STAR DEATH AND ELEMENT BIRTH

We have seen that the oldest stellar groups within the Milky Way - the globular star clusters - contain red giant stars in place of the hot blue main-sequence stars which characterise young stellar groups. This observation tells us that once a star's main-sequence career is over it becomes a red giant. In this chapter we will explore the processes by which stars die, and in doing so we will uncover the mechanisms by which the chemical makeup of the Universe is being determined.

1. The formation of the red giants

The helium produced by hydrogen fusion in a main-sequence star accumulates in the centre of the star, as that is where the fusion reactions initially take place. This helium residue is hot, the nuclei emerging from the fusion reactions with kinetic energies corresponding to a temperature of tens of millions of Kelvin, but it is not hot enough for significant numbers of these helium nuclei to penetrate the Coulomb barrier and take part in further fusion reactions.

A basic difficulty in helium fusion is the great stability of He^4 itself. The nucleus formed by fusing a proton with an He^4 would be Li^5; as this has less binding energy than an He^4 such a process would actually absorb energy from the star and cool the core down. Even if it did occasionally occur, the result would be short-lived, for the Li^5 arrangement of nucleons is unstable to decay into a proton and an He^4 precisely because of the tighter binding of the He^4. The same difficulty also appears in helium-helium fusion; the nucleus which can be formed directly by the fusion of two He^4 nuclei is Be^8, which breaks up again into two He^4 nuclei in about 3×10^{-16} second. This means that no significant fusion reactions can occur in a helium core until conditions are reached which permit the essentially simultaneous fusion of <u>three</u> He^4 nuclei:

$$He^4 + He^4 + He^4 \longrightarrow C^{12} + \gamma$$

This "triple-alpha" process faces two physical obstacles. The first is the intrinsic implausibility of a collision between three He^4 nuclei effectively within the 3×10^{-16} lifetime of a Be^8 combination of two of them. The triple collisions are unthinkably rare except in helium of very high density, where collisions between nuclei are very frequent. The second obstacle is the Coulomb repulsion between the Be^8 nucleus (formed for 3×10^{-16} second by the fusion of the first two He^4) and the third arriving He^4. The Be^8 contains four protons and the third He^4 contains two, so the Coulomb barrier is eight times higher for this reaction than it was for the proton-proton reaction. This means that temperatures about eight times higher (in practice close to 100 million Kelvin) must be reached before the triple-alpha process can be significant.

Before the accumulating helium core in a main-sequence star can supply further energy through nuclear fusion, it must therefore be both compressed and heated. The star's gravity ensures that this will indeed take place - a helium core inside a main-sequence star is effectively a helium star-within-a-star faced with the problem of supporting not only its own weight but also that of the outer hydrogen envelope pressing down on it. Because it cannot initially generate the energy necessary for support by fusing He^4 to C^{12}, it must succumb to gravitational squeezing. At this stage, the hydrogen-fusing level of the star has become a shell surrounding the helium core, as in Figure 1.

The collapse of the helium core does release energy however; by slowly contracting the core allows the star's gravity to do work on it, and hence releases gravitational potential energy as kinetic energy (temperature) in the core. Until the core density is high enough to permit the triple-alpha collisions, the main effect of this rise in temperature is to increase the amount of radiation leaving the core and thus to "cook" the hydrogen-fusing level immediately above. The result is spectacular.

As the core collapse begins, the hydrogen-fusing level is responding to the gravitational squeezing from above by liberating energy from fusion at just the rate necessary to maintain the pressure gradient which supports the star as a whole. Indeed, its temperature has adjusted to make this rate of energy release exactly that required for equilibrium. The release of gravitational potential energy by the collapse of the helium core then raises the temperature in the adjacent hydrogen-fusing shell beyond that necessary for support of the star as a whole. The higher temperature in the fusion shell means that far more protons penetrate the Coulomb barrier there each second than are necessary just to support the outer layers of the star. The hydrogen fusion actually begins to run <u>too fast</u> for equilibrium.

It is important to appreciate the nature of the change which is overtaking the star at this stage. Before the helium accumulation became significant, the entire star was living off the energy proceeds of the one very efficient process - hydrogen fusion. It was therefore possible for the density, temperature, pressure and energy flow demands to be met at all levels by a unique stable structure which evolved only very slowly as its interior chemistry slowly changed. But the development of the helium core now introduces a dichotomy between the core and the rest of the star; the core cannot support itself by fusion and so must collapse. Its temperature is then governed by its own gravitational collapse and not by the requirements of hydrogen fusion. As a result it "loses contact" with the equilibrium needs of the fusion level and suceeds in overheating that level. The days of the star's existence as a coherent, well-regulated fusion reactor are now over; as different levels become out of kilter with one another in their demands for support and their energy flows, large fluctuations in the star's condition become possible.

The "overcooking" of the hydrogen fusion shell, and the enormous extra release of energy by fusion that results, increases the gas pressure everywhere in the star outside the core, and so the star begins to inflate itself. For a while the increased energy flow is used up doing work against the gravitational self-squeezing of the hydrogen, which re-expands towards a size it had not had since it was a protostar. Eventually the hydrogen envelope reaches a size where it can radiate away the surplus energy from its newly-bloated surface even though its expansion has cooled the surface down. It is then a luminous "red giant" (Figure 2).

The red giant is in a most bizarre condition. Theoretical calculations suggest that typically one-quarter of the mass of the star is compressed into a collapsing core only a few times larger than the Earth but containing many tens of thousands times Earth's mass; the core density is thus some 10,000 times that of water. At the same time the remaining three-quarters of the star is inflated to a size comparable with that of Earth's orbit around the Sun, reducing its density to that of a respectable laboratory vacuum. When the Sun reaches this stage of development approximately 5 billion years from now the Earth will be barbecued by the radiation from the swollen stellar surface, which may even surround it instead of being comfortably 150 million kilometres away !

2. Degeneracy pressure and the "helium flash"

The helium core inside a red giant eventually reaches a new equilibrium which arises from a quantum-mechanical effect of extreme compression. As the helium is squeezed to very high densities, the volume of space per particle - helium nucleus or electron - steadily decreases. The gravitational squeezing of the core increasingly crowds each particle. When subatomic particles are localised, their wave nature becomes apparent, and the helium cores of red giants are no exception to this rule. The individual particle-waves are required by gravity to fit into a core of steadily decreasing size; as in the atom the particle-wave storage is quantised, with only the standing-wave modes being allowed. In the core at a given temperature the nuclei and electrons have the same average kinetic energy so

$$\tfrac{1}{2} m_e v_e^2 = \tfrac{1}{2} m_\alpha v_\alpha^2$$

where m_e and m_α are the masses of the electrons and helium nuclei respectively, and v_e and v_α are the average velocities of these particles. This means that the momenta of the electrons will be less than the momenta of the nuclei:

$$m_e v_e = m_e v_\alpha \sqrt{(m_\alpha/m_e)} = \sqrt{m_e m_\alpha}\, v_\alpha$$

and $\sqrt{m_e m_\alpha}$ is less than m_α, so $m_e v_e$ is less than $m_\alpha v_\alpha$.

so the de Broglie wavelengths of the electrons will be <u>longer</u> than those of the nuclei. The electrons will therefore experience difficulty fitting integral numbers of their half-wavelengths into the helium core before the nuclei run into the same problem. An important role is played here by the Pauli Principle, which requires the electron waves in the stellar core to fit in with <u>different</u> integral numners of half-wavelengths, so that no two electrons fit into the same region of space with exactly the same set of quantum numbers. For very large numbers of electrons in a given volume this becomes a serious constraint as all the available long-wavelength standing-wave modes become occupied (Figure 3).

When all the long-wavelength modes are occupied the electrob gas in the stellar core is said to be "degenerate". Pauli himself predicted what would happen in such circumstances should they ever be realised in nature. When all the long-wavelength modes are "in use" by electrons further reduction of the size of their "container" (in this the gravitationally-confined core of the star) forces the electron wavelengths to decrease in proportion to the size of the container. Decreasing the de Broglie wavelengths corresponds to increasing the electron momenta, and so increases the pressure exerted by the electron gas. A "degenerate" electron gas exerts a much greater pressure on its surroundings than does an ordinary non-degenerate one, and thus becomes very rigid, strongly resisting further compression. It is the appearance of this unavoidable consequence of the wave nature of the electron - "degeneracy pressure" - that first slows down the collapse of the helium core of a red giant.

Once degeneracy pressure becomes significant in the core, the core would settle down to a stable size were it not for the fact that hydrogen fusion in the level above it continues to add more helium to the core mass. Thus the core collapse is slowed down rather than stopped altogether. Because degeneracy pressure depends on the core density rather than its temperature it also has the effect of ironing out the original temperature gradients in the core, so that the core begins to resemble a single coherent rigid object yielding only slowly to the gravitational squeezing.

Eventually the density and temperature throughout the core become so high that the triple-alpha process becomes possible there. Because degeneracy has equalised temperature and density conditions throughout the core this happens everywhere at once within the core. Suddenly a helium core that was very close to holding itself up with degeneracy pressure finds itself producing energy again by nuclear fusion, this time of helium into carbon. Obviously once again a level in the star is now releasing energy at a rate that has nothing to do with simple support of that level. Indeed, the onset of helium fusion in the already nearly-stable core is like the detonation of a bomb deep inside the star, causing the core to ~~re-expand and~~ again overheat~~ing~~ the hydrogen level immediately above it, so that hydrogen fusion runs much too fast there as well.

The sudden onset of helium fusion rapidly produces a carbon core within the helium at the centre of the star. The helium briefly has an energy surplus and the excess energy removes the degeneracy ~~so re-expands against its gravity, reducing the density and~~ replac~~ing~~es degeneracy pressure with conventional gas pressure. All levels in the star must now seek a new equilibrium. This set of phenomena, known as the "helium flash", does not disrupt the star but signals the beginning of a complex series of events in which the energy flows within the star become almost anarchic in comparison with the simple state of affairs on the main sequence.

The details of stellar evolution beyond the helium flash are both complex and controversial. We cannot observe the processes directly and our understanding of them comes from observations of the external effects of changes in the balance between fusion, degeneracy, and gravitation, and from stellar "models" - calculations of the equilibrium of older stars using computers which have been programmed to take into account the known rates of nuclear reactions and the fundamental processes known to present-day physics. The finer details of the picture of late stellar evolution are therefore subject to many uncertainties arising from our incomplete understanding of nuclear processes. Some predictions emerge consistently from the model-making and correspond to observed phenomena however, so we can expect that they are at least qualitatively correct.

3. Variable stars, novae and supernovae.

Once a star develops a carbon core and helium fusion migrates upwards into a shell outside this core, its days of stability are all but over. The detailed behaviour of such a multi-layered star depends on a combination of parameters, particularly its total mass and initial chemical composition (i.e. initial ratios of heavier elements to hydrogen). The onset of fusion in a level that was previously holding itself up by degeneracy pressure will always be explosive and will force rapid changes in the equilibrium of adjacent levels in the star.

In many stars it appears that the re-expansion following the "turning on" of new fusion processes overshoots what might be a new equilibrium structure, thus overcooling the stellar gases until gravity pulls them back in again and reheats them. Such "overshoot" behaviour can set up radial oscillations (pulsations) in a star, so that it alternately overexpands and overcontracts around its 'new' equilibrium size. Pulsating stars continuously seek equilibrium but always pass through it as their gases are always in motion inwards or outwards at the moment when the equilibrium structure is achieved. The situation is exactly analogous to the motion of a pendulum, which after an initial disturbance (raising the bob) passes through its ultimate (vertical) equilibrium condition twice per swing, but cannot actually stop there because its kinetic energy is greatest at the moment when the equilibrium condition is reached. Indeed some stars pulsate as regularly as a pendulum clock ticks, oscillating back and forth between an undersized, overheated, overluminous extreme and an oversized, overcooled, underluminous extreme with a regular period which can be a few years, weeks , or even hours. Such stars vary regularly in their luminosity and colour (i.e. surface temperature) and are known as <u>periodic</u> <u>variables</u>.

Sometimes the sudden onset of new fusion processes causes a star that is normally inconspicious in the sky to flare into brilliance, increasing its luminosity by factors of a thousand or more. A star previously undetectable with given equipment may thus become easily detectable within the space of a few days. Such apparitions were once thought to be the birth of "new stars" and the Latin name "<u>nova</u>" ("new") is still applied to the phenomenon even though we now recognise them as precursors of stellar death. The light flare of a nova usually occurs in a matter of days, then slowly decays over a period of several months. Oscillations in light output are sometimes seen as the flare decays, as in the case of V603 Aquilae (Figure 4), a nova which flared in 1918. Telescopic observations of some novae have shown that shells of gas can be ejected from the stars during the nova process (Figure 5). Some stars have had several outbursts in modern times and are therefore known as <u>recurrent</u> <u>novae</u>. The different physical processes which can cause novae are poorly understood in detail; many novae are members of binary star systems and it is possible that exchange of material between the components of such systems may play a role in triggering some nova outbursts.

Far more spectacular than the novae are the stellar explosions known as <u>supernovae</u>. In these, the most violent of known stellar phenomena, a single star briefly becomes as brilliant as ten billion Suns. Supernovae are detected regularly in other galaxies, where they are found to occur at an average rate of one per galaxy per thirty years. Supernovae in our own Milky Way galaxy are harder to detect because of the dimming of their light by the interstellar dust; although the line of sight to other galaxies is much longer than that through our own, most known external galaxies are in directions in which there is relatively little dust in ours, which more than compensates for the great extragalactic distance (Figure 6). The outburst in Cassiopeia witnessed by Tyge Brahe in 1572 was in fact a supernova within our Milky Way in a relatively favourable position.

The enormous luminosities of supernova explosions, causing single stars to compete in brilliance with entire galaxies, tell us that extremely potent energy supplies have been tapped, yet we know that it is on the main sequence that the most efficient nuclear fuel is being used. Supernova outbursts expend in a few months an amount of energy comparable with that released by the Sun during its entire main-sequence career so far. If this is indeed the result of nuclear processes that are not individually very efficient we must conclude that large masses of material and large numbers of fusion steps are involved within a very short space of time. Detailed computations of stellar models confirm this basic picture, suggesting that supernova explosions involve the most massive stars, in which the gravitational squeezing becomes so intense that their cores collapse virtually continuously despite degeneracy pressure and fusion of helium, carbon and other light elements into heavy nuclei. Models of the supernova phenomenon indeed suggest that fusion in the most massive cores proceeds all the way from carbon to iron, the most stable species of nucleus, in a matter of minutes, creating a dense hot environment in which virtually every conceivable nuclear process becomes possible. Computer simulations of this regime are obviously only the roughest of approximations, but many studies have shown that these most violent conflicts between gravity and nuclear forces can eject large amounts of matter into interstellar space, as well as leaving some very intriguing residues whose nature we will discuss below.

4. The abundances of the chemical elements.

We will now look in more detail at the stellar processes which build up heavy nuclei from lighter ones. Whereas up until now we have been considering these processes from the point of view of the star in its battle for support against gravity, now we will be concerned with the abundances of the heavy-element products.

As we discussed in the previous chapter, the abundances of the elements on the surfaces of stars today indicate the mix of elements that was present in the gas from which these stars condensed. They also tell us that the heavy-element content of this gas has been increasing with time. Now that we have briefly described the late stages of stellar evolution, with their violent instabilities and occasional ejection of material, we may ask if the composition of the interstellar gas has actually been established by the processes of stellar evolution.

Figure 7 shows the observations that we should attempt to explain. The relative abundances of the elements shown in this plot come from a list based on stellar spectra and meteorite compositions compiled by Cameron in 1973. The main features of this observed element-abundance curve, which is the best average we can determine for the local universe, are as follows:

1) There are hardly any heavy nuclei. The entire plot for elements heavier than helium amounts to only about 1 per cent of the total. Although the details of the abundances of the rarer elements are very important to life on Earth, the universe we inhabit is primarily a hydrogen-helium world.

2) In general , the heavier the nucleus the less abundant it is in nature. With some significant exceptions, e.g. iron, the trend of the abundance curve is towards rarer occurrence with increasing nuclear mass (and nuclear charge).

3) The nuclei between helium and carbon - lithium, beryllium and boron - are very rare compared with the other light nuclei. They are only one-millionth as abundant as carbon, nitrogen and oxygen, for example.

4) The nuclei which can be made up as multiples of He^4 nuclei - C^{12}, O^{16}, Ne^{20}, Mg^{24}, Si^{28}, S^{32}, A^{36} and Ca^{40}, are more abundant than the other stable nuclei of comparable mass.

5) There is a conspicuous peak in the abundance curve at and near iron.

The theory of nuclear processes in stars can explain all of these phenomena.

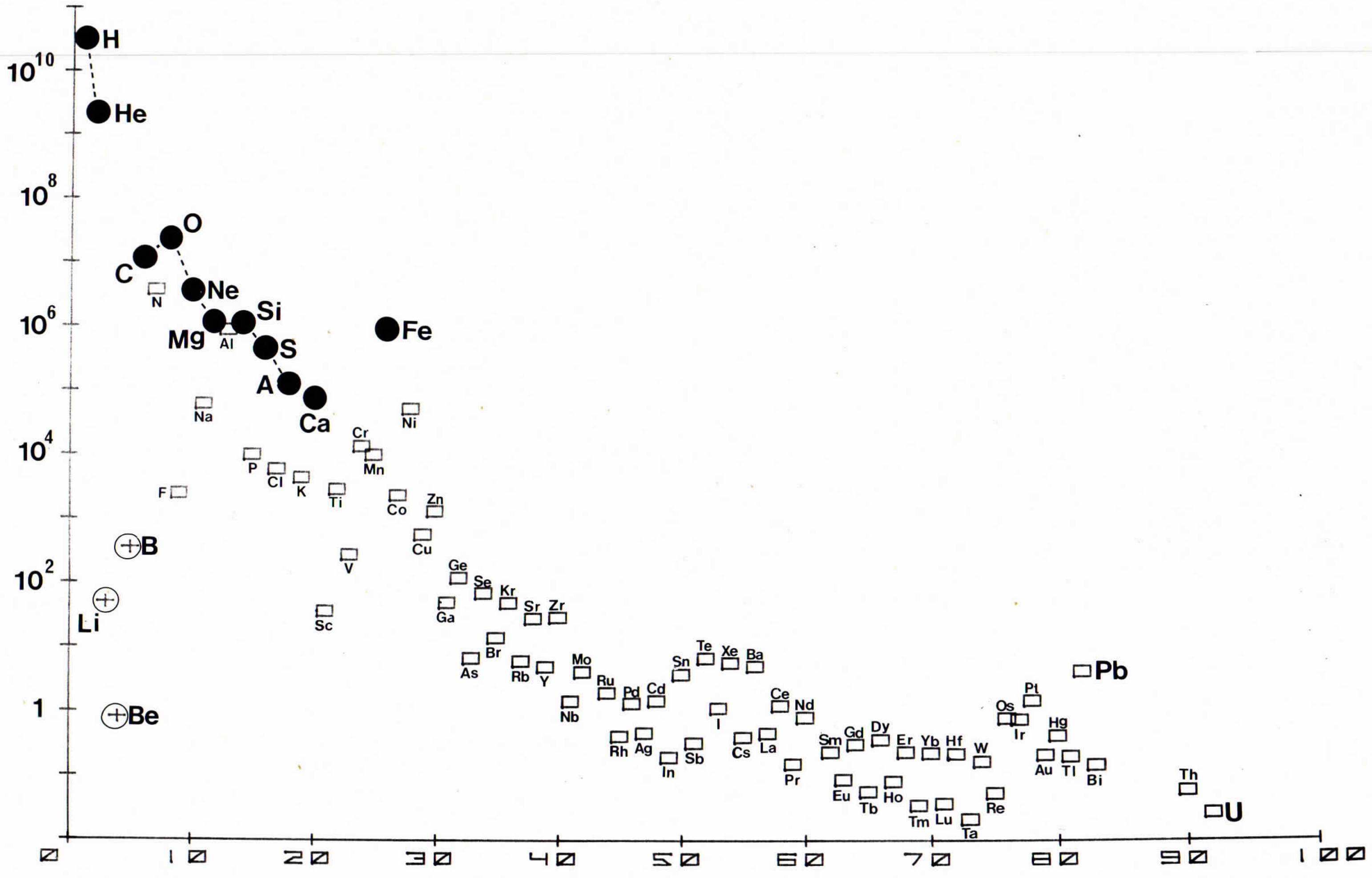
5 Element production by hydrogen fusion.

Hydrogen fusion is the main long-term energy source in stars. What does it do to produce heavy elements ? We saw earlier that its main effect is to convert hydrogen into He^4. The principal hydrogen-fusing reactions:

$$H^1 + H^1 \rightarrow H^2 + e^+ + \nu$$
$$H^2 + H^1 \rightarrow He^3 + \gamma$$

produce deuterons (H^2) and the lighter helium isotope He^3, but break them down again on the way to making the very stable He^4. At any

ABUNDANCES OF THE ELEMENTS



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given instant in a hydrogen-fusing level, some H^2 and He^3 will be present, but they will usually be consumed again as the $H \rightarrow He^4$ sequence goes to completion. The stable closed-shell He^4 nuclei continually build up in abundance however. Some other side-reactions which can occur occasionally in the hydrogen-fusing levels are:

$$\begin{aligned}
&He^3 + He^4 \rightarrow Be^7 + \gamma \\
&Be^7 + e^- \rightarrow Li^7 + \nu \\
&Li^7 + H^1 \rightarrow He^4 + He^4 \\
\text{or } &Be^7 + H^1 \rightarrow B^8 + \gamma \\
&B^8 \rightarrow He^4 + He^4 + e^+ + \nu
\end{aligned}$$

These reactions will produce small quantities of lithium, beryllium and boron nuclei, which will in turn mostly be broken down to make more He^4. During the violent events in stellar old age however it is possible that the contents of the hydrogen-fusing levels can be blown off into interstellar space as the result of the onset of fusion in a degenerate level deeper in the star. The explosive nature of fusion in a degenerate stellar level now has an important consequence for the composition of the interstellar gas -- stellar deaths can enrich the interstellar gas with heavy elements produced during stellar evolution.

Stars which condense from enriched interstellar gas may then contain heavy nuclei which were manufactured during the later stages of the evolution of earlier stellar generations. Second-generation stars may therefore contain carbon nuclei produced by helium fusion in earlier stars. Studies of nuclear reactions in the laboratory indicate that another hydrogen-fusion sequence may then be possible at somewhat higher temperatures than the ten million degrees or so at which simple proton-proton fusion begins:

$$\begin{aligned}
&H^1 + C^{12} \rightarrow N^{13} + \gamma \\
&N^{13} \rightarrow C^{13} + e^+ + \nu \\
&C^{13} + H^1 \rightarrow N^{14} + \gamma \\
&N^{14} + H^1 \rightarrow O^{15} + \gamma \\
&O^{15} \rightarrow N^{15} + e^+ + \nu \\
&N^{15} + H^1 \rightarrow C^{12} + He^4
\end{aligned}$$

This sequence needs higher temperatures to begin because the Coulomb repulsion between C^{12} nucleus and a proton is six times that between two protons; it will therefore be significant only in the more massive stars whose core temperatures are higher, or in the later stages of stellar development where the hydrogen-fusing levels are cooked from below by the collapse of a helium core. This reaction scheme does not use up the supply of C^{12} in the stellar interior, because a C^{12} is generated at the end of the process to replace the one which fused with a proton at the beginning; the net result is again the conversion of hydrogen into helium. It does however mean that at any time there may be nuclei of oxygen and nitrogen in the hydrogen-fusing levels, so that the ejecta of stellar explosions may contain some of these elements as well as those previously mentioned.

6. Helium fusion and the multiple-α nuclei

Important steps in the element-producing process are determined by the helium-fusing stage of a star's career. We saw earlier in this chapter that lithium and beryllium are bypassed during helium fusion because Li^5 and Be^8 are so unstable, and that helium fusion begins with the triple-alpha process

$$He^4 + He^4 + He^4 \rightarrow C^{12} + \gamma$$

which must produce large amounts of C^{12} in the star's interior. Once this has happened it is not hard to continue further:

$$\begin{aligned} C^{12} + He^4 &\rightarrow O^{16} + \gamma \\ O^{16} + He^4 &\rightarrow Ne^{20} + \gamma \\ Ne^{20} + He^4 &\rightarrow Mg^{24} + \gamma \end{aligned}$$

Under extreme conditions further addition of He^4 nuclei can produce significant abundances of all nuclei which are simple multiples of He^4 (the multiple-α nuclei) up to and including Ca^{40}, which is the most massive stable nucleus having equal proton and neutron numbers. At masses above Ca^{40} the saturation of the nuclear force means that extra neutrons are needed to stabilise the nuclei against the Coulomb repulsion of their protons; beyond Ca^{40} the formation of multiple-α nuclei is therefore not particularly favoured.

Again remembering that the contents of a helium-fusing level in a star may be ejected into the surroundings during a stellar explosion, we see that we can understand the low abundances of lithium, beryllium and boron, which were bypassed during helium fusion and are both manufactured and destroyed by hydrogen fusion; we can also explain the high abundances of the multiple-α nuclei between C^{12} and Ca^{40}

if these multiple-α nuclei are indeed ejected from the helium-fusing regions of earlier generations of stars.

These ideas imply that the details of the abundance curve are not random, but carry the imprint of stellar fusion processes. If the chemical elements each had an origin independent of all the others, then why should there be the deficiency of lithium, beryllium and boron, and the relative excess of the multiple-α nuclei ? The fact that such details of the abundance curve can be related to the systematics of fusion processes in stars, and the fact that the heavy-element abundances appear to have been increasing with time, have led astronomers to consider the possibility that the entire abundance curve has been produced by stellar processes acting on a "primeval" mixture of nearly pure hydrogen. To see if this could indeed be correct, we need to examine some of the processes of very late stellar life, beyond the helium-fusing stages.

7. Carbon fusion and the production of neutrons.

We referred to one carbon-fusion process above, namely fusion with He^4 to make the stable and abundant oxygen nucleus O^{16}. Direct C^{12}-C^{12} fusion forms Ne^{20}:

$$C^{12} + C^{12} \rightarrow Ne^{20} + He^4$$

making still more He^4 available and helping to account for the high abundance of Ne^{20}, but the Coulomb barrier to still heavier C^{12} fusion is formidable in all but the highest temperature regimes. Much more likely, because of the lower Coulomb barrier, is fusion of C^{12} with residual hydrogen:

$$C^{12} + H^1 \rightarrow C^{13} + e^+ + \nu$$

followed by $C^{13} + H^1 \rightarrow N^{14} + \gamma$

or $C^{13} + He^4 \rightarrow O^{16} + n$

The last reaction is particularly interesting; not only does it provide yet another route to O^{16} but it releases <u>free neutrons</u> in the stellar interior. Because neutrons have no electrical charge there is no Coulomb barrier to their entry into nuclei and they are therefore much more effective instigators of fusion reactions than are charged nuclei such as H^1 or He^4. Once carbon fusion has begun, the door is open to many more fusion reactions, leading to a greater variety of chemical elements, than before. It would not be practical at this point to write down equations for all the fusion processes which might occur, nor in fact would it be necessary. It is sufficient to realise that routes exist to all known stable nuclei through fusion processes and to ask what factors will determine the relative abundances of the various products which might result.

Firstly, not all close encounters between nuclei in a stellar interior lead to fusion reactions - those reactions which can bring a given group of nucleons to a particularly low total energy (i.e. those which release particularly large amounts of binding energy and form very stable products) are more likely to occur than those which bring about only minimal lowerings of the total energy. Because the He^4 multiples are particularly stable and because He^4 is produced by fusion of the most abundant stellar constituent (hydrogen), the multiple-nuclei are very likely to be formed. Once formed, they are harder than average to break up and so accumulate in larger-than-average abundances.

Secondly, the more steps that are necessary to form a given nucleus, the less likely is the sequence of steps to occur without interruption, and so the less abundant the resulting nucleus will be. This means that nuclei of high mass should be, in general, less abundant than nuclei of low mass, as is indeed observed. The obvious exception to this is the case of iron, which is a massive nucleus with a particularly high abundance.

The abundance of iron stems from the fact that Fe^{56} is the most stable nucleon configuration of all, representing the optimal balancing of nuclear attraction and Coulomb repulsion. If indeed old stars could continue fusing light elements indefinitely, then we might expect all matter eventually to accumulate into this most optimal form. The formation of iron will always be favoured, and its breakup will always be difficult, so it should indeed accumulate in large abundance, the ~~only~~ main factors preventing all stellar matter being converted into iron being the violent termination of the fusion sequence by the stellar explosions, and the high Coulomb barriers to reactions not involving neutrons.

8. The elements beyond iron.

The existence of <u>any</u> elements on the abundance curve of higher nuclear mass than iron seems to present severe problems if the whole curve is indeed to be explained by stellar fusion processes. How can fusion continue beyond the most stable nuclear species of them all ?

The existence of <u>some</u> matter with nuclei heavier than iron should not however be totally surprising. Given a high abundance of iron in old stellar interiors, we should expect some fusion with light nuclei and with neutrons to build up slightly heavier nuclei such as those of nickel, copper and zinc. What <u>is</u> surprising is the existence of natural nuclei with masses all the way up to uranium-238, over four times the mass of iron-56 ! That is no mere 'dribble' of fusion beyond the iron peak in the abundace curve.

What processes might bring about build-up beyond the most stable nucleus ? The reason for the fall-off in the binding-energy curve at large nuclear charges is the Coulomb repulsion of the protons in a massive nucleus. This tells us that it will be difficult to add protons, or He^4, or any other positively-charged particles, to Fe^{56} nuclei and have them accepted into the structure. Much more likely candidates for carrying the build-up beyons Fe^{56} are the uncharged neutrons. The fusion of C^{13} with He^4 is only one example of a process which can produce neutrons, so neutrons <u>will</u> be available in late stellar cores. Old stars may therefore contain both iron and neutrons.

Addition of neutrons to iron-56 produces the following results:

$$Fe^{56} + n \rightarrow Fe^{57}$$
$$Fe^{57} + n \rightarrow Fe^{58}$$
$$Fe^{58} + n \rightarrow Fe^{59}$$

Fe^{59} is now an unstable nucleon arrangement; the neutron potential well is now overful compared with the proton well (if we regard these as distinct) and a state of lower total energy can be reached through a beta-decay:

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

To make cobalt-59 directly from iron-58 would require the addition of a proton, which would have had to surmount a formidable Coulomb barrier. Neutron addition "sneaks in" another nucleon without having to deal with a Coulomb barrier, its conversion to a proton being achieved by the strong nuclear force. The neutron-addition process can now continue:

$$Co^{59} + n \rightarrow Co^{60} \rightarrow Ni^{60} + e^- + \bar{\nu}$$

If the neutron addition takes place on average more slowly than the half-lifes of the relevant beta-decays, then more and more neutron-rich isotopes of a given element are produced until the beta-decays intervene and produce isotopes of the nuclear species of next higher charge.

This process of slow neutron addition (the s-process) can convert a "seed" of Fe^{56} accumulated by the ordinary fusion reactions into more massive nuclei. We would not expect this process to be very efficient, but even the most abundant of the heavier-than-iron species beyond the iron peak has an abundance less than one hundred-thousandth that of Fe^{56}, so the process need not be very efficient to be consistent with the observations.

The s-process cannot provide all observed nuclear species however, so this is still not a complete picture. There are two major problems if we try to explain the origin of all heavier-than-iron elements in terms of the s-process.

Firstly, the s-process cannot make any nuclei more massive than bismuth-209, because both beta-decays and alpha-decays then stand in its way:

$$
\begin{array}{lll}
Bi^{209} + n \rightarrow Bi^{210} & & \\
Bi^{210} \rightarrow Po^{210} + e^{-} + \bar{\nu} & & \text{(beta-decay)} \\
Po^{210} \rightarrow Pb^{206} + He^{4} & & \text{(alpha-decay)} \\
Pb^{206} + n \rightarrow Pb^{207} & & \\
Pb^{207} + n \rightarrow Pb^{208} & & \\
Pb^{208} + n \rightarrow Pb^{209} & & \\
Pb^{209} \rightarrow Bi^{209} + e^{-} + \bar{\nu} & & \text{(beta-decay)}
\end{array}
$$

For every four steps up the nuclear-mass ladder from Pb^{206}, the rapid decays force the process four steps back and there is no net progress. Bi^{209} is the furthest this sequence can ever get in nuclear mass. But Bi^{209} is not the most massive nucleus found in nature - indeed the uranium nuclei U^{235} and U^{238} on which modern nuclear fission technology is based lie well beyond this "bismuth barrier" on the s-process.

A second problem is that some stable nuclei between Fe^{56} and Bi^{209} cannot be reached by the s-process alone. There are isotopes which contain large numbers of neutrons but which cannot be manufactured by the s-process because an isotope with a smaller neutron number is unstable to beta-decay. (The reasons for the stability of these neutron-rich nuclei depend on nuclear details that are beyond the scope of the simple discussion we have made here). Examples are

The beta-decays which stand between the s-process and the formation of neutron-rich or very heavy nuclei (heavier than Bi^{209}) have typical half-lives of 1/100 second. Addition of neutrons to "seed" nuclei can overcome these beta-decay barriers only if the additions to a given nucleus occur *more rapidly* than the beta decays can enforce equilibrium. The "brute force" hypothesis of very rapid (faster than 1/100 second) addition of neutrons to the "seed" nuclei is known as the r-process. It amounts to the hypothesis that in some stellar environments the seed nuclei are exposed to a flood of neutrons; if it *can* occur in nature then buildup from iron to uranium would take place in only a few seconds.

We described the r-process as a hypothesis, for that is what it ultimately is. We cannot be sure where [redacted] the r-process actually occurs during stellar evolution. The r-process has however been seen in man-made nuclear explosions, in which elements up to and including the unstable Californium-254 have been synthesised. Theoretical calculations of the details of the abundances [redacted] *expected* from the r-process show that it produces strong abundance peaks at nuclei with particular numbers of neutrons which correspond to "closed shells" in the nuclear structure; these "neutron magic numbers" are 50, 82 and 126 neutrons. Figure 8 compares abundances calculated from the theory of the r-process with those actually observed; the agreement is quite good, indeed remarkably good when we consider that both the calculations and the measurements are still subject to considerable uncertainties. Both the observation of the r-process in man-made nuclear fusion systems and the agreement between these calculations and the observed abundances have led astronomers to believe that the r-process has probably occurred somewhere in the stellar universe to produce the observed amounts of neutron-rich and heavy elements such as uranium.

There is still controversy however about the actual location of the r-process in nature. A neutron flood bombarding the seed nuclei 100 times per second or faster is not expected during the evolution of most stellar masses. A possibility is that the r-process occurs during supernova explosions, which we do know [redacted] to involve fusion processes at a frantic rate in order to produce the observed sudden billion-fold increase in the dying star's light output. The problem is that supernovae are also thought to involve only fairly massive stars (more than about 2 solar masses) which are not now particularly common in the Milky Way. If the r-process is associated with supernovae, a patchy distribution of "r-process nuclei" in the gas clouds around the Milky Way is expected, whereas the observed distribution of these nuclei is actually quite uniform. Possibly supernovae (i.e. massive stars) were more common (and hence more widespread) in the past than they are now and so produced a fairly uniform distribution of the r-process nuclei before the recent stellar generations were formed. Such an assumption is presently very hard to check by observations and remains controversial. An attractive feature of the supernova hypothesis for the r-process is that the heavy nuclei such as uranium could be rapidly removed from the neutron flood which produced them, due to the explosive expansion of the supernova event. This would prevent these nuclei from being broken up again by neutron-induced fission (leaving that process, and its associated energy release, for us to employ at a much later date).

9. Our environment as stellar debris.

To summarise, although details of the theory of element production (nucleosynthesis) in stars are surrounded still by a healthy amount of controversy, it seems that the combined processes of slow (one neutron per year or slower) and rapid (hundreds of neutrons per second) neutron addition can account for the existence of, and some details of the abundances of, the elements heavier than iron. The abundances up to and including the iron peak appear to bear the clear imprint of the very processes <u>required</u> to support stars of various masses and ages against gravity.

All living matter on Earth is based on carbon chemistry - the ability of carbon atoms to link up into long molecular backbones which provide the microscopic structure of living organisms. According to the viewpoint we have just described, the relatively high abundance of carbon in the universe (relative to other heavier-than-helium elements) is intimately connected with its formation from helium by stellar processes. Ten or so billion years ago, when the globular star clusters formed, there was much less (about 1/100th) the amount of carbon outside stars that there is now. For the supply of carbon (and other heavy elements vital to life, such as oxygen, sulphur and phosphorus, magnesium and iron) we must thank the explosive processes of stellar death which ejected some of the nuclei manufactured by the stars in their struggle against gravity. Without the explosive deaths those nuclei would have remained in old collapsed stellar cores instead of

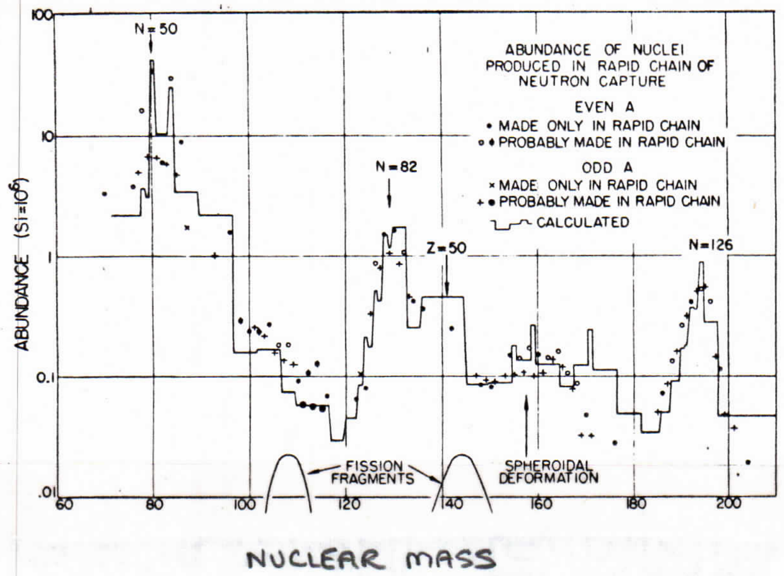
ABUNDANCE OF NUCLEI PRODUCED IN RAPID CHAIN OF NEUTRON CAPTURE
EVEN A
• MADE ONLY IN RAPID CHAIN
○ ● PROBABLY MADE IN RAPID CHAIN
ODD A
× MADE ONLY IN RAPID CHAIN
+ ● PROBABLY MADE IN RAPID CHAIN
CALCULATED
N = 50
N = 82
Z = 50
N = 126
FISSION FRAGMENTS
SPHEROIDAL DEFORMATION
ABUNDANCE (Si = 10⁶)
100
10
1
0.1
.01
60
80
100
120
140
160
180
200
NUCLEAR MASS

Fig. 8

having the chance to be incorporated into later-generation environments, including that of Earth.

Man's technology increasingly uses the exotic products of the s- and r-processes - materials such as uranium which, according to our picture, are manufactured only in the last fleeting seconds of the most pathological stellar deaths. It is perhaps sobering to recognise that in moving the basis of our technological energy generation from wood, coal, hydro and wind power towards nuclear fission power we would be moving ~~an important part of our society'~~s ~~daily interaction with stellar processes~~ from utilising the energy released by the "living" Sun beside us to utilising energy stored by a long-dead supernova; we would be moving from an energy supply drawn from the most abundant constituent of the universe - hydrogen - to an energy supply drawn from one of the least abundant - uranium. Perhaps we should be alarmed by this, as it may indicate that our own search for energy sources is getting out of kilter with the main energy flows around us; perhaps it is merely a reflection of our sophistication and no particular cause for concern. In any event, the picture of elemnt production by stellar processes reveals a more intimate connection between ourselves, our environment, and the stars than even a Nineteenth-Century romantic might have envisioned: we may literally be "children of the stars".