1

Introduction and overview

I believe that a leaf of grass is no less than the journey work of the stars.
Walt Whitman, *Song of Myself*

1.1 General introduction

The existence and distribution of the chemical elements and their isotopes is a consequence of nuclear processes that have taken place in the past in the Big Bang and subsequently in stars and in the interstellar medium (ISM) where they are still ongoing. These processes are studied theoretically, experimentally and observationally. Theories of cosmology, stellar evolution and interstellar processes are involved, as are laboratory investigations of nuclear and particle physics, cosmochemical studies of elemental and isotopic abundances in the Earth and meteorites and astronomical observations of the physical nature and chemical composition of stars, galaxies and the interstellar medium.

Figure 1.1 shows a general scheme or 'creation myth' which summarizes our general ideas of how the different nuclear species (loosely referred to hereinafter as 'elements') came to be created and distributed in the observable Universe. Initially – in the first few minutes after the Big Bang – universal cosmological nucleosynthesis at a temperature of the order of 10^9 K created all the hydrogen and deuterium, some ^{3}He, the major part of ^{4}He and some ^{7}Li, leading to primordial mass fractions $X \simeq 0.75$ for hydrogen, $Y \simeq 0.25$ for helium and $Z = 0.00$ for all heavier elements (often loosely referred to by astronomers as 'metals'!). The existence of the latter in our present-day world is the result of nuclear reactions in stars followed by more or less violent expulsion of the products when the stars die, as first set out in plausible detail by E. M. and G. R. Burbidge, W. A. Fowler and F. Hoyle (usually abbreviated to B^{2}FH) in a classic article in *Reviews of Modern Physics* in 1957 and independently by A. G. W. Cameron in an Atomic Energy of Canada report in the same year (B^{2}FH 1957; Cameron 1957).

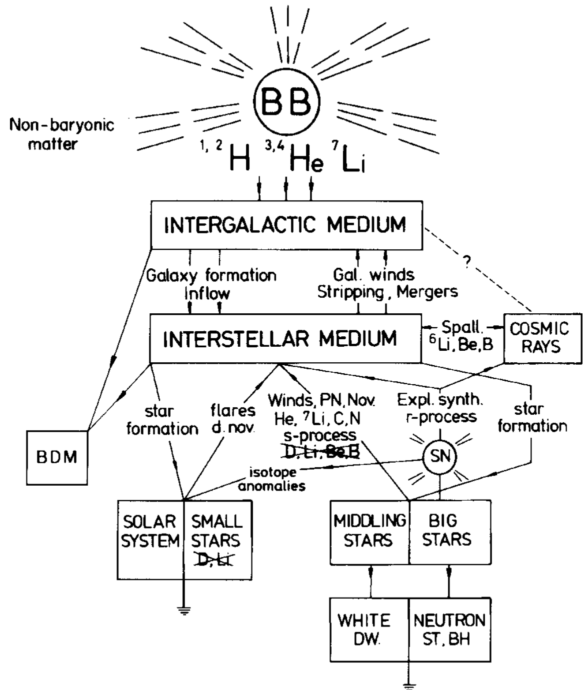

Fig. 1.1. A scenario for cosmic chemical evolution, adapted from Pagel (1981).

Estimates of primordial abundances from the Big Bang, based on astrophysical and cosmochemical observations and arguments, lead to a number of interesting deductions which will be described in Chapter 4. In particular, there are reasons to believe that, besides the luminous matter that we observe in the form of stars, gas and dust, there is dark matter detectable from its gravitational effects (including gravitational lensing). This dark matter, in turn, has two quite distinct components: one is ordinary baryonic matter, consisting of protons, neutrons and electrons, which happens not to shine detectably at accessible wavelengths. There is evidence for such baryonic dark matter (BDM) in the form of rarefied ionized intergalactic gas producing absorption lines – notably at high redshifts – and also possibly in the form of 'MACHOs' (massive compact halo objects) – stellar-mass dark objects arguably in the halo of our Galaxy detected from their gravitational micro-lensing of background sources in the Magellanic Clouds (but at least some of them are possibly normal stars in the Magellanic Clouds themselves). There could also be contributions from cold molecular hydrogen and from low surface brightness galaxies not picked up in redshift surveys.

The other kind of dark matter must be non-baryonic (NDM) and is thought to consist of some kind of particles envisaged in extensions of the 'Standard Model'

Cambridge University Press
978-0-521-84030-9 — Nucleosynthesis and Chemical Evolution of Galaxies
Bernard E. J. Pagel
Excerpt
More Information

of particle physics. The most popular candidates are so-called cold dark matter (CDM) particles that decoupled from radiation very early on in the history of the Universe and now have an exceedingly low kinetic temperature which favours the formation of structures on the sort of scales that are observed in galaxy redshift surveys. The seeds of those structures would have been quantum fluctuations imprinted very early (maybe $\sim 10^{-35}$ s) after the Big Bang during a so-called inflationary era of super-rapid expansion preceding the kind of expanding Universe that we experience now, which later enabled pockets of mainly dark matter slightly denser than the average to separate out from the general expansion by their own gravity. A small contribution to NDM also comes from neutrinos, since evidence for their flavour oscillations implies that they have a small mass, but this mass is estimated from microwave background data to be ≤ 0.2 eV (averaged over the three flavours) and their contribution to NDM ≤ 5 per cent.

The first few minutes are followed by a plasma phase lasting of the order of 10^5 years during which the Universe was radiation-dominated and the baryonic gas, consisting almost entirely of hydrogen and helium, was ionized and consequently opaque to radiation through electron scattering. But expansion was accompanied by cooling, and when the temperature was down to about 10^4 K (at a redshift of about 3450), matter began to dominate and at redshifts around 1100, some 370 000 years after the Big Bang (ABB), first helium and then hydrogen became neutral by recombination.[1] The Universe became transparent and background radiation was scattered for the last time (and is now received as black-body radiation with a temperature of 2.7 K) leading to a period commonly known as the 'dark ages'.[2] Eventually gas began to settle in the interiors of the pre-existing dark-matter halos, resulting in the formation of stars, galaxies and groups and clusters of galaxies, and in re-ionization of the intergalactic medium by newly formed massive stars and/or the compact ultra-luminous objects known as quasars or quasi-stellar objects (QSOs) associated with galactic nuclei.

The epoch and mode of galaxy formation are not well known, but both quasars and star-forming galaxies are known with redshifts up to about 7, corresponding to an era when the expanding Universe was only 1/8 of its present size, and the emission-line spectra of quasars indicate a large heavy-element abundance (solar or more; Hamann & Ferland 1999), suggesting prior stellar activity. The first stars, on the other hand, known as 'Population III', would have been devoid of 'metals'; whether they differed from normal stars in other basic characteristics, notably their mass distribution, is not known, since no completely metal-free stars have been

[1] Since this was the first time electrons were captured by protons and α-particles it might be more appropriate to talk about 'combination' rather than 'recombination'!

[2] 'Infrared ages' might be a more appropriate term.

found. Data from the WMAP[3] polarization measurements published in 2003 suggest that re-ionization took place over an extended period between redshifts of 30 and 10, corresponding to ages of the Universe between about 100 and 400 Myr.[4] In the most popular models, galaxies form by cooling and collapse of baryonic gas contained in non-gaseous (and consequently non-dissipative) dark-matter halos that build up from hierarchical clustering, with complications caused by mergers that may take place both in early stages and much later; these mergers (or tidal interactions) may play a significant role in triggering star formation at the corresponding times.

Galaxies thus have a mixture of stars and diffuse interstellar medium. (The diffuse ISM generally consists of gas and dust, but will often be loosely referred to hereinafter as 'gas'.) Most observed galaxies belong to a sequence first established in the 1920s and 30s by Edwin Hubble. So-called early-type galaxies according to this classification are the ellipticals, which are ellipsoidal systems consisting of old stars and relatively little gas or dust detectable at optical, infrared or radio wavelengths; they do, however, contain substantial amounts of very hot X-ray emitting gas. Later-type galaxies have a rotating disk-like component surrounding an elliptical-like central bulge, with the relative brightness of the disk increasing along the sequence. The disks display a spiral structure, typical of spiral galaxies such as our own Milky Way system, and the proportion of cool gas relative to stars increases along the sequence, together with the relative rate of formation of new stars from the gas, so that their colours become increasingly blue. At the end of the Hubble sequence are irregular galaxies, such as the Magellanic Clouds (the nearest major galaxies outside our own), and outside the sequence there is a variety of small systems known as dwarf spheroidals, dwarf irregulars and blue compact and H II (i.e. ionized hydrogen) galaxies. The last three classes actually overlap (being partly classified by the method of discovery) and they are dominated by the light of young stars and (in the case of H II and some blue compact galaxies) the gas ionized by those young stars (see Chapter 3). There are also radio galaxies and so-called Seyfert galaxies with bright nuclei that have spectra resembling those of quasars; these are collectively known as active galactic nuclei (AGNs), and are associated with large ellipticals and early-type spirals. The increase in the proportion of cool gas along the Hubble sequence could be due to differences in age, the most gas-poor galaxies being the oldest, or to differences in the rates at which gas has been converted into stars in the past or added or removed by interaction with other galaxies and the intergalactic medium (IGM), or perhaps some combination of all of these.

[3] Wilkinson Microwave Anisotropy Probe, launched in 2001.
[4] Assuming the currently favoured flat Λ-CDM cosmology with $\Omega_m = 0.24$, $H_0 = 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

The figure illustrates very schematically some possible interactions between galaxies and the intergalactic medium. The IGM can be roughly considered as a combination of a diffuse medium and discrete clouds, the latter being manifested in the local Universe by absorption lines of H I Lyman-α λ 1216 and O VI $\lambda\lambda$ 1032, 1038 detected in the far ultraviolet,[5] by high-velocity H I clouds detected from the hyperfine 21-cm transition of neutral atomic hydrogen at high Galactic latitudes (which may be of extragalactic origin in some cases, although this is quite controversial) and by hot X-ray emitting gas in clusters and groups of galaxies. H I gas is detected in disk and blue compact galaxies but no isolated intergalactic H I clouds have been found. At high redshifts, Gunn and Peterson (1965) predicted[6] that, as one looks through to the re-ionization epoch, one should see a broad absorption trough shortward of the Lyman-α emission line from a quasar, due to diffuse neutral hydrogen at a range of redshifts in the foreground. This effect was first found for the corresponding line of He^+, λ 304 (redshifted to wavelengths near 1200 Å accessible to HST[7] and FUSE), accompanied by discrete absorption lines from the knots and filaments in which most of the CDM (and associated gas) has gathered by the corresponding epoch in accordance with numerical simulations of gravitational clustering. In the case of H I, which is much less abundant owing to the ionizing radiation field at those epochs, one only sees discrete lines, called the 'Lyman-α forest', resulting from the knots and filaments, at redshifts up to 4 or so (see Figs. 4.5, 12.5), but the classical Gunn–Peterson effect of diffuse intergalactic hydrogen does appear at redshifts greater than about 6, deeper into the re-ionization epoch.

The interactions between the ISM and IGM include expulsion of diffuse material from galaxies in the form of galactic winds driven by supernova energy ('feedback'), stripping of (especially the outer) layers of the gas content of galaxies by tidal forces or by ram pressure in an intra-cluster medium when the galaxy is a member of a cluster; and/or inflow of intergalactic gas into galaxies, which latter may be manifested by some of the high-velocity H I clouds in our own Milky Way system.

Figure 1.1 also gives a schematic illustration of the complex interactions between the ISM and stars. Stars inject energy, recycled gas and nuclear reaction products ('ashes of nuclear burning') enriching the ISM from which other generations of stars form later. This leads to an increase in the heavy-element content of both the ISM and newly formed stars; the subject of 'galactic chemical evolution' (GCE) is really all about these processes. On the other hand, nuclear products may

[5] Notably by the FUSE (Far UV Spectroscopic Explorer) mission launched in 1999.
[6] Similar considerations were put forward independently by Shklovsky (1964) and Scheuer (1965).
[7] Hubble Space Telescope.

be lost from the ISM by galactic winds or diluted by inflow of relatively unprocessed material. The heavy-element content of the intra-cluster X-ray gas in rich clusters like Coma,[8] amounting to about 1/3 of solar, may have resulted from winds from the constituent galaxies (see Chapter 11), or possibly from the destruction of dwarf galaxies in the cluster.

The effects of different sorts of stars on the ISM depend on their (initial) mass and on whether they are effectively single stars or interacting binaries; some of the latter are believed to be the progenitors of Type Ia supernovae (SN Ia) which are important contributors to iron-group elements in the Galaxy. Big stars, with initial mass above about 10 $M_\odot$ ($M_\odot$ is the mass of the Sun), have short lives ($\sim$ 10 Myr), they emit partially burned material in the form of stellar winds and those that are not too massive eventually explode as Type II (or related Types Ib and Ic) supernovae, ejecting elements up to the iron group with a sprinkling of heavier elements. (Supernovae are classed as Type I or II according to whether they respectively lack, or have, lines of hydrogen in their spectra, but all except Type Ia seem to be associated with massive stars of short lifetime which undergo core collapse leading to a compact remnant.) The most massive stars of all are expected to collapse into black holes, with or without a prior supernova explosion; the upper limit for core collapse supernovae is uncertain, but it could be somewhere in the region of 50 $M_\odot$.

Middle-sized stars, between about 1 and 8 $M_\odot$, undergo complicated mixing processes and mass loss in advanced stages of evolution, culminating in the ejection of a planetary nebula while the core becomes a white dwarf. Such stars are important sources of fresh carbon, nitrogen and heavy elements formed by the slow neutron capture (s-) process (see Chapter 6). Finally, small stars below 1 $M_\odot$ have lifetimes comparable to the age of the Universe and contribute little to chemical enrichment or gas recycling and merely serve to lock up material.

The result of all these processes is that the Sun was born 4.6 Gyr ago with mass fractions $X \simeq 0.70$, $Y \simeq 0.28$, $Z \simeq 0.02$. These abundances (with perhaps a slightly lower value of Z) are also characteristic of the local ISM and young stars. The material in the solar neighbourhood is about 15 per cent 'gas' (including dust which is about 1 per cent by mass of the gas) and about 85 per cent stars or compact remnants thereof; these are white dwarfs (mainly), neutron stars and black holes.

1.2 Some basic facts of nuclear physics

(i) An atomic nucleus consists of Z protons and N neutrons, where Z is the *atomic number* defining the charge of the nucleus, the number of electrons in the neutral atom and hence the chemical element, and $Z + N = A$, the *mass number* of the nuclear species.

[8] The nearest rich cluster of galaxies, in the constellation Coma Berenices.

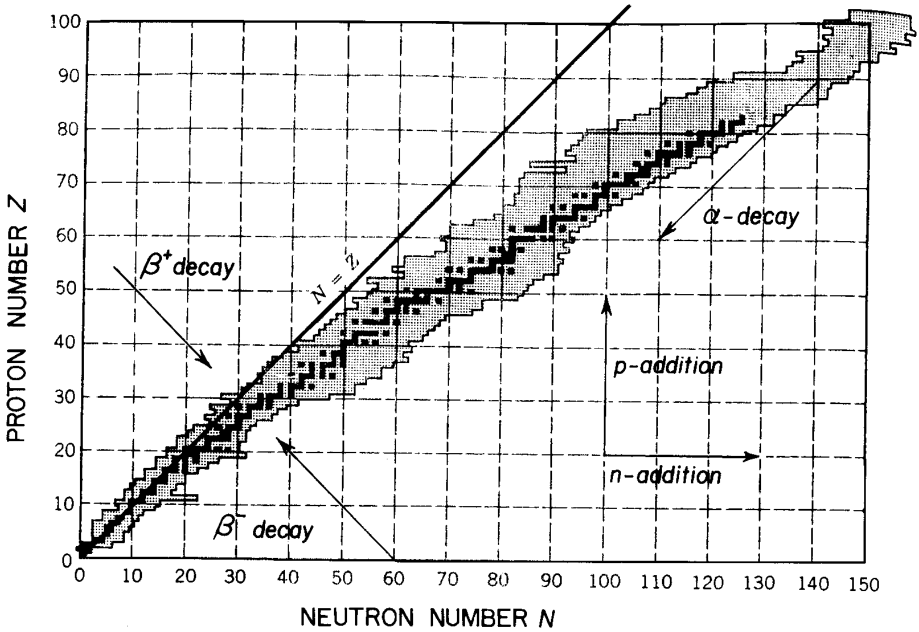

Fig. 1.2. Chart of the nuclides, in which Z is plotted against N. Stable nuclei are shown in dark shading and known radioactive nuclei in light shading. Arrows indicate directions of some simple nuclear transformations. After Krane (1987). Reproduced by permission of John Wiley & Sons, Inc.

Protons and neutrons are referred to collectively as *nucleons*. Different values of A and N for a given element lead to different *isotopes*, while nuclei with the same A and different Z are referred to as *isobars*. A given nuclear species is usually symbolized by the chemical symbol with Z as an (optional) lower and A as an upper prefix, e.g. $^{56}_{26}$Fe.

Stable nuclei occupy a 'β-stability valley' in the Z, N plane (see Fig. 1.2), where one can imagine energy (or mass) being plotted along a third axis perpendicular to the paper. Various processes, some of which are shown in the figure, transform one nucleus into another. Thus, under normal conditions, a nucleus outside the valley undergoes spontaneous decays, while in accelerators, stars and the early Universe nuclei are transformed into one another by various reactions.

(ii) The binding energy per nucleon varies with A along the stability valley as shown in Fig. 1.3, and this has the following consequences:

(a) Since the maximum binding energy per nucleon is possessed by ^{62}Ni, followed closely by ^{56}Fe, energy is released by either fission of heavier or fusion of lighter nuclei. The latter process is the main source of stellar energy, with the biggest contribution (7 MeV per nucleon) coming from the conversion of hydrogen into helium (H-burning).

(b) Some nuclei are more stable than others, e.g. the α-particle nuclei ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca. Nuclei with a couple of A-values (5 and 8) are

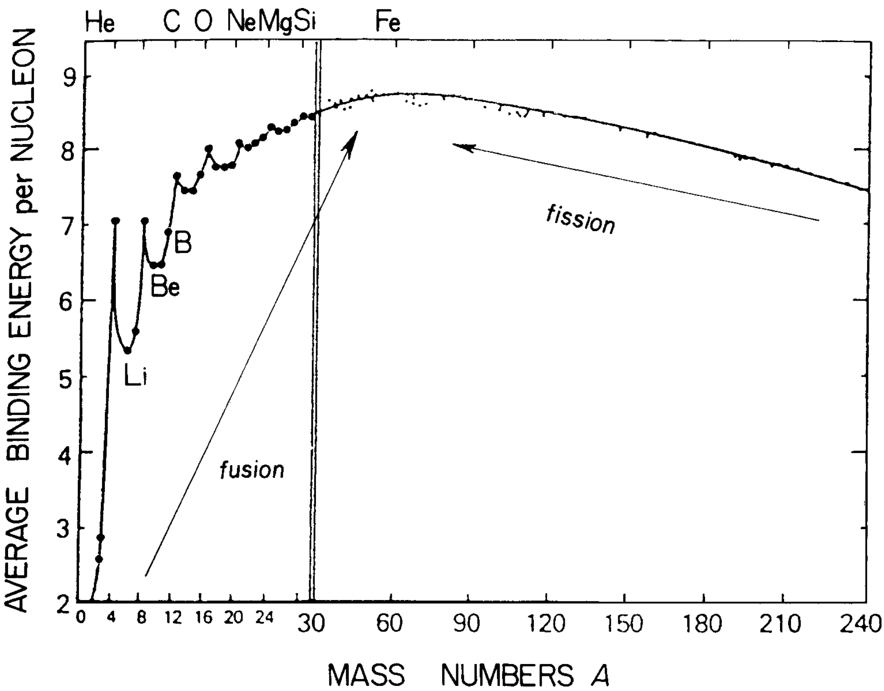

Fig. 1.3. Binding energy per nucleon as a function of mass number. Adapted from Rolfs and Rodney (1988).

violently unstable, owing to the nearby helium peak. Others are stable but only just: examples are D, ^{6,7}Li, ^{9}Be and ^{10,11}B, which are destroyed by thermonuclear reactions at relatively low temperatures.

(iii) Nuclear reactions involving charged particles (p, α etc.) require them to have enough kinetic energy to get through in spite of the electrostatic repulsion of the target nucleus (the 'Coulomb barrier'); the greater the charges, the greater the energy required. In the laboratory, the energy is supplied by accelerators, and analogous processes are believed to occur in reactions induced in the ISM by cosmic rays (see Chapter 9). In the interiors of stars, the kinetic energy exists by virtue of high temperatures (leading to *thermonuclear* reactions) and when one fuel (e.g. hydrogen) runs out, the star contracts and becomes hotter, eventually allowing a more highly charged fuel such as helium to 'burn'.

There is no Coulomb barrier for neutrons, but free neutrons are unstable so that they have to be generated *in situ*, which again demands high temperatures.

1.3 The local abundance distribution

Figure 1.4 shows the 'local Galactic' abundances of isobars, based on a combination of elemental and isotopic determinations in the Solar System with data from

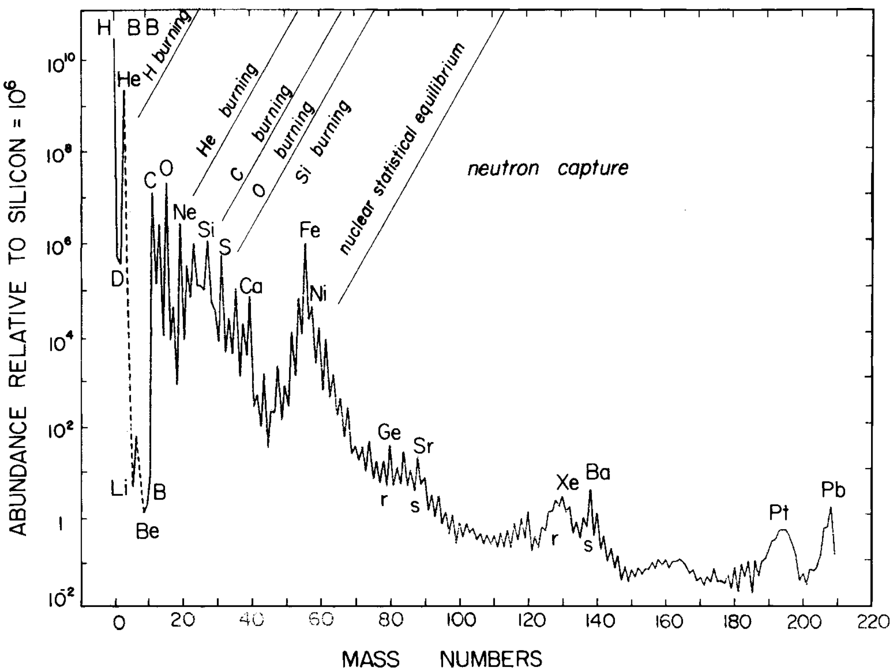

Fig. 1.4. The 'local Galactic' abundance distribution of nuclear species, normalized to 10^6 ^{28}Si atoms, adapted from Cameron (1982).

nearby stars and emission nebulae. These are sometimes referred to as 'cosmic abundances', but because there are significant variations among stars and between and across galaxies this term is best avoided. The curve shows a number of features that give clues to the origin of the various elements:

(i) Hydrogen is by far the most abundant element, followed fairly closely by helium. This is mainly formed in the Big Bang, with some topping up of the primordial helium abundance ($Y_P \simeq 0.25$) by subsequent H-burning in stars ($Y \simeq 0.28$ here and now). Only a small fraction ($Z \simeq 0.02$) of material in the ISM and in newly formed stars has been subjected to high enough temperatures and densities to burn helium.

(ii) The fragile nuclei Li, Be and B are very scarce, being destroyed in the harsh environment of stellar interiors, although some of them may also be created there. (The lithium abundance comes from measurements in meteorites; it is still lower in the solar photosphere because of destruction by mixing with hotter layers below.) On the other hand, they are much more abundant in primary cosmic rays as a result of $\alpha - \alpha$ fusion and spallation reactions between p, α and (mainly) CNO nuclei at high energies. The latter may also account for the production of some of these species in the ISM. Some ^{7}Li (about 10 per cent) is also produced in the Big Bang.

(iii) Although still more fragile than Li, Be and B, deuterium is vastly more abundant (comparable to Si and S). D is virtually completely destroyed in gas recycled through

Cambridge University Press
978-0-521-84030-9 — Nucleosynthesis and Chemical Evolution of Galaxies
Bernard E. J. Pagel
Excerpt
More Information

stars and there are no plausible mechanisms for creating it there in such quantities, but it is nicely accounted for by the Big Bang. The observed abundance is a lower limit to the primordial abundance. The light helium isotope ^{3}He is the main product when deuterium is destroyed and can also be freshly produced in stars as well as destroyed. It has comparable abundance to D and some is made in the Big Bang, but in this case the interpretation of the observed abundance is more complicated.

(iv) Nuclei from carbon to calcium show a fairly regular downward progression modulated by odd:even and shell effects in nuclei which affect their binding energy (see Chapter 2). These are produced in successive stages of stellar evolution when the exhaustion of one fuel is followed by gravitational contraction and heating enabling the previous ashes to 'burn'. The onset of carbon burning, which leads to Mg and nearby elements, is accompanied by a drastic acceleration of stellar evolution due to neutrino emission caused by lepton and plasma processes at the high densities and temperatures required for such burning. The neutrinos directly escape from the interior of the star, in contrast to photons for which it takes of the order of 10^5 yr for their energy to reach the surface, and they eventually carry away energy almost as fast as it is generated by nuclear reactions; it is this rapid loss of energy[9] that speeds up the stellar evolution (see Chapter 5).[10]

(v) The iron-group elements show an approximation to nuclear statistical equilibrium at a temperature of several $\times 10^9$ K or several tenths of an MeV leading to the iron peak. This was referred to by B^{2}FH as the 'e-process' referring to thermodynamic equilibrium. Because the reactions are fast compared to β-decay lifetimes, the overall proton:neutron ratio remains fixed so that complete thermodynamic equilibrium does not apply here, but one has an approach to statistical equilibrium in which forward and reverse nuclear reactions balance. The iron peak in the abundance distribution is thought to result from explosive nucleosynthesis which may occur in one or other of two typical situations. One of these involves the shock that emerges from the core of a massive star that has collapsed into a neutron star; heat from the shock ignites the overlying silicon and oxygen layers in a Type II (or related) supernova outburst, and they are expelled with the aid of energetic neutrinos from the collapsed object ('neutrino heating' or 'drag'). Another possible cause is the sudden ignition of carbon in a white dwarf that has accreted enough material from a companion to bring it close to or over the Chandrasekhar mass limit (supernova Type Ia, often referred to as 'thermonuclear'). In either case, the quasi-equilibrium is frozen at a distribution characteristic of the highest temperature reached in the shock before the material is cooled by expansion, but the initial proton:neutron ratio is another important parameter. Calculations and observations both indicate that the dominant product is actually

[9] Sometimes referred to as 'neutrino cooling', although it does not in general lead to lower temperatures.

[10] Neutrinos are also generated by purely nuclear processes involving weak interactions, e.g. in the Sun. Such neutrinos can be an important cause of energy losses in compact stars through the 'Urca' process, in which an inverse β-decay is followed by a normal β-decay resulting in a neutrino–antineutrino pair.