4

Fusion, fission, sunlight, and element formation

Introduction

The understanding of the origin of sunlight (and starlight in general) was a nineteenth and early twentieth century development that culminated in the release of nuclear energy in human-made devices on Earth. Beyond the implications (both negative and positive) of such developments, however, lies the profound perspective gained in the latter half of the twentieth century regarding the origin of the elements of the periodic table. The existence and abundances of the 90-odd elements that make up Earth, the planets, the solar system, and the universe beyond have an explanation that lies in natural nuclear reactions that have taken place in the several generations of stars preceding the formation of the Sun and the solar system.

4.1 Stars and nuclear fusion

The observable cosmos around us is, by and large, made of stars. Stars are spheres made primarily of hydrogen and helium gas; the size of the spheres is determined by a balance between the attractive force of gravity pulling everything inward and the pressure associated with the high temperatures of stars' interiors, which is a force tending to push the material outward. Most stars eventually evolve, through nuclear processes described below, into dense spheres of carbon, oxygen, or exotic neutrons; some collapse into the mysterious and incredibly dense *black holes*.

The copious amounts of photons coming out of stars, including the Sun, are a signature of the enormous temperatures in their interiors. The origin of these high temperatures, and hence of sunlight or starlight, was a matter of debate throughout the nineteenth century. A hypothesis by the British physicist Lord Kelvin, that the Sun was radiating away the energy associated with its initial collapse from clouds of interstellar gas and dust, met with a timescale problem: the Sun would cool in several tens of millions of years, but various lines of evidence suggested that terrestrial rocks were older by at least a factor of 10. However, the essential and simple concept that the infall of material by gravity toward a common center, forming a star or planet, would generate heat is essential to understanding the heat budget of Earth, as we discuss in Chapter 11. Another possible source, radioactivity of heavy elements, was advanced around the same time, but the spectroscopic determination that the Sun is mostly nonradioactive hydrogen and helium made this hypothesis also untenable.

By the 1930s, physicists began to grasp the essential workings of the atomic nucleus, including the fact that with sufficient force, one could overcome the repulsive barriers between the nuclei of atoms and induce lighter nuclei to combine to form heavy nuclei, in a process called fusion. In the case of four hydrogen nuclei (each of which is just a single proton) combining together, the most stable resulting nucleus requires that two of the protons transform to neutrons. This is accomplished only through a modestly complex series of steps, outlined below, but the important point is that the resulting nucleus *has less mass than the original four protons*. The missing mass ΔM has been converted to energy ΔE, according to the Einstein formula $\Delta E = \Delta M c^2$.

Analogous to electrons, certain numbers of protons and neutrons assembled as nuclei represent especially stable structures. In general, the stability of the nonradioactive nuclei increases as the atomic number increases toward iron; beyond iron, the stability tends to decrease. Therefore, fusion reactions tend to produce energy as heavier nuclei are assembled, only up to iron (Figure 4.1). Nonetheless, this does not mean that it is easy to fuse two nuclei together; sufficient pressure (or collisional force, and hence temperature) is required to overcome first electronic repulsion and then repulsion associated with the two colliding nuclei.

Production of heavier elements from lighter ones by fusion in stars appears to be a process of fundamental importance to the evolution of the cosmos and in particular to the existence of solid planets. It is therefore worth getting a flavor for the kinds

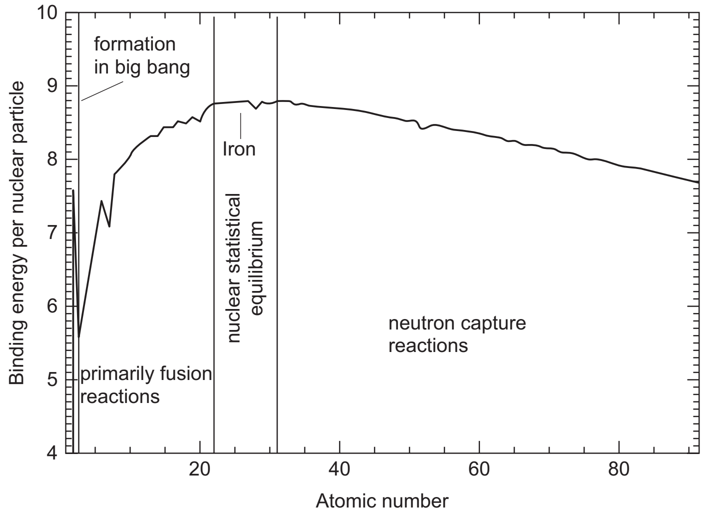

Figure 4.1 Binding energy of the nucleus as a function of atomic number. The higher the energy, the more stable is the nucleus against fragmentation or other decay. Note that stability is highest around the atomic number corresponding to iron. The binding energy is expressed relative to the number of protons and neutrons in the nucleus, and the units are millions of *electron volts*. One electron volt is 1.6×10^{-19} joules, and is a convenient unit for energies on the small scale of atoms. The curve was computed from a model that roughly fits the measured value for most elements, but there are small deviations from the experimental values. Vertical lines delineate the regions within which elements are produced (a) primordially, from the Big Bang; (b) via thermonuclear fusion inside stars; (c) through reactions at very high temperature during the stellar collapse that engenders a supernova explosion; and (d) neutron capture. Each of these is explained in the text.

of reactions that take place. We focus on the fusion of hydrogen to heavier elements. The simplest and most basic fusion process is called the *p–p chain*, or proton–proton chain, and requires that only hydrogen and helium be present.

The simplest of the p–p chains, often called ppI, involves three separate *reactions*, as sketched in Figure 4.2. A reaction is defined as a discrete step in the process in which one or more atomic nuclei are fused to form certain products. In ppI, step 1 involves two hydrogen nuclei (protons) colliding to form a deuterium nucleus (one proton and one neutron) and two atomic fragments. One such fragment is identical to an electron in mass, but of opposite charge, and is called a *positron*. Also released is an exotic particle with little or no mass and a propensity for passing easily through matter. Such *neutrinos* have been detected experimentally.

In step 2, the deuterium nucleus collides with another hydrogen nucleus, i.e., proton. The net result is the release of light, or photons, and the generation of the two nuclei into a light isotope of helium, consisting of two protons and one neutron. This isotope, helium-3 (^{3}He), is quite rare in the cosmos, because it is destroyed easily by further fusion reactions. However, some of it escapes from the Sun in the solar wind, and has been detected.

Finally, two ^{3}He nuclei collide and form the most stable isotope of helium, helium-4 (^{4}He), consisting of two protons and two neutrons. This nucleus stays intact under present conditions in the Sun's interior but undergoes further fusion in more massive stars. In addition to the ^{4}He, two protons (i.e., the hydrogen nuclei) are produced.

If we take all of the reacting nuclei and the product nuclei from the three stages of the ppI chain, we see that, in net form, four protons have been converted into one helium nucleus, which consists of two protons and two neutrons. A net loss of mass has occurred, and that lost mass (a small fraction of the total) is liberated as energy, mostly as photons, and generates the light we see coming from the stars.

The ppI chain is not the only proton–proton fusion reaction chain that occurs in stars. Indeed, it is possible for ^{3}He to collide with a ^{4}He nucleus to form beryllium, and from there lithium (ppII chain) and, in a fraction of reactions, boron (ppIII chain), but in the end these heavier elements are destroyed in favor of ^{4}He again. Beryllium and lithium act as *catalysts* in the nuclear reaction; they control the speed of the reaction sequence, in this case by being good targets for electrons and protons, without being consumed in the process. We see examples of catalysts in *chemical* reactions (that is, involving whole atoms as opposed to just the bare nuclei) in Chapter 13 but the principle is the same as with the nuclear reactions discussed here.

The energy liberated per helium nucleus produced is 4×10^{-12} joules, enough to power a 40-watt (40-joule per second) light bulb for only 10^{-13} seconds. However, the Sun contains enough hydrogen to produce 10^{56} helium atoms; if all of the hydrogen were so converted, the amount of energy released would be 4×10^{44} joules. The Sun is observed to emit photon energy, its main form of removal of the energy, at a rate of 4×10^{26} watts; therefore, the p–p chain could sustain this process for 10^{17} seconds, or 30 billion years. This calculation is a bit off because (a) much of the hydrogen is too far from the Sun's center to experience high enough temperatures to undergo fusion and (b) the Sun's brightness (luminosity, or power) has varied with time. More careful calculations yield roughly 12 billion years of steady hydrogen fusion for the Sun, of which 4.5 billion years has already transpired.

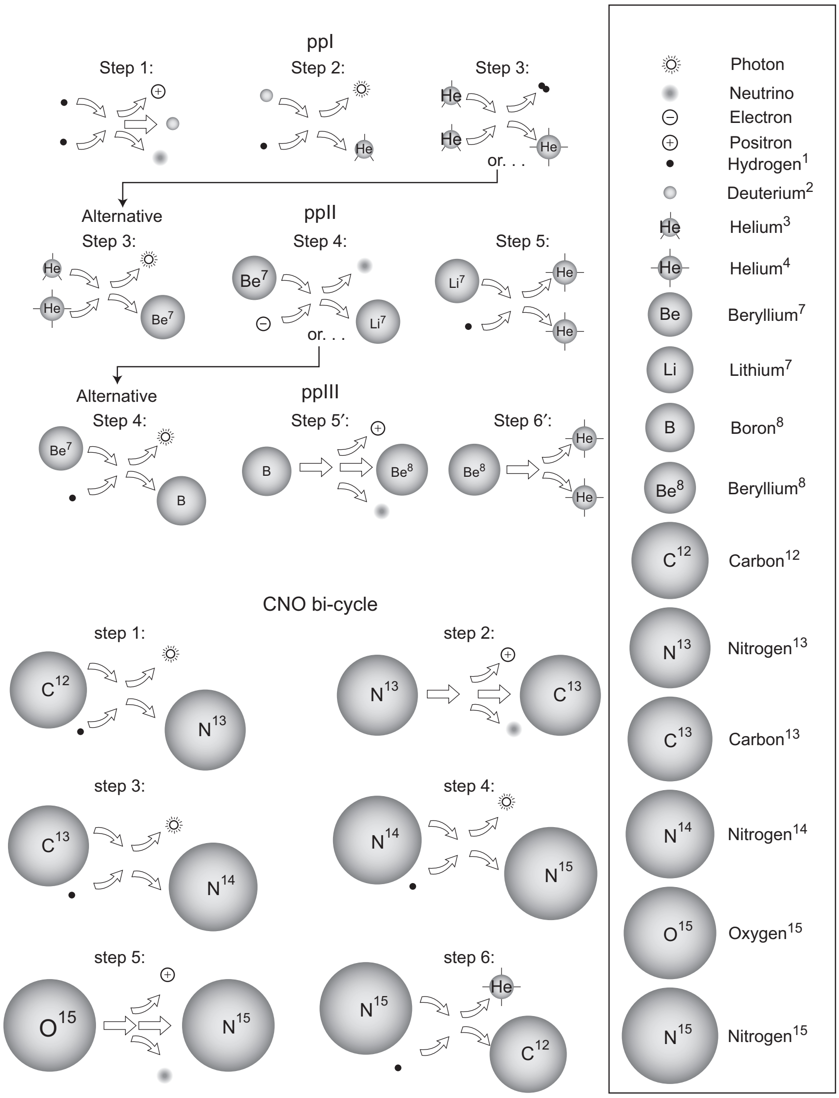

Figure 4.2 Steps involved in four kinds of fusion reactions in stars, all of which convert hydrogen to helium.

The p–p chain is only one of two cycles converting hydrogen to helium in stars. The carbon–nitrogen–oxygen, or *CNO* cycle, requires that the three heavier elements, so familiar to us on Earth, be present in the region of nuclear burning. In this cycle, carbon acts as a catalyst to facilitate, through the intermediate formation and destruction of nitrogen and oxygen, the creation of the ^{4}He nucleus from four protons. The sequence is potentially much faster than the p–p chain because, in the latter chain, two hydrogen nuclei (protons) must collide to initiate the process, and this is inefficient because of the small size of the protons. In the CNO cycle, all collisions are between protons and larger nuclei such as the carbon nucleus (six protons and six neutrons). However, there is so little carbon in the center of the Sun that the CNO cycle is currently less important than the p–p cycle. As fusion proceeds in the Sun and helium builds up, the interior temperature of the Sun will increase; as the temperature increases, the CNO cycle will gain in importance and eventually dominate.

Fusion requires very high temperatures to provide nuclei with enough velocity to overcome the repulsive electric force between the protons. In stars, the high temperatures are achieved through the enormous pressure associated with the mass of the star: our Sun is 1,000 times more massive than Jupiter and 300,000 times more massive than Earth. Most stars, however, are smaller than the Sun, and in the interiors of the smallest stars, or *red dwarfs*, nuclear reactions barely proceed, and are much slower than in the Sun. These stars are cooler, and hence appear red rather than yellow, but they are much longer lived because they burn hydrogen more slowly. Stars more massive than the Sun undergo hydrogen fusion much more rapidly, are much brighter and bluer than the Sun, but are far shorter lived. During the time over which stars undergo hydrogen fusion, their brightness and

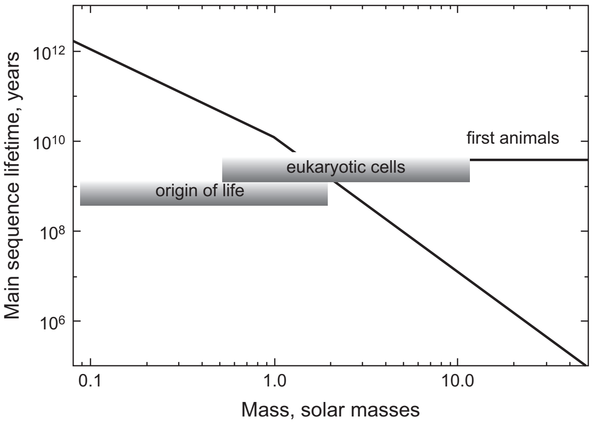

Figure 4.3 Main sequence lifetime of stars over which they stably undergo hydrogen fusion, as a function of mass of the star expressed in solar masses. The Sun's mass on this scale is 1. The lifetime is given in years. The timescales for the appearance on our planet of life, of complex cells, and of animals are shown. Note that the lifetime and mass must be expressed in powers of 10 because of the broad range of stellar masses and ages.

size change only slowly; this stable portion of their evolution is referred to as the stellar *main sequence*.

The lifetime and luminosity of main sequence stars, sorted according to their mass, have important implications for the habitability of orbiting planets and the chance that life will have enough time to evolve into complex forms before these stars become unstable. Figure 4.3 shows the time for stable hydrogen fusion in stars as a function of their mass; this is the main sequence lifetime. Stars several times more massive than our Sun do not last long enough to give complex life a foothold on any planets orbiting them, if the timing of evolution of life on our planet is a fair guide (Chapter 12).

Like normal hydrogen, deuterium is being depleted today by fusion processes in stars. in fact, deuterium can undergo fusion at lower temperatures than can hydrogen. The reaction is simple: it is the second step of the ppI chain in which a deuterium nucleus and hydrogen nucleus collide to form a ^{3}helium nucleus with liberation of energy in the form of a photon. The reaction of two protons, the first step of the ppI chain, requires much higher collision velocities and hence limits hydrogen fusion to objects more massive than those that just undergo deuterium burning. The threshold for hydrogen fusion in stars of solar composition is 85 times the mass of Jupiter; for deuterium burning it is only 13 times Jupiter's mass. Because of the very small abundance of deuterium in the cosmos – 50 parts per million relative to hydrogen – deuterium fusion can only power a star for a few million years at most, compared to the billions of years that stars such as the Sun shine by hydrogen fusion.

4.2 Element production in the Big Bang

Hydrogen fusion produces helium, which builds up as a kind of thermonuclear "ash" in the interiors of main sequence stars. Stellar explosions, which we discuss below, can deliver helium to the gas in interstellar space, the *interstellar medium*. This production of helium from hydrogen is just one example of *stellar nucleosynthesis*, or the production of elements within stars. It is a somewhat special case, however, because, unlike most of the elements, much of the helium present today in the cosmos is thought to be primordial, like hydrogen. The origin of the primordial material is presumed to lie in the initial explosion that started the universe, that is, the Big Bang.

Evidence for an initial explosion of matter to create the cosmos exists primarily in the observed expansion of groups of galaxies away from each other, and in the pervasive background static, mentioned in Chapter 2, which can be heard at radio wavelengths. This background static is produced over a range of wavelengths, and the energy is distributed so as to be a nearly perfect black body with a temperature of 2.7 K. The most straightforward interpretation of this cosmic static is that it is the last light from the initial explosion, red-shifted by its great distance from us, marking a transition from a universe that in its first moments was suffused with photon radiation scattering off of a dense gas of subatomic matter.

During the initial phases of the expansion after the Big Bang, the universe consisted mostly of neutrons compressed to an extremely high density, much like the present-day interiors of *neutron stars*, the remnants of stellar collapse. Very quickly, however, β decay created a population of electrons and hydrogen nuclei, that is, protons. Helium was formed in this dense soup of matter through capture of a neutron by hydrogen to form its heavy isotope, deuterium, followed by collision between two deuteriums to make tritium (the next heavy, and unstable, isotope of hydrogen) plus hydrogen, and terminating with a collision between tritium and deuterium to make ^{4}He. A branch-off in the step involving two colliding deuterium nuclei produces ^{3}He, some of which survives today as a primordial remnant.

The Big Bang production of helium was a different process than the p–p chain in stars, emphasizing that different ambient conditions (in this case, the much higher densities in the Big Bang than are obtained in stars) force the nuclear reaction sequence to be different. In addition to most of the present-day helium coming from Big Bang nucleosynthesis, it is thought that most lithium available today was made at that time.

4.3 Element production during nuclear fusion in stars

Fusion reactions beyond hydrogen burning in stars require increasingly higher temperatures because the nuclei, up through iron, are progressively more stable (Figure 4.1). Consider the Sun as a typical star of intermediate mass and age. The temperature near the Sun's center is computed from physical models to be roughly 1.5×10^7 K, fully adequate for hydrogen fusion, but a temperature of 10^8 K is required to initiate the next stage in which helium fusion takes place. However, as more hydrogen is consumed, leaving a core of helium, the density increases and the temperature rises. Computer models suggest that temperatures near the center of the Sun are already 10% higher than they were at the time hydrogen fusion was initiated. The continued slow increase in the Sun's internal temperature leads to increasing luminosity, which will have profound consequences for Earth's habitability well before the end of our star's main sequence lifetime.

As the Sun approaches the end of its main sequence life some 6 billion years hence, hydrogen fusion will become progressively concentrated in a shell around the then-helium core. This core no longer will be supported by the heat from fusion reactions, and will begin to contract rapidly, heating up to the threshold temperature for helium fusion. Two helium nuclei, that is, α particles, each composed of two neutrons and two protons, will collide to form ^{8}Be. This is an unstable isotope of beryllium, with a large cross section, and hence will easily capture another helium nucleus, producing the most abundant carbon isotope, carbon-12 (^{12}C).

Although the energy production of helium fusion is small compared with that of hydrogen fusion, the sudden pulse of ignition will force the Sun to expand dramatically and become a *red giant*, which will extend out beyond the orbit of Venus, almost to Earth. The luminosity of the Sun will increase sufficiently to bake the Earth and melt the water ice of Jupiter's Galilean moons.

Helium burning produces heavier elements by capture of additional α particles, each succeeding element having a mass number 4 higher than the previous element. Thus, α-particle capture by carbon produces ^{16}O; capture by ^{16}O produces ^{20}Ne, and ^{24}Mg then is produced from neon. In addition to this rather simple production by helium nuclei, which explains the high abundance of elements with mass numbers divisible by 4, other reactions are going on. The CNO cycle during hydrogen fusion has produced other elements such as ^{14}N. Addition of α particles leads to heavy isotopes of oxygen (^{18}O), neon (^{22}Ne), and magnesium (^{25}Mg). Other products of the CNO cycle are converted to ^{13}C, ^{15}N, and ^{17}O.

Further cycles of nucleosynthesis occur as helium is exhausted and the star again goes through core collapse and resulting heating. At a temperature of about 1 billion Kelvin, carbon fusion is initiated. Two carbons combine, releasing a helium nucleus and producing ^{20}Ne or releasing a proton and yielding heavy neon (^{23}Ne). Isotopes of magnesium, sodium, aluminum, and silicon are produced in the carbon fusion process as well. Oxygen nuclei also undergo fusion to produce isotopes of silicon, phosphorus, sulfur, magnesium, and aluminum.

Finally, temperatures exceeding 4 billion K permit silicon fusion to take place. These enormous temperatures occur only in the collapse of the most massive stars, and allow a variety of nuclear reactions to occur rapidly, creating iron and elements of similar atomic mass. This is the end of element production by fusion in stars, however, because beyond iron nuclei decrease in stability; fusion thus requires energy input and is not self-sustaining. Other processes associated with fusion, described in the next section, produce elements not directly made by fusion.

Only the more massive stars make it all the way to silicon burning; the Sun and smaller stars will only progress through helium fusion, after which final collapse will produce a small *white dwarf star*. For stars massive enough to produce iron by silicon fusion (nine or more times more massive than the Sun), the end is more dramatic: the termination of silicon fusion and core collapse compress a star's interior intensely, producing a violent *supernova* explosion. It is within the extreme environment of such an explosion, as well as other exotic astrophysical environments associated with massive stars, that additional element formation occurs.

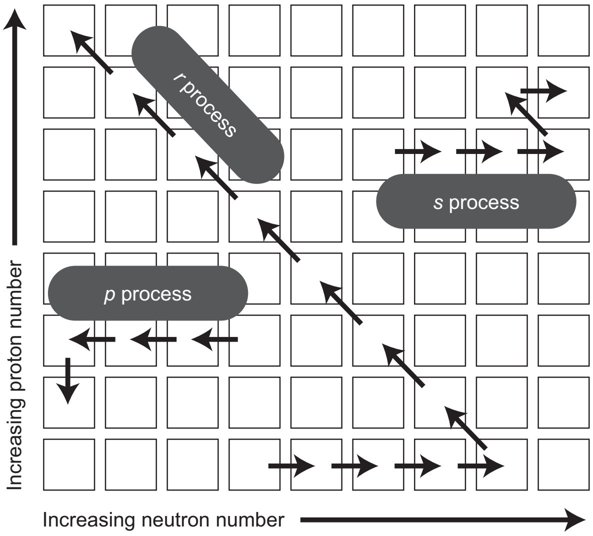

Figure 4.4 Graph of s, r, and p processes. Elements and isotopes exist in squares defined by a proton number (vertical axis) and a neutron number (horizontal axis). Straight horizontal arrows to the right are neutron captures; diagonal arrows represent β decays. Because of its complex nature, the p process cannot be shown directly but is equivalent to the horizontal line moving to the left accompanied by a downward vertical step. Adapted from Broecker (1985).

4.4 Production of other elements in stars: s, r, and p processes

The deep interiors of stars undergoing fusion reactions are dense fluids of protons, neutrons, electrons, and heavier nuclei (composites of protons and neutrons). In addition to the direct fusion reactions considered above, the capture of protons and neutrons by nuclei can build up the atomic mass (and in the case of proton capture, the atomic number) in ways distinct from the main fusion reaction sequences. Neutron capture is much more likely than proton capture, because electrostatic repulsion does not have to be overcome. Sources of free neutrons become important in the helium burning stage of a star's life. The production of ^{25}Mg from ^{22}Ne and an α particle, and the conversion of ^{13}C and an α particle to ^{16}O both liberate neutrons and are thought to be their primary sources.

The process of neutron capture in a stable stellar interior is the s, or slow, process. It is so defined because the flux of neutrons is such that the time between successive captures of neutrons by a nucleus may range from 10 to 10^5 years. An understanding of neutron capture is greatly aided by the sort of diagram shown in Figure 4.4. The graph shows the various elements and their isotopes, collectively called the *nuclides*, plotted as the number of neutrons on the horizontal axis versus the number of protons, defined earlier as the atomic number, on the vertical axis. Thus, a horizontal movement on the graph is from one isotope to another of the same element; a vertical movement is from one element to another. The atomic mass of a species is given by the sum of the neutron number and the proton number. *Isobars*, or species of the same atomic weight, lie on a diagonal line from lower right to upper left on the chart.

Capture of a free neutron moves an isotope horizontally along the graph, converting it to a heavier isotope of the same element. Eventually, the isotope reaches a neutron number that is not stable, and decays radioactively. Because of the long time between neutron captures in the s process, such an unstable nucleus will undergo radioactive decay before the next capture, and the relevant radioactive process is β decay, in which a neutron converts to a proton and an electron, but the atomic mass of the nucleus (number of protons and neutrons) is preserved. On the graph, such an event moves the isotope diagonally up and to the left, along the isobaric line. β decay continues until a stable nucleus is reached, and then continued neutron capture moves the isotope, now a different element, horizontally to the right again.

The resulting abundances of elements and isotopes are determined both by the neutron flux and the relative cross sections of the various nuclei created. As mentioned earlier, the stability of nuclei depends separately on the numbers of both neutrons and protons. Certain of these numbers, as with electrons, are particularly stable whereas others are not. This is in addition to the unstable situation of having too many neutrons relative to the number of protons, leading to β decay. Very stable nuclei have small cross sections for capturing neutrons and hence tend not to be converted to heavier isotopes or isobars. The limited rate of neutron addition relative to β decay forces the pattern of diagonal movement along an isobar as soon as an unstable isotope is reached. Thus, although the s process is important in making many elements and isotopes above iron, it cannot produce the more neutron-rich isotopes.

The question of which stellar environments are the most important contributors of s-process elements is a continuing debate. Presumably, the s process goes on in all stars undergoing fusion beyond the hydrogen stage, but we are interested in stars from which material eventually is expelled in sufficient quantities that it is an important contributor to the interstellar medium and, eventually, to new generations of stars and planets. *Asymptotic Giant Branch* (AGB) stars swell in the late stages of nuclear burning and consist of a core of carbon and oxygen that is not undergoing fusion, surrounded by a shell undergoing helium fusion and a final, outer hydrogen layer. These stars appear to be abundant and might be important sites for s-element production.

Not all heavy elements can be made by the s process. Some neutron-rich isotopes require that neutron capture proceed quite far to the right, through the unstable isotopes, before β decay takes over. Rapid addition of neutrons, or an *r process*, is required. Here, capture of neutrons is rapid enough that very neutron-rich nuclei are produced, until the binding of additional neutrons becomes so unfavorable that the net capture rate is no longer competitive with β decay, and a cascade of β decays moves the neutron-heavy elements diagonally to the left in Figure 4.4 until a stable nuclide is reached.

Once one understands the stability of the various nuclides, charting their production by the s and r processes becomes a kind of board game in which the pieces are moved according to rules determined by nuclide stability, neutron fluxes, and the ambient physical conditions, elucidated through laboratory experiments and computer models. But what environment could be so neutron-rich as to enable the r process to occur? Stars several times more massive than the Sun that have completed fusion cycles up through production of the iron-group elements explode as supernovas. Neutron-rich environments within the rapidly expanding envelopes of supernovas have been invoked as possible sites for production of elements by the r process, but none seems capable of producing the full mix of r-process elements seen in the galaxy. The problem is an intricate one because not only must conditions be right for r-process element production, but the material then must be ejected into interstellar space without being further altered significantly.

A exotic, neutron-rich wind coming from a “neutron star” might be an additional site of the r process. After the explosion of a star as a supernova, the remnant cinder collapses with no further prospect of fusion reactions to halt the collapse. If the star is massive enough, collapse will continue “forever” and a black hole will be formed. Most supernova remnants, however, stop collapsing when the pressures are high enough that all electrons and protons are squeezed together to make neutrons. This incredibly dense neutron star is only a few kilometers across, yet it contains potentially as much mass as the Sun. For the first 10 seconds or so of its existence, an intense wind of neutrons flows from the neutron star, and it is in this cosmic neutron breeze that many or most of the r-process nuclides might be produced. The rate of neutron star births is thought to be high enough to make these winds a primary source. The reader should regard this model not as the last word, but as an illustration that the search for the birth sites of the elements is tied closely to an understanding of the exotic processes by which stars evolve and die.

Some nuclides in Figure 4.4 are relatively proton rich and are shielded from s- and r-process production by other stable nuclides. Some 35 nuclides out of the hundreds of stable and near-stable nuclides known to exist are in this state. For some time it was thought that a *p process* to produce such material must involve addition of protons. This is difficult because high temperatures are required to produce sufficiently energetic collisions for protons to overcome the electrostatic repulsion of other protons. Appropriate environments for proton addition within stars were difficult to find.

An alternative mechanism that enriches protons in a nucleus is removal of neutrons. To make the p-process nuclides, the removal would have to occur from stable nuclides, ones for which β decay will not operate. Exposing nuclides to very high temperatures for short periods of time is one possibility, because the neutrons will “drip” off of the nuclides first, followed by protons; if the process is truncated early enough, the net result is relatively proton-rich nuclides. Certain regions of the interiors of supernovas have been identified as providing the right environment for the p process, in which the supernova shock itself provides a short high-temperature burst. At least two different kinds of supernovas appear to be required to produce the right mix of the p-process nuclides, and it is clear that much more work will be required to fully understand how these are formed.

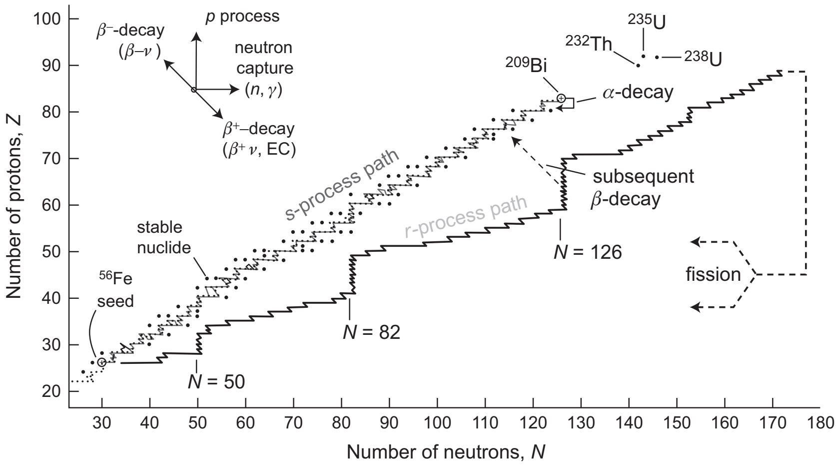

Figure 4.5 The processes of neutron addition plotted on a graph of proton (atomic) number versus neutron number. Beginning with iron and nearby elements, the more regular *s* process follows a zig zag line as neutrons are added and beta decay occurs, the path corresponding to "valleys" of high stability of nuclei with given proton and neutron numbers. The *r* process, on the other hand, adds neutrons so rapidly that the products are neutron rich, truncated by larger cascades of beta decay until the heaviest nuclei simply split through atomic fission. The *p* process is sketched as well for comparison with the neutron addition processes.

4.5 Nonstellar element production

Once expelled into interstellar space by supernova explosions or the more quiescent ejection of envelopes around lower-mass stars, element production and evolution are not terminated. Most nuclei that are ejected from supernovas have initial velocities an appreciable fraction of the speed of light. Nuclei that intersect our solar system and hit Earth are called high-energy *cosmic rays*. Collisions between ambient interstellar hydrogen and the high-energy nuclei cause spallation or splintering of portions of the heavy nuclei. This *l process* is a primary one in the production of lithium, beryllium, and boron.

Additionally, once produced, isotopes not fully stable begin to radioactively decay, which is another kind of element and isotope production process. Decay times range over large values, from seconds through billions of years. As described in Chapter 5, the abundance of decay products of some of these isotopes, trapped in rocks, provides a wealth of information ranging from the age of the solar system to the timing of geologic events on Earth.

4.6 Element production and life

Figure 4.5 provides a larger scale view in atomic number and neutron number space of the neutron addition processes that operate in astrophysical environments. Beginning with the elements around, and including, iron as seeds, neutrons are added either slowly or rapidly until beta decay converts neutrons to protons. Ultimately the production of the heaviest elements is truncated by fission of the nucleus or alpha decay in the case of the *r* and *s* processes, respectively.

The extent to which it is possible to understand the sources of elements and their isotopes is remarkable, given that only a century ago scientists were still struggling with the concept of the nature of elements and the underlying structure of the atom. Today we have a glimpse of the wide range of processes – from the Big Bang through stellar fusion and supernova explosions – responsible for the mix of elements present today in the cosmos.

It is particularly intriguing to examine the elemental abundances and notice that the fundamental building blocks of life – carbon, hydrogen, nitrogen, and oxygen – are quite abundant relative to most other elements. Except for hydrogen, which is the primordial element, these others are abundant because they are direct products of the fusion reactions powering stars.

The high abundances of silicon and iron-group elements have planetary implications. Silicon is the last of the source materials for main fusion reactions, the products being iron and elements close to it. These elements of moderate atomic weight are the basic building blocks, with oxygen, of Earth and its sister terrestrial planets; the compounds of such elements are loosely referred to as rocks and metals.

Go out into the dark skies of a moonless night in the countryside and gaze at the multitude of stars. Let your eyes run from the seven sisters of the Pleiades to the red giant Betelgeuse in the constellation Orion. In this visual sweep, one captures the alpha and omega of element production: young stars just beginning their conversion of hydrogen to helium by fusion, and the red giant going through its terminal stages of fusion before the frenetic final neutron production of heavy elements. There in the sky are the cosmic factories making the elements that, in the distant future, might become part of some strange biology on an as yet unformed world.

Summary

Normal stars are spheres of mostly hydrogen and helium, held together by the force of gravity, and heated by their original collapse to very high temperatures in their interiors. The high temperatures translate to vigorous random motions and high-speed collisions deep in their interiors. The collisions create an outward pressure balancing the inward force of gravity, and also strip electrons off of the atoms to create bare atomic nuclei or ions. Stars more than about 80 times the mass of Jupiter, or 25,000 times the mass of the Earth, have interiors at temperatures so high that the collisions are sufficiently energetic to cause nuclear fusion – a process whereby hydrogen is concerted to helium with release of energy. The process of fusion is actually a sequence of nuclear reactions involving the splitting off and recombination of various atomic particles. One set of nuclear pathways from hydrogen to helium, called the p–p chain, occurs predominantly in stars the size of the Sun and smaller, while the so-called CNO cycle occurs in more massive stars. A star's structure can be stably sustained by hydrogen fusion for millions of years in the more massive stars to trillions of years in the smallest, "red dwarf", stars. As hydrogen is converted to helium, the star's interior becomes denser, the temperature goes up, and the reaction rates increase. Eventually stable hydrogen fusion is no longer possible and the star expands, then contracts in several cycles, leaving the stable "main-sequence" of hydrogen fusion and undergoing additional cycles of fusion of heavier elements to produce carbon, oxygen, and heavier elements. Fusion ceases to generate energy for element numbers at and above iron, and so the most massive stars will cease fusion as iron is produced, collapsing catastrophically and blowing off much of their mass in the form of a supernova. The remnant core may be a dense clump of exotic neutrons or a black hole. Stars the mass of the Sun never reach this stage, ending as white dwarfs rich in carbon and oxygen, which cool slowly over cosmic time. The stages of stellar evolution after the main sequence may also be responsible for the production of elements not directly produced by fusion, or which are heavier than iron. In this way, most elements are produced during the life cycle of stars. The formation of the cosmos in the Big Bang produced hydrogen, some helium, and lithium, so that the first generation of stars were bereft of the heavy elements needed to make planets and organic molecules for life. It is thus the progressive formation of heavy elements in the interiors of stars, their expulsion into the cosmos at the end of the stellar main sequence, and recycling through later generations of stars, that has produced the mix of elements we see today in the cosmos.

Questions

1. Given the story of element production described in this chapter, would you expect life to have been possible during the very first generation of stars after the Big Bang?
2. Why might one not expect to encounter intelligent life on a planet orbiting a star twice the mass of the Sun?
3. It is said that if the relative strengths of the fundamental forces were slightly different than they actually are, fusion and element production would not be possible. Do a literature search to find the details behind this statement.
4. Speculate on the final demise of stellar nucleosynthesis in the far future: based on how much hydrogen has been converted to heavier elements since the Big Bang, how long might it take for hydrogen to become too rare a commodity for stable fusion to occur. Could "helium stars" be generated by collapse of helium-rich interstellar gas? What would the minimum stellar mass be (roughly) for such helium-burning stars?
5. Which hydrogen fusion process would not have been possible in the earliest history of stellar evolution, and why?
6. Explain why, for the lighter elements, the abundances are higher for those with an even number of protons.
7. Red dwarf stars undergo fusion at a slower rate, and hence are less luminous than the Sun typically by a factor of 100 to 1,000. If a planet orbiting a red dwarf is to receive as much starlight per second as the Earth receives from the Sun, how much closer to its star must the planet be than the Earth is to the Sun (pick either factor given in the previous sentence)?