Chapter 19

Neutrino Astrophysics and the Synthesis of Elements

19.1 Introduction

Neutrinos play a very important role in astrophysics. Due to their weakly interacting nature, they give information about the interior of stars, supernova explosions, the distant galaxies, the possible origin of the cosmic rays, etc. In Chapter 17, we have observed that astrophysical sites are the major contributors to low energy neutrinos. In this chapter, we discuss the importance of neutrinos in the creation of the chemical elements (see Figure 19.1) in the universe. We know that the universe started around 13.8 billion years ago with a singularity, that is, Big Bang and since then, it has been expanding and becoming cooler. The very early universe consisted only of radiation, which during the expansion and cooling phase gave rise to quark–antiquark and lepton–antilepton pairs. With further fall in temperature, the quarks combined to form

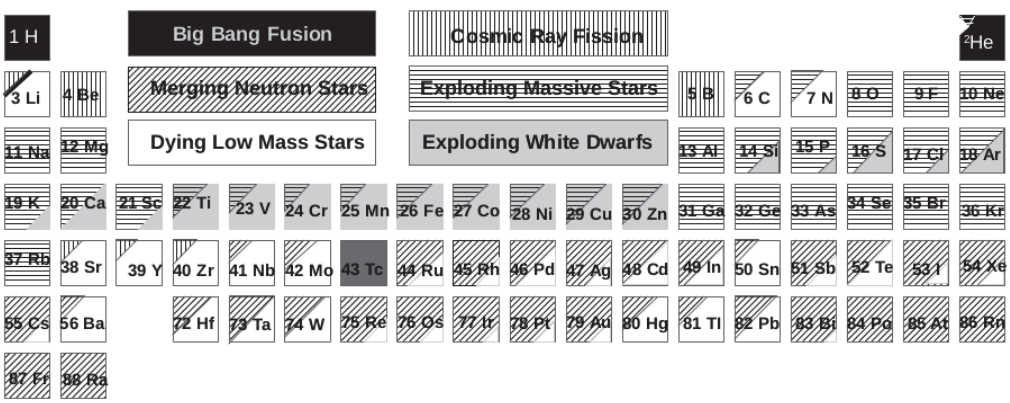

Figure 19.1 Origin of the elements through different processes [1047]. The figure has been taken from Ref. [1048].

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nucleons, which in turn fused to form the lighter elements like hydrogen, helium, and lithium, the first ever nuclei created in the universe. Thus, the early universe consisted of about 75% hydrogen nuclei, 25% helium nuclei, and traces of lithium nuclei. It should be noted that hydrogen is the only element that was solely created during the Big Bang nucleosynthesis; all the other elements including helium and lithium are synthesized by several processes as shown in Figure 19.1. Therefore, all the hydrogen in water molecules were produced during the first few minutes of the Big Bang.

The process of creation of new nuclei from pre-existing nucleons is known as nucleosynthesis. The nucleosynthesis of the lighter elements does not require the emission or absorption of neutrinos while all the elements heavier than lithium require neutrinos directly or indirectly in their synthesis. The nucleosynthesis of intermediate and heavy elements require a very high temperature and pressure environment. Elements up to iron were/are synthesized in the core of stars through the nuclear fusion reaction and it is believed that the heavier elements were synthesized outside the newly formed neutron star in a core collapse supernova. Without neutrinos, we cannot think of energy from the stars. Moreover, neutrino properties figure prominently in many astrophysical environment. Neutrinos are involved in different types of nucleosynthesis processes like the ν-process, νp-process, etc., in the creation of proton-rich nuclei as well as in the synthesis of neutron-rich nuclei through the r-process and s-process. Figure 19.2 shows some of the processes responsible for the synthesis of elements which we shall discuss later in the chapter. During the death phase of massive stars, in a supernova

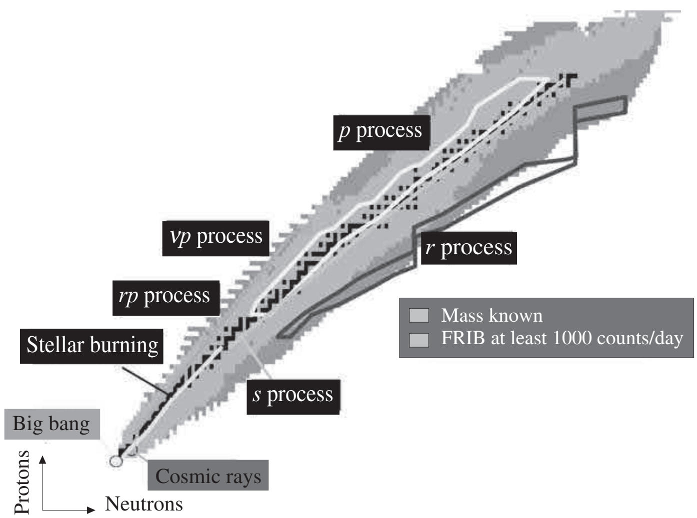

Figure 19.2 Formation of the elements in the universe through the Big Bang nucleosynthesis, stellar nucleosynthesis, and the supernova nucleosynthesis by the s- and r-processes. This figure has been taken from Ref. [1049].

explosion, almost 10^{58} neutrinos are released in a very short span of time of the order of a few seconds and these neutrinos move outwards carrying almost 10^{59} MeV of energies. These neutrinos give rise to a neutrino driven wind where matter from the neutron star is pushed outward through the interactions of neutrinos with matter as shown in Figure 19.3.

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The neutrinos share energy with matter and the temperature of the matter rises resulting in large mass outflow within the neutron star through various reactions. Table 19.1 illustrates some of the neutrino processes which have played a very important role in supernova and proto-neutron star matter. As these neutrinos leave the neutron star, they take away energy and therefore, cool the neutron star which also gives rise to the possibilities of νp and weak r-processes [1050, 910] (discussed later in Section 19.6.2). This results in the formation of heavier nuclei through proton and neutron capture. In this chapter, we will learn about the formation of different elements through various processes, and the important role of neutrinos in the formation of elements.

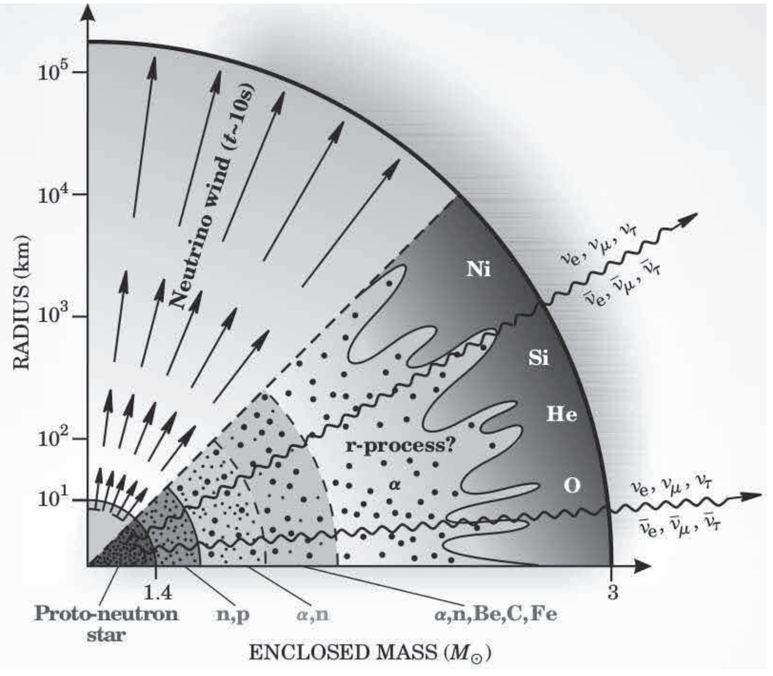

Figure 19.3 Neutrino driven wind [1052].

This chapter also throws some light on the interesting question that every inquisitive mind, at least once, must have pondered on: "how the universe came into existence?"; the quest to understand this is still going on. The idea that the universe started with a Big Bang and is expanding was first given by Lemaitre in 1927, on purely theoretical grounds by assuming that the universe started with a "primordial atom". It was Hubble, who in 1929 [1051] confirmed the expansion of the universe by observing the galactic redshifts. This expansion when extrapolated back in time takes us to the point, known as "singularity", from where space and time started. Today, the most accepted theory describing the origin and expansion of the universe is known as the "Big Bang theory" (Figure 19.4). What existed before the Big Bang and how it started is still a mystery and a topic of research. What we know today as the Big Bang is assigned a time $t = 0$, when the universe was extremely hot($T > 10^{40}$ K) with infinite density and consisted of radiation only. As time evolved, the universe started expanding and due to this expansion,

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the temperature decreased. Through this expansion, the universe has passed through various phases (known in literature as eras) and built up matter from radiation through the process of nucleosynthesis.

Table 19.1 Different neutrino processes in supernova and proto-neutron star matter.

Process	Reaction[a]
Electron and ν_e absorption by nuclei	$e^- + (A,Z) \rightleftharpoons (A,Z-1) + \nu_e$
Electron and ν_e capture by nucleons	$e^- + p \rightleftharpoons n + \nu_e$
Positron and $\bar{\nu}_e$ capture by nucleons	$e^+ + n \rightleftharpoons p + \bar{\nu}_e$
Nucleon–nucleon Bremsstrahlung	$N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
Electron–positron pair process	$e^- + e^+ \rightleftharpoons \nu + \bar{\nu}$
Neutrino pair annihilation	$\nu_e + \bar{\nu}_e \rightleftharpoons \nu_x + \bar{\nu}_x$
Neutrino scattering	$\nu_x + \{\nu_e, \bar{\nu}_e\} \rightleftharpoons \nu_x + \{\nu_e, \bar{\nu}_e\}$
Neutrino scattering with nuclei	$\nu + (A,Z) \rightleftharpoons \nu + (A,Z)$
Neutrino scattering with nucleons	$\nu + N \rightleftharpoons \nu + N$
Neutrino scattering with electrons and positrons	$\nu + e^{\pm} \rightleftharpoons \nu + e^{\pm}$

[a] $\nu \in \{\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$, $\nu_x \in \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$

Broadly, nucleosynthesis can be categorized as follows:

- **Big Bang nucleosynthesis:** This created the first atomic nuclei, viz., hydrogen, helium and traces of lithium, a few minutes after the Big Bang. The details of the Big Bang nucleosynthesis will be discussed in Section 19.2. Elements like ^{9}Be and ^{11}B were/are synthesized in interstellar space due to the interaction of cosmic rays with gas clouds, mainly C, N, and O atoms present in interstellar matter.

- **Stellar nucleosynthesis:** The fusion of hydrogen and helium in the core of a star created many nuclei, from carbon to iron, by the process known as stellar nucleosynthesis, which will be discussed in Section 19.5. The formation of elements through pp- and CNO-cycles in the core of a star (depending upon the mass of the star) during nuclear fusion reactions has been discussed in Chapter 17. In general, the most common process through which different elements are formed in the universe is the fusion of two nuclei to give rise to a heavier nucleus. The nuclear processes are responsible for the production of energy and synthesis of elements in the various astrophysical sites.

- **Supernova nucleosynthesis:** Heavy mass stars end their life with a supernova explosion where huge amount of energy is released in a few seconds. Supernova nucleosynthesis creates isotopes of lighter mass nuclei as well as nuclei heavier than iron. In the case of heavier elements, different processes contribute to the synthesis of proton- and neutron-rich elements. The synthesis of neutron-rich elements is well studied both theoretically as well as experimentally; however, the synthesis of proton-rich nuclei is not well known. Two processes, in neutron-rich environments like during the supernova explosion and the neutron star merger, known as the r-process (rapid capture of neutrons) and the s-process (slow capture of neutrons) are assumed to be responsible for the creation of a majority of the elements. In the s-process, the neutron capture happens in time scale τ_n

much longer than the mean time for the β-decay τ_β, that is, $\tau_n >> \tau_\beta$. In the r-process, the neutron capture happens in time scale τ_n much shorter than the mean time for the β-decay τ_β, that is, $\tau_n << \tau_\beta$.

The synthesis of the proton-rich elements proceeds through different processes like p-process, ν-process, γ-process, rp-process, np-process and νp-process (Section 19.6.2). In all these processes, there is a capture of proton from the surroundings.

Let us first understand the formation of primordial atoms during the course of journey from the Big Bang (Figure 19.4) and thereafter.

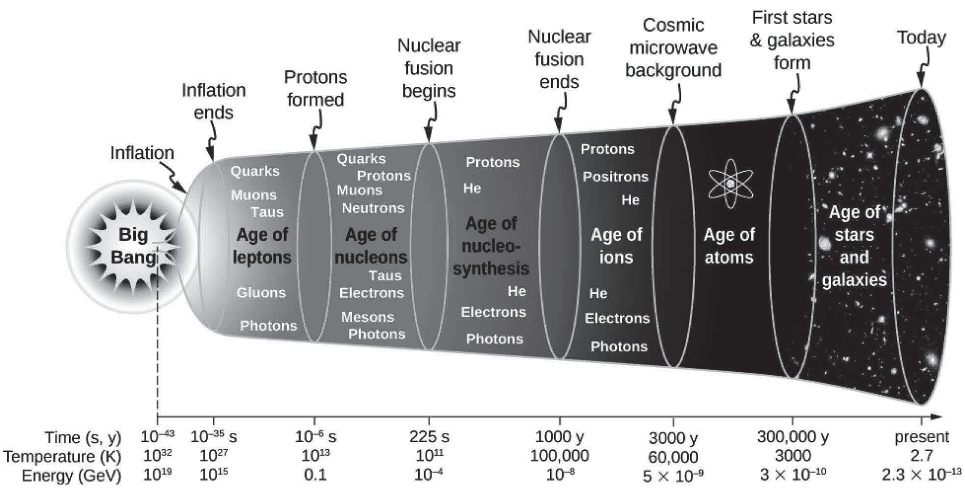

Figure 19.4 Timeline of the Big Bang [1053].

19.2 The Big Bang and the Nucleosynthesis of the Lighter Elements

- **Planck and Grand Unification eras**

  The timeline of the Big Bang started with the Planck era which extended from 0 to 10^{-43} s, known as Planck's time. Presently, limited information is available about this era; it is believed that during this time, all the fundamental forces of nature, viz., gravitational, electromagnetic, weak, and strong, had the same strength or in other words, they were unified into a single force called "superforce". At the end of the Planck era, the temperature of the universe was about 10^{40} K and its size as small as 10^{-35} m known as the Planck's length. After the Planck era came the Grand Unification era which spanned the time from 10^{-43} to 10^{-36} s. During this era, the gravitational force separated out from the other three forces.

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- **Inflation era**

  In this era, the temperature of the universe dropped to 10^{36} K. During this time, the strong force got separated out from the electroweak force. The separation of the strong force released huge amounts of energy which caused the universe to expand exponentially. The size of the universe increased by a factor of about 10^{26} in a fraction of a second which spanned the time from 10^{-36} to 10^{-32} s. At the end of this era, the universe cooled down to a temperature of about 10^{33} K, to a size of about 10 cm. Up to the inflation era, the universe entirely consisted of radiation.

- **Electro-weak era**

  As the temperature fell below 10^{33} K, the electroweak force created a large number of particles, including W and Z bosons and the Higgs boson. This electroweak era created a universe made up of particles which earlier consisted of radiation only and spanned from 10^{-36} to 10^{-12} s. By the end of this era, the temperature dropped down to 10^{20} K.

- **Quark era**

  As the temperature further fell below 10^{20}K and almost up to 10^{16}K, the electromagnetic and weak forces got disentangled and the four fundamental forces took their present form. This era is called the quark era as a large number of quark–antiquark pairs from the radiation were created which were present in the form of a hot, opaque soup of quark–gluon plasma. The radiation resulted in the production of an equal number of quarks and antiquarks in the universe. However, we live in a matter dominated universe, then the question arises where did the antiquarks that were present initially in equal numbers go? There are scientific works which argue that there could be a universe made up of antimatter running backward in time. On the other hand, the majority of the scientists believe that a process known as baryogenesis created the asymmetry in the number of quarks and antiquarks; there is no experimental evidence that such a process has occurred. The quark era spanned from 10^{-12} to 10^{-6} s.

- **Hadron era**

  After the quark era, came the hadron era spanning from 10^{-6} to 1 s. The temperature of the universe fell to about 10^{16}K to 10^{12}K and allowed the quark–gluon plasma to form primordial nucleons.

- **Lepton era**

  As the temperature further fell from 10^{12}K to 10^{10}K, the highly energetic photons gave rise to lepton–antilepton pairs (electron–positron and neutrino–antineutrino pairs). The lepton era spanned from 1 second to 3 minutes during which the mass of the universe was dominated by leptons. The electrons and the positrons got annihilated to give energy in the form of photons. Also, the colliding photons gave electron–positron pairs. However, a process known as leptogenesis, similar to the baryogenesis in the case of quarks, resulted in the dominance of leptons over the antileptons. During this era, neutrinos decoupled from the quark–gluon plasma and traveled freely in the universe. These neutrinos today constitute the "cosmic neutrino background" and are also known as relic neutrinos which

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have been discussed in Chapter 17. At the end of the lepton era, the universe consisted of highly energetic photons, hadrons (protons and neutrons), and leptons. The temperature fell to about 10^{10}K.

- **Era of nucleosynthesis**

  This is the time during which the first ever nuclei in the universe were created. The era spanned from 3 to 20 minutes and the temperature fell below 10^{10}K. During this time, the collisions between the protons and the neutrons became very effective and the protons and the neutrons combined to form atomic nuclei through the following processes:

$$\begin{aligned} p + n &\longrightarrow {}^{2}\mathrm{H} + \gamma, & p + {}^{2}\mathrm{H} &\longrightarrow {}^{3}\mathrm{He} + \gamma, \\ {}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\longrightarrow {}^{3}\mathrm{He} + n, & {}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\longrightarrow {}^{3}\mathrm{H} + p, \\ {}^{3}\mathrm{He} + {}^{2}\mathrm{H} &\longrightarrow {}^{4}\mathrm{He} + p. \end{aligned}$$

  The formation of ^{7}Li and ^{7}Be took place through the processes:

$$\begin{aligned} n + {}^{3}\mathrm{He} &\longrightarrow {}^{3}\mathrm{H} + p, & {}^{3}\mathrm{He} + {}^{4}\mathrm{He} &\longrightarrow {}^{7}\mathrm{Be} + \gamma, \\ {}^{3}\mathrm{H} + {}^{2}\mathrm{H} &\longrightarrow {}^{4}\mathrm{He} + n, & {}^{3}\mathrm{H} + {}^{4}\mathrm{He} &\longrightarrow {}^{7}\mathrm{Li} + \gamma, \\ n + {}^{7}\mathrm{Be} &\longrightarrow {}^{7}\mathrm{Li} + p, & p + {}^{7}\mathrm{Li} &\longrightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}. \end{aligned}$$

  Thus, the atomic nuclei of the three lightest elements were created when the universe was only a few minutes old. As the universe became about 20 minutes old, the temperature fell below 10^{9}K and the nuclear fusion process stopped. At the end of this era, the baryonic matter dominated the universe with a composition of about 75% hydrogen nuclei, 25% helium nuclei, and traces of lithium nuclei.

- **Photon era**

  Next came the photon era which spanned for an extremely long time, from 20 minutes to 2.4×10^{5} years and the universe was again dominated by radiation. During this era, the universe was filled with a hot opaque soup of atomic nuclei and electrons. However, the temperature was still very high, that is, from 10^{9} K to 10^{6} K, for the atomic nuclei to combine with electrons to form atoms.

- **Era of recombination and decoupling**

  Next came the era of recombination and decoupling which spanned from 2.4×10^{5} to 3×10^{5} years and the temperature dropped from 10^{6} K to around 3000 K. The atomic nuclei of hydrogen and helium captured electrons to form atoms by the process known as "recombination". With the formation of atoms, the photons were able to move freely throughout the universe, and the universe finally got transparent to light. This is the earliest era which is accessible today. The photons which were interacting with the atomic nuclei and electrons till the recombination era were now released in the universe; they are still present today as cosmic microwave background radiation (CMBR). These photons decoupled because they did not have sufficient energy to interact and participate in particle creation. The cosmic microwave background radiation were first observed by

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Penzias and Wilson in 1965 [1054], and their observation is a strong evidence in support of the Big Bang theory. The density (400–500 photons/cm^3) of these radiations were almost isotropic throughout the universe. At the end of this era, that is, around 3,00,000 years after the Big Bang, the universe consisted of a fog of about 75% hydrogen, 25% helium, and traces of lithium atoms. This fog, also known as the interstellar matter, acted (and they still act) as the progenitor of the stars. It may be recalled that the nuclei of these atoms were synthesized when the universe was only a few minutes old, whereas, the atoms were created much later.

- **Dark era**

  From 3,00,000 to 150 million years, the universe is said to have been in the dark era as during this time, neither were there stars to give light nor did the cosmic microwave radiation interact with the atoms to give any light.

- **Era of stars and galaxies and the present universe**

  From 150 million years to 1 billion years, the universe expanded and its temperature fell down to about 20 to 30 K which was sufficient for interstellar matter to form stars. Therefore, this is the era which marks the beginning of the formation of stars and galaxies. A star is formed when a disturbance, due to a shock wave, compresses the interstellar matter into a confined region. After millions of years, this region becomes gradually hotter and hotter, hot enough for nuclear fusion to take place. The origin of the shock wave responsible for the formation of the very first star is not known and is well beyond the understanding of the present scientific theories. Thus, it must be noted that the formation of the first star in the universe is still not known. From 1 billion years to 13.8 billion years, the universe appeared to be similar to what we find today. At present, the average temperature of the universe is about 2.73 K and its average density is about 9.9×10^{-30} gm/cm^3.

In the following, we will discuss how the stars are formed and what is their fate. Also, we will discuss how the chemical elements heavier than lithium were created in the universe.

19.3 Interstellar Matter

Before going into the details of star formation, we first focus on interstellar matter (ISM). The space between two stars is not empty, but filled with interstellar matter which consists of gas and dust clouds. Modern observations of the ISM indicate that in terms of mass, it consists of 71% hydrogen, 27% helium, and 2% heavier elements while initially, at the time when the stars and galaxies were not formed, the ISM consisted of 75% hydrogen, 25% helium, and traces of lithium without the presence of any heavier element. It should be emphasized that the difference in terms of the mass have been used in the formation of stars. The density of ISM is about 10^{-24} gm/cm^3(or 1 atom/cm^3). Moreover, this distribution of ISM is not uniform in the universe. There are regions in space where the density of ISM is significantly higher by about tens of thousand times; and these regions are known as interstellar cloud or nebula. The nebulae are found in the galactic plane and are enormous in size, typically, in the range 1

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– 10,000 AU (astronomical unit), with 1 AU = 1.5×10^{11} m. The mass of these clouds vary between 10^4 to 10^6 $M_\odot$, where $M_\odot$ is the mass of the sun (2×10^{30}kg); the temperature of these clouds is extremely low, that is, between 10 to 30 K. These clouds are known to be the progenitors of stars.

19.4 Formation of Stars

The matter particles in the interstellar cloud, where the density is comparatively high, experiences gravitational attraction. However, their random motion, known as gas pressure, prevents them from collapsing. Stars are formed when the matter comprising the interstellar cloud collapses; what triggers a collapse is not well understood. However, there are evidences which suggest that the collapse is triggered by the perturbations created by shock waves in interstellar matter. The possible sources of these shock waves are as follows:

i) intergalactic waves, the origin of which is not yet known. These waves are considered to be the predominant trigger for the collapse of matter to form stars, and may be responsible for the formation of the very first star in the universe.

ii) pressure waves caused by the supersonic bursts during the formation of very massive stars. The star undergoes a period where it releases enormous quantities of matter in space traveling at great speeds. These cause pressure waves which may trigger disturbances when they pass through any nebula.

iii) shock waves, released when a massive star at its end phase explodes and ejects lots of matter which move out in space almost at the rate of about 10000 km/s.

When a shock wave hits the interstellar cloud, it affects a particular portion of the cloud and compresses it (Figure 19.5). If the gas pressure of the cloud fights back against the perturbation

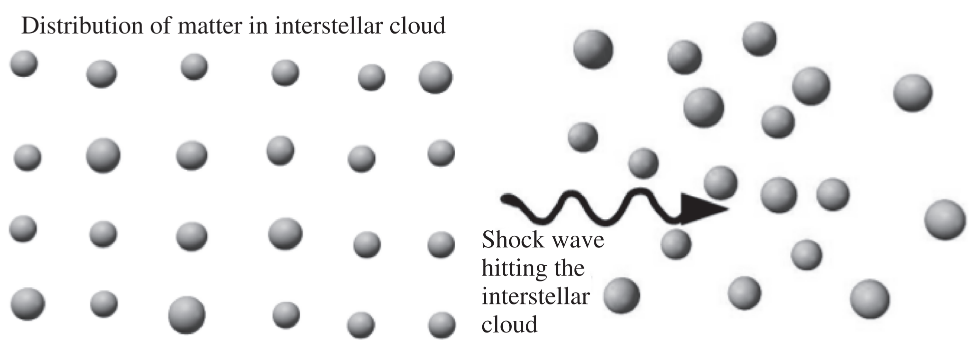

Figure 19.5 Interstellar cloud and the shock wave hitting the cloud.

created by the shock waves, then the perturbation dies out. However, if the perturbation dominates the gas pressure, then the disturbance compresses the gas to a confined region as shown in Figure 19.6(a) which, in turn, increases the gravitational force between the particles

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within that vicinity. Due to this increase in the gravitational force, the particles get closer and closer resulting in further increase of the gravitational force, which results in the accumulation of matter in the confined space. The gravitational energy of these infalling particles is converted into kinetic energy and particle collision transfers the kinetic energy into thermal energy.

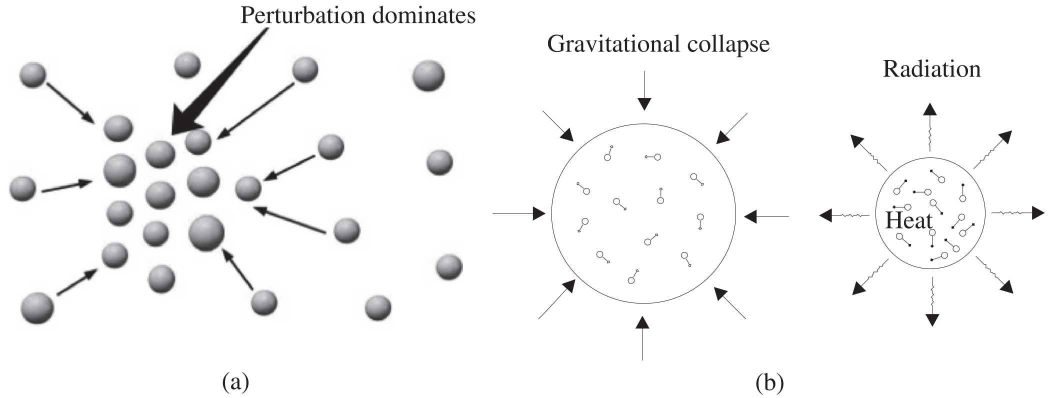

Figure 19.6 (a) Accumulation of the matter of the interstellar cloud in a region. (b) Hydrostatic equilibrium.

As more and more particles collapse, the temperature and density of the gas increase which, in turn, raises the opacity of the gas. When this contracting gas becomes opaque to its own radiation, a photosphere is formed which defines the boundary between the inside and outside of this collapsing cloud. When hydrostatic equilibrium is achieved, that is, the gravitational force is balanced by the thermal pressure, this collapsing gas becomes a protostar (Figure 19.6(b)). The temperature of the protostar is hotter than its surroundings and its formation takes about millions of years. The protostar further shrinks and heats. Eventually, the temperature of the core reaches the threshold of the hydrogen burning ($T \sim 10^9$ K). This takes more than millions of years. When hydrogen in the core starts to fuse, a star becomes a member of the main sequence of the Hertzsprung–Russell diagram.

19.4.1 The Hertzsprung–Russell diagram

The Hertzsprung–Russell (HR) diagram is a plot (Figure 19.7) which shows the relationship between the star's absolute magnitude (or its luminosity) versus the surface temperature (or the spectral class) of the star. The term spectral class describes the ionization state of the star which gives information about the temperature of the star and is directly related to its temperature. An important point to keep in mind is that the temperature of the star means the temperature of the photosphere and not the temperature of the core of a star. The term "absolute magnitude" is a measure of the brightness of the star if it is placed at a distance of 10 parsecs (1 parsec = 3.26 light years).

Most of the stars fall in the diagonal group starting from the top left to the bottom right of the plot (Figure 19.7). They are called the main sequence stars in which hydrogen fusion is taking place in the core. The hottest stars ($T > 30,000$ K) appear blue in color and belong to the spectral class "O" while the coldest stars ($T < 4,000$ K) appear red and belong to the spectral

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class "M". Our sun, having a surface temperature of about 5780 K, belongs to the spectral class "G" and appears orange in color. The luminosity of a star depends on the temperature (T) and radius (R) of the star, that is, $L \propto R^2T^4$. Therefore, a hot star of the same size is more luminous than another star of the same size having a lower surface temperature. The period of time a star lives in the main sequence depends upon its mass. The mass and the lifetime of a star are inversely proportional and hence, as the mass increases, the main sequence lifetime decreases. This relationship can be understood as follows:

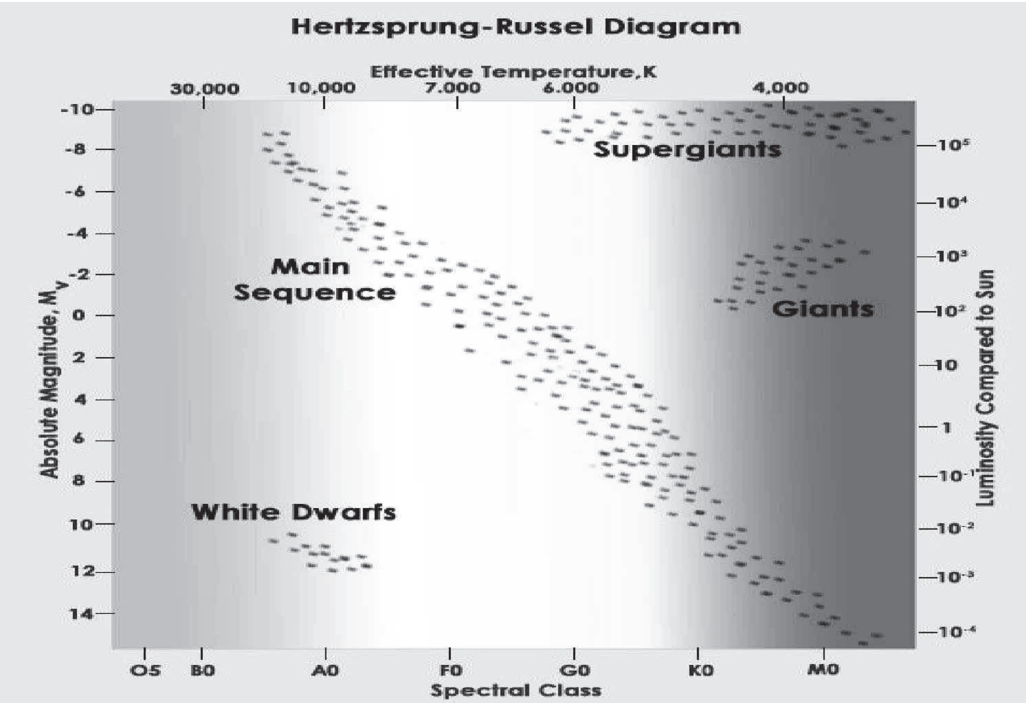

Figure 19.7 The Hertzsprung–Russell diagram: This classifies stars according to their luminosity, spectral class, surface temperature and evolutionary stage [1055].

With increase in the mass of a star, its gravitational collapse and density of the core increases, which results in an increased fusion rate in order to balance the collapse. This causes the star to fuse hydrogen in the core within a shorter time.

For example, our sun's life, as a main sequence star is about 9×10^9 years; however, for a star of mass around $5M_\odot$, the main sequence life is about 1.6×10^8 years and for a star of mass around $25M_\odot$, the main sequence life is about 2.88×10^6 years.

The stars on the lower left side of the HR diagram are white dwarfs. In the name "white dwarf", white color signifies the higher temperature of the star and dwarf signifies their small size as compared to the main sequence stars. In contrast, the stars on the upper right side of the HR diagram are called red giants and red supergiants signifying their temperature (red color means comparatively cooler objects) and their huge size.

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19.5 Stellar Nucleosynthesis

In this section, we give a general description for the hydrogen fusion process and in Section 19.5.1, we discuss the fate of stars having mass in the range $0.08\text{M}_\odot$ to $50\text{M}_\odot$. When a star is in the main sequence, the fusion of hydrogen creates new chemical elements depending upon the mass of the star. The dominant reaction that takes place during the hydrogen fusion process is $4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + 24.73$ MeV (Chapter 17). These two positrons annihilate with two electrons by the process $e^- + e^+ \rightarrow \gamma + \gamma$ and release 2.04 MeV energy. The aforementioned hydrogen burning reaction is not a one-step process; however, for low mass stars, the fusion of hydrogen into helium is dominated by the pp chain through three channels known as pp-I, pp-II, and pp-III cycles, and for massive stars, the fusion of hydrogen is dominated by the CNO cycle, which were already discussed in Chapter 17.

The fusion of hydrogen takes place only in the core of the star; the hydrogen of the outer layers does not participate in the fusion process as the temperature of these layers is not sufficient. The fusion of hydrogen into helium serves as the energy source for the main sequence stars. The energy produced by the fusion process is transferred outward by radiation or convection. Since the temperature required for the fusion increases with the increase in the atomic number of the nuclei, that is, the fusion of carbon requires higher temperature ($T \sim 6 \times 10^8$ K) than the temperature required for the helium burning ($T \sim 10^8$ K) which in turn requires higher temperature than the hydrogen burning threshold ($T \sim 4 \times 10^6$ K) due to the increase in the height of Coulomb's barrier. The silicon which is the last nuclear fuel in the core requires about 3×10^9 K to start the fusion process. With the increase in mass number (helium burning, carbon burning, etc., up to the silicon burning), the time scales of the burning phases of heavier elements decrease. For example, H burning takes around 7×10^6 years, C burning happens for about 600 years, while Si is exhausted in the core of the star in almost a day.

Next, we shall discuss the death phase of stars, which depends mostly on the mass of the star in its main sequence life.

19.5.1 Death of a star

Brown dwarf

Stars having mass $< 0.08\ \text{M}_\odot$ do not even ignite the hydrogen for fusion as the temperature of their core is less than the threshold for hydrogen burning. Although such stars become hot due to gravitational collapse, it is not hot enough to start the fusion of hydrogen into helium. After reaching the maximum possible temperature, depending upon the mass, the star starts to cool. Such objects are called brown dwarfs.

Black dwarf

For stars having mass in the range $0.08\ \text{M}_\odot < M < 0.4\text{M}_\odot$, the temperature of the core becomes high enough for the hydrogen fusion to take place. However, after the exhaustion of hydrogen fuel, the stars again collapse and heat up but the thermal energy produced by the gravitational collapse is not sufficient enough to ignite helium burning. Due to this contraction

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and rise in temperature due to convection, the star moves toward the lower left portion of the HR diagram and becomes a white dwarf. Once a white dwarf shrinks to its minimum size, it radiates energy. As there exists no fresh source of energy, it starts to cool gradually and ultimately becomes a black dwarf. In such type of stars, the energy is transmitted outward by convection only.

White dwarf

Now we consider the evolution of stars having mass lying in the range 0.4 $M_\odot$ and 4 $M_\odot$. This category is very exciting as our sun belongs to this mass range. During the main sequence, the energy produced by the hydrogen burning prevents the core from collapse. When the core runs out of hydrogen fuel, most of the it consists of helium nuclei and there is no source of energy to balance the gravitational force. The core starts shrinking due to gravitational collapse, as in the case of protostar, and this contraction converts the gravitational energy into thermal energy which in turn increases the temperature of the core. This energy is more than the energy produced by the fusion process which results in the increase in the temperature of the shell surrounding the core. Hence, hydrogen burning starts in this surrounding shell.

Now, there are two sources of energy at the center of the star, viz., the gravitational energy due to the collapse of the outer core and the fusion energy in the shell surrounding it. These two sources result in an increase in the radiation output arising from the center toward the outer envelope of the star and cause the outer portion of the star to expand. Due to this expansion, the outer envelope cools, but the core remains at a very high temperature, and the star becomes a red giant and moves towards the upper right side of the HR diagram. In Figure 19.8, we have shown the expansion of the outer envelope of the sun during its red giant phase. Although the

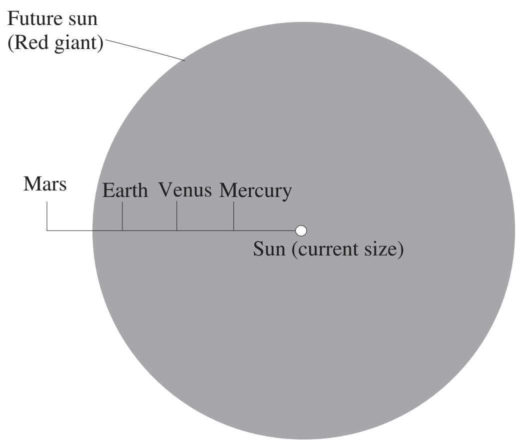

Figure 19.8 The future of sun (a red giant).

outer envelope expands, the core continues to collapse due to gravitation thereby increasing the temperature of the core until it becomes sufficient for helium burning. Helium burning proceeds through two cycles, viz., α cycle and triple α cycle:

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$$\begin{array}{cc}
3\alpha \text{ cycle} & \alpha \text{ cycle} \\
{}^{4}\text{He} + {}^{4}\text{He} \longrightarrow {}^{8}\text{Be} + \gamma, & {}^{4}\text{He} + {}^{12}\text{C} \longrightarrow {}^{16}\text{O} + \gamma \\
{}^{4}\text{He} + {}^{8}\text{Be} \longrightarrow {}^{12}\text{C} + \gamma, & {}^{4}\text{He} + {}^{16}\text{O} \longrightarrow {}^{20}\text{Ne} + \gamma \\
{}^{4}\text{He} + {}^{12}\text{C} \longrightarrow {}^{16}\text{O} + \gamma, & {}^{4}\text{He} + {}^{20}\text{Ne} \longrightarrow {}^{24}\text{Mg} + \gamma \\
 & {}^{4}\text{He} + {}^{24}\text{Mg} \longrightarrow {}^{28}\text{Si} + \gamma \\
 & {}^{4}\text{He} + {}^{28}\text{Si} \longrightarrow {}^{32}\text{S} + \gamma
\end{array}$$

As helium burning takes place at the center of the core, there is a carbon shell which is surrounded by a helium burning shell which, in turn, is surrounded by a hydrogen burning shell as shown in Figure 19.9. A red giant uses helium as a fuel for only about 10 to 20% of

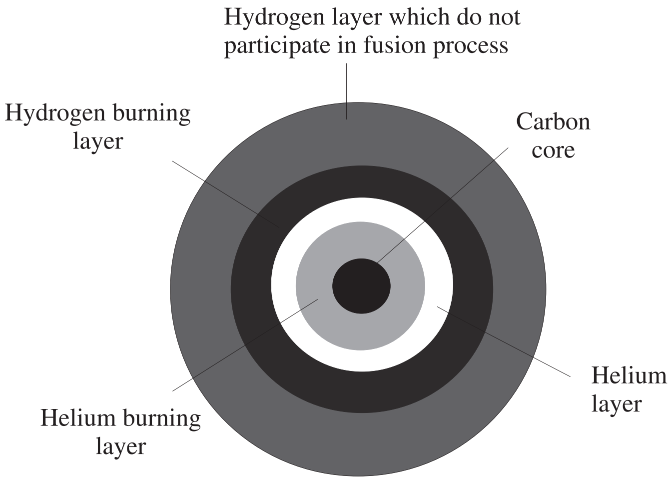

Figure 19.9 Different layers of a red supergiant.

the time as it uses hydrogen as a fuel in the main sequence. When the core runs out of helium fuel, it again contracts due to gravitational collapse making the star unstable. With increase in the gravitational energy, the luminosity increases and the star becomes a red super giant. The core collapses but the temperature is not sufficient enough to ignite carbon burning. Therefore, the core continues to shrink and heat up quickly due to the conversion of gravitational energy into thermal energy. This thermal energy causes the outer envelope of the star to blow with a speed of about 20–30 km/s. As the outer envelope explodes, it cools down but the core left behind is extremely hot ($\sim$ 100,000 K). We know that an extremely hot object emits ultraviolet radiation; the ultraviolet radiation emitted by the core makes the outer envelope of the star which was blown outward glow. Such a glowing object is called a planetary nebula (Figure 19.10). The word "planetary nebula" is a misnomer as the glowing object is neither associated with planets nor with nebula, but is a remnant of the outer envelope of a star.

The material blown out with the outer envelope gets dispersed in the ISM while the hot and bright core left behind remains very luminous for a short time and quickly moves toward the

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bottom of the HR diagram becoming a white dwarf. White dwarfs have approximately the same size as that of the earth but they have a density of $\sim 10^6$ gm/cm^3 while the average density of earth is 5.5 gm/cm^3. White dwarfs must have mass in the range $0.8\ M_\odot < M_{WD} < 1.4\ M_\odot$. This upper limit of $1.4 M_\odot$ is known as the "Chandrasekhar limit" [1056].

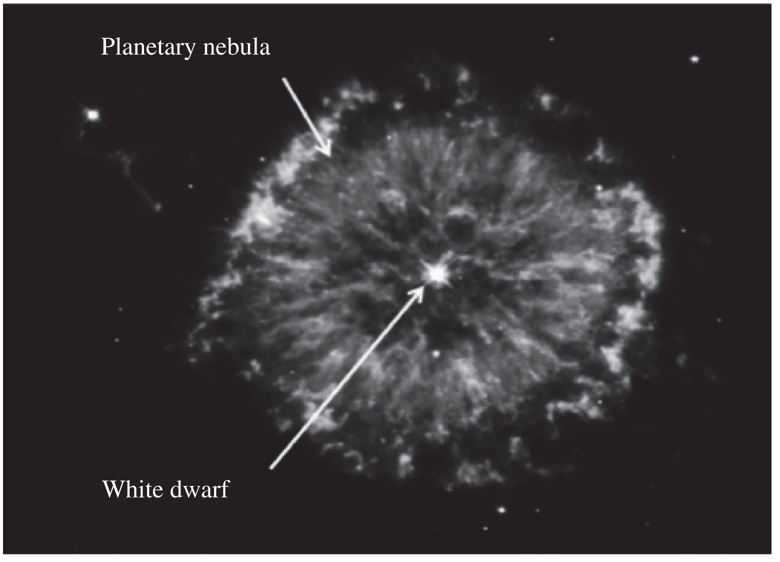

Figure 19.10 Planetary nebula and the white dwarf [1057].

19.5.2 Chandrasekhar limit

In the case of a main sequence star, the core is a gas (consisting mainly of hydrogen and helium). With increase in the gravitational energy, the temperature of the core increases. As more pressure is exerted on the core, the matter becomes so compressed that the electrons no longer move freely in the core but become degenerate electron gas, as the compression of the core causes the energy levels to be completely filled. The size of the core, now, is not proportional to its temperature, but is determined by the electron degeneracy pressure. It was Chandrasekhar, who in 1930, calculated this limit for the case of a white dwarf. It must be pointed out that in the case of low mass stars ($M_{\text{core}} < 1.4\ M_\odot$), it is the electron degeneracy pressure that halts the collapsing core.

19.5.3 Death of middle mass stars

Next, we consider stars having mass more than $4M_\odot$. Specifically, there are two categories, viz., the middle mass stars (having mass $4M_\odot < M < 8M_\odot$) and the heavy mass stars (having mass $> 8M_\odot$). Although the final products of these two categories of stars are different, before the outer envelope explodes, the two types of stars spend their lives more or less in a similar way. Therefore, we will discuss them together for the intermediate steps. It may be recalled

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that in the case of low mass stars, the core has carbon at its center surrounded by a helium shell which is surrounded by the hydrogen shell, but the core does not have sufficient temperature to ignite carbon burning. In massive stars, the temperature and the pressure are high enough to ignite the fusion of carbon and oxygen into heavier elements by the processes:

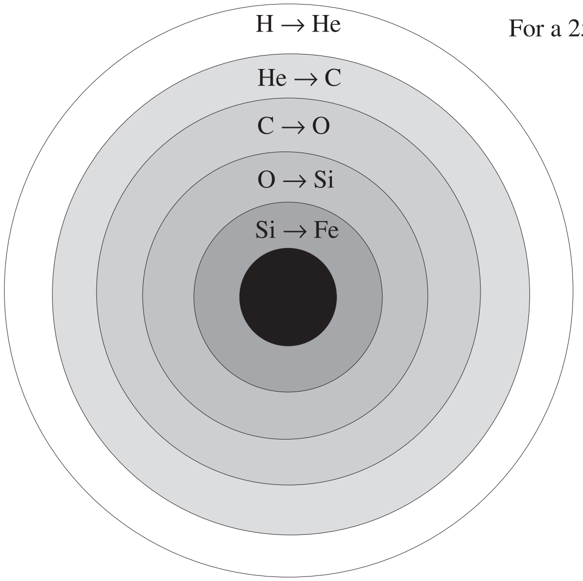
$$\begin{array}{cc}
\text{Carbon burning} & \text{Oxygen burning} \\
{}^{12}\text{C} + {}^{12}\text{C} \longrightarrow {}^{24}\text{Mg} + \gamma, & {}^{16}\text{O} + {}^{16}\text{O} \longrightarrow {}^{32}\text{S} + \gamma, \\
{}^{12}\text{C} + {}^{12}\text{C} \longrightarrow {}^{23}\text{Mg} + n, & {}^{16}\text{O} + {}^{16}\text{O} \longrightarrow {}^{31}\text{S} + n, \\
{}^{12}\text{C} + {}^{12}\text{C} \longrightarrow {}^{23}\text{Na} + p, & {}^{16}\text{O} + {}^{16}\text{O} \longrightarrow {}^{31}\text{P} + p, \\
{}^{12}\text{C} + {}^{12}\text{C} \longrightarrow {}^{20}\text{Ne} + {}^{4}\text{He}, & {}^{16}\text{O} + {}^{16}\text{O} \longrightarrow {}^{28}\text{Si} + {}^{4}\text{He}, \\
{}^{12}\text{C} + {}^{12}\text{C} \longrightarrow {}^{16}\text{O} + {}^{4}\text{He} + {}^{4}\text{He}, & {}^{16}\text{O} + {}^{16}\text{O} \longrightarrow {}^{24}\text{Mg} + {}^{4}\text{He} + {}^{4}\text{He}.
\end{array}$$

When a star runs out of its oxygen fuel, its core consists mainly of silicon and sulfur. If the mass of the star is sufficiently high such that the compression increases the temperature of the core to about 3×10^9 K, the fusion of silicon takes place. The fusion of two silicon nuclei to form iron and nickel is forbidden because of the very high Coulomb barrier; however, a different type of nuclear reaction, known as photodisintegration takes place, where a highly energetic photon interacts with a heavy nucleus and disintegrates it into a helium nucleus or a proton and other lighter nuclei. The silicon and sulfur capture these helium nuclei produced in the photodisintegration process and a number of reactions take place

$$\begin{array}{cc}
{}^{28}\text{Si} + {}^{4}\text{He} \longrightarrow {}^{32}\text{S} + \gamma, & {}^{32}\text{S} + {}^{4}\text{He} \longrightarrow {}^{36}\text{Ar} + \gamma, \\
{}^{36}\text{Ar} + {}^{4}\text{He} \longrightarrow {}^{40}\text{Ca} + \gamma, & {}^{40}\text{Ca} + {}^{4}\text{He} \longrightarrow {}^{44}\text{Ti} + \gamma, \\
{}^{44}\text{Ti} + {}^{4}\text{He} \longrightarrow {}^{48}\text{Cr} + \gamma, & {}^{48}\text{Cr} + {}^{4}\text{He} \longrightarrow {}^{52}\text{Fe} + \gamma, \\
{}^{52}\text{Fe} + {}^{4}\text{He} \longrightarrow {}^{56}\text{Ni} + \gamma, & {}^{56}\text{Ni} + {}^{4}\text{He} \longrightarrow {}^{60}\text{Zn} + \gamma.
\end{array}$$

In general, these reactions are reversible (the direct and reverse reactions occur at the same rate), although the nuclear equilibrium is not perfect. For example, the reaction produces neon at around 10^9 K but the reaction reverses direction above 1.5×10^9 K. As the temperature reaches $\sim 7 \times 10^9$ K, elements like iron, cobalt, and nickel resist the photodisintegration process and are produced in the core. The burning of silicon as a fuel lasts for only about one day. As both nickel and cobalt are radioactive nuclei with half-lives of 6.02 days and 77.3 days, respectively, ^{56}Ni decays to ^{56}Co via β^+ decay which in turn decays to ^{56}Fe. Hence, at the end, the core consists of mostly iron and iron like elements. The fusion process stops at iron as it is the most stable element. Therefore, in order to create nuclei heavier than iron, the fusion of iron must consume energy so as to overcome the Coulomb barrier. The lighter elements release energy by the fusion process while the heavier elements release energy by the fission process; however, iron and iron like elements require energy for both fusion as well as fission processes.

Now, the core resembles a multilayered onion structure as shown in Figure 19.11 and fusion takes place at the boundary between the two layers. This iron core is a degenerate gas consisting of iron nuclei and electrons. The iron core grows until it reaches the critical mass, known as the Chandrasekhar mass limit ($M_{Ch} \sim 1.4 M_\odot$), and then collapses. From here, the star begins its



For a 25 solar mass star:

State	Duration
H → He	3×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core collapse	1/4 second

Figure 19.11 Onion like layers in the core of a massive star ($M_{\rm star} = 25 M_\odot$). The table shows the duration of fusion taking place during the fusion of various elements.

journey toward death. As the mass of this core exceeds the Chandrasekhar limit, the pressure of the degenerate electron gas becomes unable to balance the force of gravity. Due to this, the core contracts more rapidly, which in turn increases the temperature of the core, releasing very high energy gamma rays. As the temperature of the core reaches to about 8×10^9 K and the density becomes $\sim 10^9$ gm/cm^3, two processes take place that consume energy:

i) The photodisintegration of iron by high energy photons into helium nuclei and neutrons, as shown in Figure 19.12, via the reaction

$$\gamma + {}^{56}\text{Fe} \longrightarrow 13\, {}^{4}\text{He} + 4n - 124.4 \text{ MeV}.$$

This reaction takes place by absorbing ~ 2 MeV per nucleon, which is contrary to the fusion process where ~ 2 MeV per nucleon is released. This loss in energy enhances the gravitational collapse, which almost becomes a free fall of the matter from the outer layers of the core there by further increasing the temperature and density of the inner core.

ii) With further increase in temperature, the photons become so energetic that the disintegration of helium into proton and neutron takes place; this disintegration absorbs ~ 6 MeV per nucleon in the reaction

$$\gamma + {}^{4}\text{He} \longrightarrow 2p + 2n - \text{energy}.$$

Since the core still continues to contract, a stage is reached where the density becomes sufficient for the protons and electrons to combine and form neutrons giving rise to the proto neutron star.

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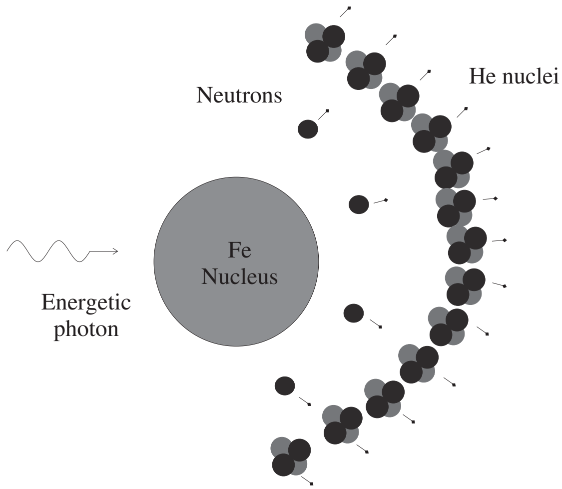

Figure 19.12 Photodisintegration of iron nucleus.

The process of electron capture by protons (Table 19.1) releases neutrinos in large numbers; neutrinos also carry substantial amounts of energy. Neutrinos released due to the capture of electrons in the stellar interior, initially come out of the core as their mean free path is sufficiently large due to the comparatively low density of the core. As the density rises to about 10^{11} gm/cm^3, the mean free path for the neutrinos reduce in such a way that they get trapped inside the core and are unable to come out. During the electron capture by heavy nuclei, several new nuclei having masses in the range $A \sim 80 - 100$, with almost 50 neutrons, are produced. This process absorbs energy; it also reduces the number of particles which in turn reduces the pressure, but the core collapse continues. When the collapsing core reaches a density of $\sim 10^{14}$ gm/cm^3, which is approximately the same as the density of the atomic nuclei, neutrons become degenerate due to the repulsive nature of the nuclear forces at short distances. This neutron degeneracy pressure halts the collapse like the electron degeneracy in the case of low mass stars. The inner core fights with the the gravitational force of the infalling matter, and due to this the infalling matter rebounds, which results in the formation of shock waves (like the sea waves at the shore when they strike rocks and produce sound waves which can be heard even from far distances). These outgoing shock waves moving almost at a speed of about 30,000 km/s, reverse the infalling motion of the material in the star and accelerate it outward. Thus, the outer envelope explodes, and constitutes the core collapse supernovae, which may give rise to the birth of a neutron star or a black hole. With this explosion, almost 10^{58} neutrinos of all flavors (notice from Table 19.1 how neutrinos of all flavors may be produced) are released which were earlier trapped due to the high density of the core. These neutrinos act as energy carriers and carry about 10^{59} MeV of energy deposited in the core of the star.

Neutron stars and pulsars

Stars having mass in the range $4\mathrm{M}_\odot < M < 8\mathrm{M}_\odot$ end their life as neutron stars. Neutron stars must have mass greater than 1.4 $\mathrm{M}_\odot$ and lesser than 2.17 $\mathrm{M}_\odot$; this limit is known as the

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Tolman–Oppenheimer–Volkoff limit [1058]. A typical neutron star has a diameter of about 20 km which implies the enormous density of the neutron star (about 10^{14} gm/cm^3). Due to such high density, the neutron star has immense gravity which, in turn, makes the escape velocity enormously large varying between 100,000 km/s to 150,000 km/s. Neutron stars have very strong magnetic fields varying in the range 10^4 to 10^{11}T at the surface. During the core collapse, the size of the star shrinks; thus, in order to conserve the angular momentum, the rotation rate of the star increases. Some neutron stars may rotate several hundred times per second in order to conserve the angular momentum. These rotating neutron stars emit electromagnetic radiation originating from their magnetic poles. If the magnetic pole and the rotation axis do not coincide, then for a distant observer, these radiations appear as pulses emitting from a fixed source at a fixed interval of time. These electromagnetic radiations are known as pulsars, discovered in 1967 by Burnell and Hewish.

Black hole

The heavier mass stars having mass more than $8M_{\odot}$ spend their life in the same manner as the middle mass stars but their fate is different. In the case of heavier mass stars, the mass of the core exceeds $2.17M_{\odot}$, and the neutron degeneracy becomes unable to counter the core collapse. Matter from the outer shells of the star falls freely toward the core and the core becomes a black hole. A black hole is a celestial object on which the escape velocity exceeds the speed of light which means that whatever light or matter falls on the black hole, it can never come back. Since no light can escape from a black hole, there is no possibility of seeing it directly. The details of a black hole are beyond the scope of this book.

Next, we will discuss the supernova nucleosynthesis which is responsible for the creation of heavier nuclei.

19.6 The Supernova Nucleosynthesis: Formation of Heavy Elements

Before discussing the supernova nucleosynthesis, we first point out the difference between the stellar and supernova nucleosynthesis. In the case of stellar nucleosynthesis, the elements are created in the core of the star and the process takes place for a longer time (approximately billions of years) depending upon the mass of the star whereas in the latter case, the chemical elements are created during the supernova explosion which takes place in a very short time (a few seconds).

In the formation of the neutron star, we have seen that a supernova explosion takes place when a massive star runs out of its nuclear fuel and the explosion of the outer envelope of the star takes place. Such kinds of supernova are known as Type II, Ib, and Ic. The classification of supernova into different types are characterized by the presence of various chemical elements in their spectrum. However, another category of supernova exists, known as type Ia supernova (see Figure 19.13), which occurs in a system of binary stars. One of the stars in the binary system is a white dwarf and the other star can be a main sequence star or a red giant or a white dwarf. In type Ia supernova, the white dwarf, which is composed mainly of carbon and oxygen

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accretes mass from the other star until it reaches the temperature for carbon burning. The white dwarf is degenerate so it does not expand with the increase in temperature. Thus, due to the fusion process, the temperature of the core increases rapidly which, in turn, increases the fusion rate. The entire star participates in the fusion process and exhausts its nuclear fuel in a shorter time. This generates huge energy that overcomes electron degeneracy and the star expands in a supernova explosion. This supernova explosion disperses chemical elements in space.

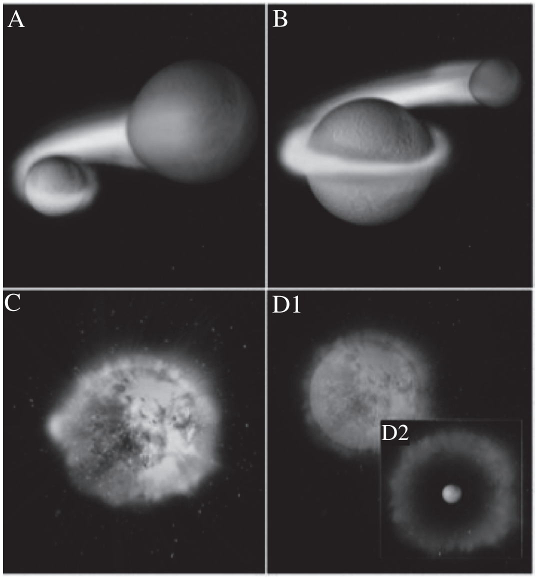

Figure 19.13 Type Ia supernova explosion [1059].

19.6.1 Nucleosynthesis of neutron-rich elements

s-process

The slow neutron capture process (s-process), depicted diagrammatically in Figure 19.14, is responsible for the creation of isotopes of lighter elements like carbon, nitrogen, oxygen, as well as the creation of heavier elements up to bismuth. In the s-process, an atomic nucleus captures a neutron at a time. If the resulting nucleus is stable, it may or may not capture another neutron but if the resulting nucleus is unstable, β-decay occurs before the capture of the next neutron. The neutron density required for the s-process to take place lies between 10^6 to 10^{11} neutrons/cm^3. The s-process is supposed to take place in thousands of years. If neutron capture rates are slow compared to β-decay rates, only isotopes near the stability line are synthesized. The s-process occurs in massive stars where the burning of carbon and helium takes place in consecutive layers called the weak s-process and in the low mass stars when they become red giants called the main s-process.

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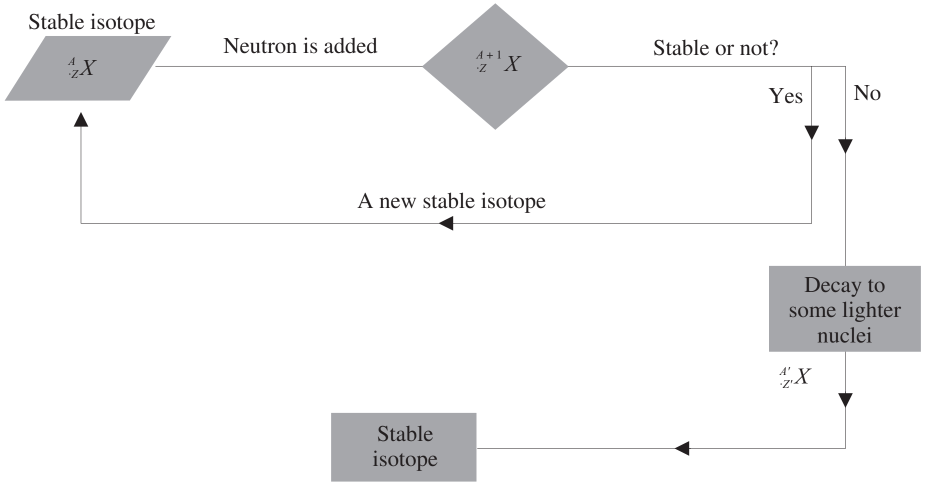

Figure 19.14 Slow neutron capture process.

The weak s-process creates isotopes of iron like elements up to strontium and yttrium with atomic number $Z = 38, 39$ and neutron number $N = 42$ to 52. The required density of neutrons in such a scenario is provided by a process like:

$$^{22}\text{Ne} + {}^{4}\text{He} \longrightarrow {}^{25}\text{Mg} + n.$$

In a massive star, where the fusion of carbon, helium, and hydrogen takes place in consecutive layers, mixing of elements between the layers occur. The carbon produced in the helium burning shell mixes with the hydrogen burning shell and produces ^{14}N through the following processes:

$$^{12}\text{C} + p \longrightarrow {}^{13}\text{N} + \gamma, \qquad {}^{13}\text{N} \longrightarrow {}^{13}\text{C} + e^+ + \nu_e, \qquad {}^{13}\text{C} + p \longrightarrow {}^{14}\text{N} + \gamma.$$

This ^{14}N is again mixed with the helium burning shell and produces isotopes of nuclei up to neon. At the exhaustion of helium fuel, the capture of helium by ^{22}Ne produces large amounts of neutrons which leads to the production of various isotopes of carbon, nitrogen, and oxygen.

$$^{14}\text{N} + {}^{4}\text{He} \longrightarrow {}^{18}\text{F} + n, \qquad {}^{18}\text{F} + e^- \longrightarrow {}^{18}\text{O} + \nu_e, \qquad {}^{18}\text{O} + {}^{4}\text{He} \longrightarrow {}^{22}\text{Ne} + \gamma.$$

The s-process also takes place in low mass stars during their red giant phase and requires comparatively low neutron density of the order of 10^7neutrons/cm^3.

The production of bismuth, polonium, and lead are cyclic in the s-process:

$$\begin{aligned} {}^{209}\text{Bi} + n &\longrightarrow {}^{210}\text{Bi} + \gamma, & {}^{210}\text{Bi} &\longrightarrow {}^{210}\text{Po} + e^- + \bar{\nu}_e \\ {}^{210}\text{Po} &\longrightarrow {}^{206}\text{Pb} + {}^{4}\text{He}, & {}^{206}\text{Pb} + 3n &\longrightarrow {}^{209}\text{Pb} \\ {}^{209}\text{Pb} &\longrightarrow {}^{209}\text{Bi} + e^- + \bar{\nu}_e. \end{aligned}$$

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The net result of this cycle is the conversion of four neutrons into a helium nucleus and two pairs of e^- and $\bar{\nu}_e$. The process may be represented as $4n \rightarrow^4 He + 2e^- + 2\bar{\nu}_e +$ energy. The elements heavier than bismuth are synthesized by the r-process, which will be discussed in the next section.

r-process

In the rapid neutron capture process (r-process), a nucleus absorbs neutrons rapidly in such a way that it happens before the nuclei undergo β-decay (Figure 19.15). Heavier elements and more neutron-rich isotopes like europium, gold, platinum, etc. are produced by the r-process. The r-process is responsible for about half of the production of elements heavier than iron; it also contributes to the abundances of some lighter nuclides. The total process of the capture of neutron is extremely fast and takes place in about 0.01 to 10 s in contrast to the s-process which occurs in thousands of years. The r-process occurs at a very high temperature ($\sim 10^9$ K) and requires higher density of neutrons $\sim 10^{20}$ gm/cm^3. There are two astrophysical sites where such density of neutrons is found: the core collapse supernova explosion (supernova type II) and the neutron star merger.

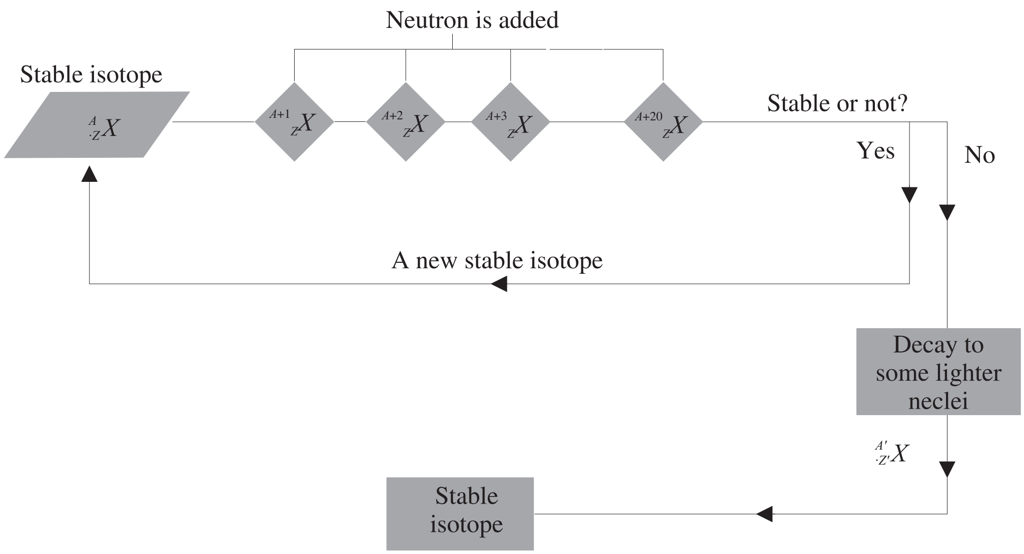

Figure 19.15 Rapid neutron capture process.

Now, we will explain type II supernova or the supernova explosion that takes place during the core collapse of a massive star. As we have seen earlier in the case of middle and heavy mass stars, the core collapse is stopped by neutron degeneracy pressure. The infalling matter from the outer envelope of the star produces a shock wave that blows up the outer envelope of the star at very high speeds in a few seconds resulting in a supernova explosion. The synthesis of elements during the supernova explosion is known as supernova nucleosynthesis. During the propagation of the shock wave from the core, the r-process creates heavier elements. The neutron density during a supernova explosion is 10^{14} gm/cm^3 while the density required for the r-process to

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take place is 10^{20} gm/cm^3. Now, the question arises from where would the neutrons come so as to reach such density to initiate the r-process? The answer is that during the core collapses, the core compresses the electrons in such a way that β-decay($n \longrightarrow p + e^- + \bar{\nu}_e$) is stopped. However, the capture of electrons by the atomic nuclei takes place which further enhances the density of the neutrons up to what is required for the r-process to start.

Neutrinos play a very important role in the understanding of the supernova explosion because neutrinos are the only source which provides information about the interior of the core. The nuclear fusion reactions taking place in the core produce neutrinos and antineutrinos of electron type only. However, the other flavors of neutrinos, viz., muon and tauon type neutrinos and antineutrinos are also produced by the following reactions of pair production and annihilation:

$$N + N \to N + N + \nu_l + \bar{\nu}_l, \;\; e^- + e^+ \to \nu_l + \bar{\nu}_l, \;\; \gamma + \gamma \to \nu_l + \bar{\nu}_l, \;\; \nu_e + \bar{\nu}_e \to \nu_l + \bar{\nu}_l.$$

Therefore, all the flavors of neutrinos and antineutrinos are produced in the core. These neutrinos are emitted from the core of a neutron star at very high speed ($\sim$ 30,000 km/s) when the supernova explosion takes place. As the high energy neutrinos travel outward, they interact with the matter of the outer layers of the star. This process continues for more than 10 s and it is assumed that during this outflow of matter, the r-process takes place. The outflow of matter from the surface of the neutron star to the outer shells at such high speed is known as the neutrino driven wind, shown in Figure 19.3, which is a very important topic from the point of view of the creation of heavier elements as it is supposed to be an astrophysical site, responsible for the creation of almost half of the heavy elements through the r-process.

Now, we will discuss the r-process taking place in the neutron star merger. Two neutron stars in a binary system orbit each other. As time passes, the gravitational radiation (energy carried by the gravitational waves) between the two increases which causes them to approach each other and orbit in the form of spiral geometry which increases the gravitational pull between the two. When these neutron stars meet each other, a massive neutron star or a black hole (depending upon the mass of the merged star) is formed.

In 2017, two gravitational wave observatories LIGO and VIRGO [1060] detected gravitational waves which were assumed to be emitted by the merger of two neutron stars. Merging neutron stars have a high density of neutronized matter and during their spiral path, they throw away heavy elements created by the r-process. Hence, the merging of two neutron stars gives information about the formation of heavier elements due to the r-process (Figure 19.16). The bulk of the matter thrown by the neutron star merger seems to be of two types:

(a) highly radioactive r-process matter of heavier nuclei with comparative lower mass ($A < 140$) which appears blue in color due to their higher temperature,

(b) higher mass number r-process nuclei ($A > 140$) rich in actinides (such as uranium, thorium, californium, etc.) and appear red in color due to their relatively lower temperature.

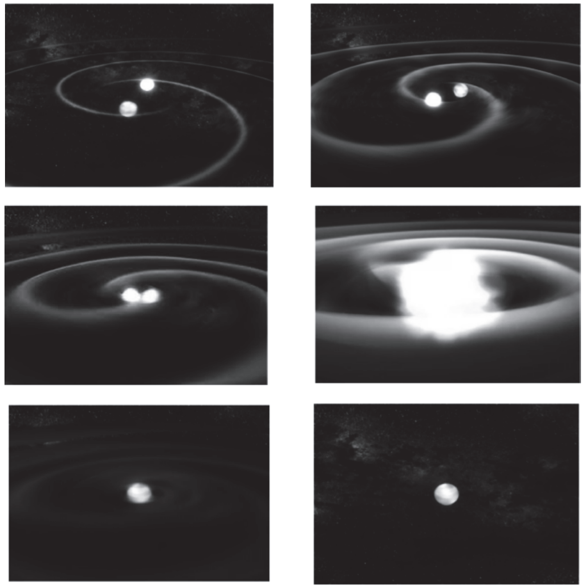

Figure 19.16 Two merging neutron stars [1061].

19.6.2 Nucleosynthesis of proton-rich elements

The nucleosynthesis of proton-rich nuclei in the universe is not very well understood. There is not a single process which is responsible for the synthesis of all the proton-rich nuclei; however, there are different processes, in various astrophysical sites responsible for their creation, which are discussed in the following sections.

p-process

In a p-process, an atomic nucleus absorbs one or more proton (depending upon the stability of the synthesized nuclei) from the surroundings before the β-decay takes place. Generally, the proton capture reactions are represented by the type (p, γ). The possible synthesis site for the p-process is still not known.

ν-process

The ν-process takes place in the outer layers of the star during the supernova explosion, where almost 10^{58} neutrinos of all flavors are released, and it is possible for the neutrinos to interact directly with the nuclei. Since all the flavors of neutrinos are released, both charged as well as neutral current induced neutrino interactions contribute to this process. The supernova neutrinos have average energy of the order of few tens of MeV. Thus, the charged current reactions are induced only by ν_e and $\bar{\nu}_e$; the other flavors participate only through the neutral current interactions. This process creates a few isotopes of ^{7}Li, ^{11}B, ^{15}N, ^{19}F, ^{138}La and ^{180}Ta as well as the long-lived radioactive nuclei like ^{22}Na and ^{26}Al.

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The light nuclei ^{7}Li and ^{11}B are synthesized by the interactions of neutrinos, induced both by charged as well as neutral currents, with helium and carbon as:

$$\begin{aligned} \nu_e + {}^4\text{He} &\longrightarrow e^- + p + {}^3\text{H}, \\ \nu_x + {}^4\text{He} &\longrightarrow \nu_x + n + {}^3\text{He}, \\ {}^3\text{H} + {}^4\text{He} &\longrightarrow {}^7\text{Li} + \gamma, \\ {}^3\text{He} + {}^4\text{He} &\longrightarrow {}^7\text{Be} + \gamma, \\ {}^7\text{Be} + e^- &\longrightarrow {}^7\text{Li} + \nu_e, \end{aligned} \qquad \begin{aligned} \nu_e + {}^{12}\text{C} &\longrightarrow e^- + p + {}^{11}\text{B}, \\ \bar{\nu}_e + {}^{12}\text{C} &\longrightarrow e^+ + n + {}^{11}\text{C}, \\ \nu_x + {}^{12}\text{C} &\longrightarrow \nu_x + n + {}^{11}\text{C}, \end{aligned}$$

where ν_x can be $\nu_{e,\mu,\tau}$ or $\bar{\nu}_{e,\mu,\tau}$. ^{11}C has a half-life of $\sim$ 20 min, which then decays to ^{11}B. Similarly, the synthesis of ^{19}F is also induced both by the charged as well as the neutral current reactions:

$$\begin{aligned} {}^{18}\text{O} + p &\longrightarrow {}^4\text{He} + {}^{15}\text{N}, \\ {}^{15}\text{N} + {}^4\text{He} &\longrightarrow {}^{19}\text{F} + \gamma, \end{aligned} \qquad \begin{aligned} \nu_x + {}^{20}\text{Ne} &\longrightarrow \nu_x + {}^{20}\text{Ne}^*, \\ {}^{20}\text{Ne}^* &\longrightarrow {}^{19}\text{Ne} + n, \\ {}^{19}\text{Ne} &\longrightarrow {}^{19}\text{F} + e^+ + \nu_e. \end{aligned}$$

The heavier isotopes, that is, ^{138}La and ^{180}Ta are produced only by the charged current interaction of ν_e and $\bar{\nu}_e$, through the reaction

$$\nu_e + {}^{138}\text{Ba} \longrightarrow {}^{138}\text{La} + e^- \qquad \text{and} \qquad \nu_e + {}^{180}\text{Hf} \longrightarrow {}^{180}\text{Ta} + e^-.$$

The radioactive nuclei ^{22}Na and ^{26}Al are also synthesized in a similar manner as discussed earlier.

γ-process

The photodisintegration of the elements produced through the s- and r-processes also yields proton-rich elements by the process known as γ-process. This process takes place at sufficiently high temperature $T \sim 2 - 3 \times 10^9$ K during the core collapse supernova as well as in type Ia supernova explosions.

rp-process

In the rapid proton capture process, the atomic nuclei capture more protons before the β-decay takes place. The rp-process requires very high proton densities of the order of 10^{28} protons/cm^3 as well as high temperature $\sim 2 \times 10^9$ K. This process is dominant in the binary system of neutron stars and creates a proton-rich nuclei having mass number $A \leq 104$.

pn-process

The neutron-rich rapid proton (np) capture process is much faster than the p-process and proceed by the (n, p) type of reactions. This process requires a considerable neutron density which is provided by the type Ia supernova explosion. It is assumed that pn-processes take place in type Ia supernova explosions.

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νp-process

The νp-process is also a process of rapid capture of protons, where the proton captures an antineutrino to produce a neutron in the final state. This neutron then interacts with an atomic nucleus by (n, p) type of reaction and creates a proton-rich nuclei. A high flux of antineutrinos is required for this process which is available from the core collapse supernova explosion.

Thus, neutrinos have been involved in the formation of elements beyond hydrogen; they are still playing an important role in the production of elements in the astrophysical environment.