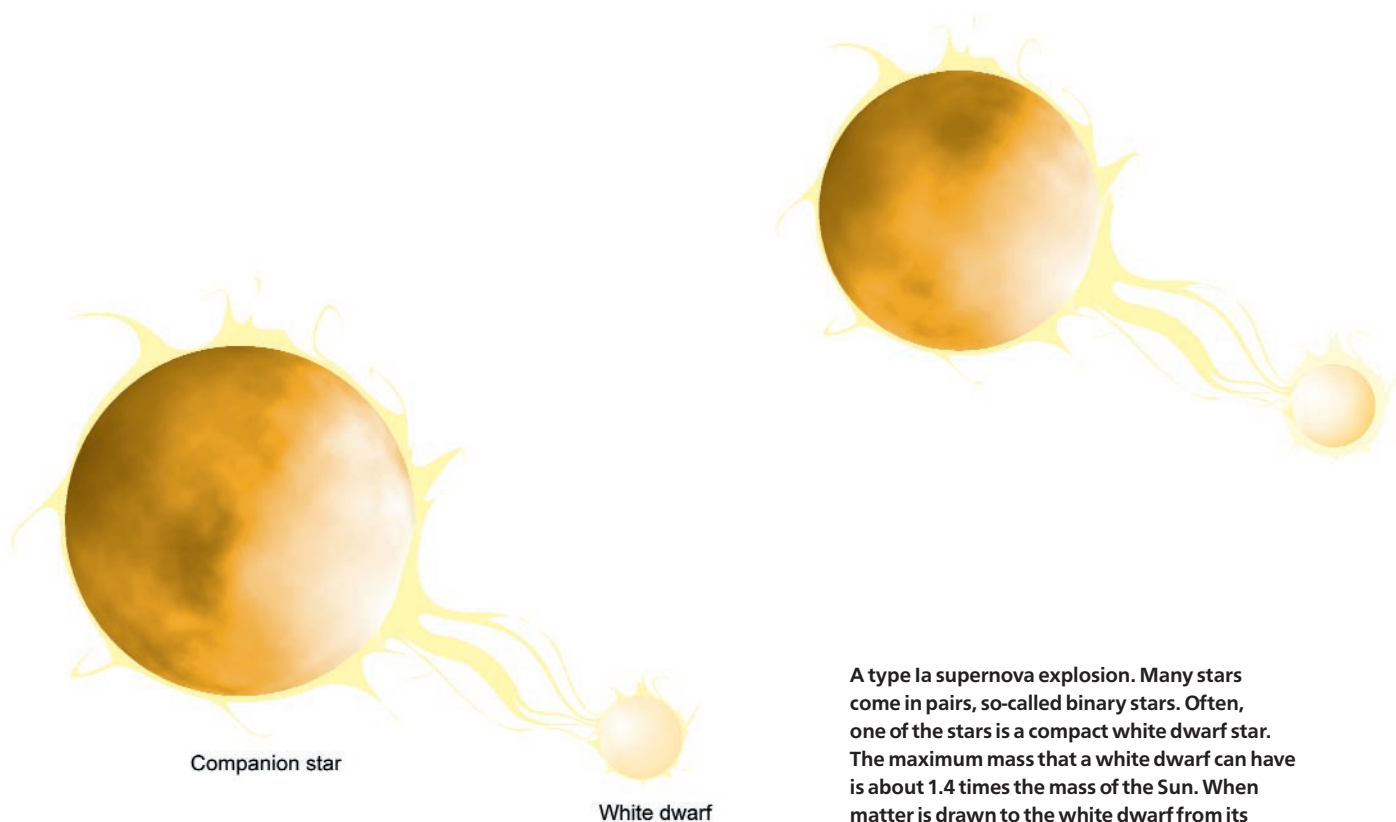


JET, the Joint European Torus, is located at Culham, near Oxford in the UK. Deuterium and tritium ions, held in place by strong magnetic fields, are made to collide and fuse within the donut-shaped vacuum chamber. The cut-away shows the huge magnetic pole-pieces around the vacuum vessel. The height inside the vacuum vessel is more than 4 metres and the whole apparatus is 12 metres high. JET is just part of the long and difficult international effort to harness fusion energy for peaceful purposes on Earth.
(Photographs courtesy EFDA-JET.)

made by a process known as spallation, which follows the collision of a very high energy proton with a ^{12}C or ^{16}O nucleus in interstellar space. Such high energy protons are a major part of the cosmic rays that bombard the Earth from all directions. When the high energy proton strikes the heavier nucleus, it smashes it, producing a variety of lighter nuclei, known as spallation products, including ^6Li and ^9Be , which are not made elsewhere.

It is not surprising there is still uncertainty about the very complex processes in which heavy nuclei are made. Much of our understanding comes from painstaking measurements on unimaginably remote stars. A sample of material can never be taken directly from stars, but we do have access to matter produced in stars. After all, this is the matter of which we are composed.

The meteorites that sometimes fall to Earth are an even purer sample of the ash from exploding stars. Using data from meteorites and from the spectra of stars, astronomers and nuclear physicists have achieved an understanding of how the stars produce both heat and new elements. Many remarkable and surprising processes have been discovered and behind them all is the guiding hand of the nuclear energy valley.



A type Ia supernova explosion. Many stars come in pairs, so-called binary stars. Often, one of the stars is a compact white dwarf star. The maximum mass that a white dwarf can have is about 1.4 times the mass of the Sun. When matter is drawn to the white dwarf from its companion star and its mass is pushed over this limit, the star detonates in spectacular fashion.



The Crab Nebula is the remnant of a supernova that occurred in AD 1054 in the constellation of Taurus. At its heart is a pulsar. We now know that the pulsar is a neutron star, all that remains of the exploding star whose outer layers now fill vast regions of space.
(Courtesy European Southern Observatories.)

