UNIT 10 NUCLEOSYNTHESIS AND STELLAR EVOLUTION

Structure

10.1 INTRODUCTION

In Unit 9, you have learnt that the gravitational collapse of interstellar cloud leads to the formation of stars. You may recall that a stable star is formed when an equilibrium between gravitational force in the collapsing cloud and the radiation pressure due to nuclear energy generated in its core is attained. In this regard, some logical questions which might come to your mind are: Since nuclear fuel burning at the core of a star like the Sun is finite, what happens when the fuel is exhausted? Does the same type of nuclear energy generation process take place in all stars? What happens to the material produced in the nuclear reactions in the stars? If all the new born stars find place on the main-sequence of the H-R diagram, how do we explain the existence of red giants, supergiants and white dwarfs? To answer these questions, you need to learn about the life of a star (that is, stellar evolution) after it has been formed and found its place on the main-sequence. This is the subject matter of the present Unit.

An interesting approach to understand stellar evolution is to ask ourselves: **How did the ninety-three natural (chemical) elements, which are the building blocks of all living and non-living matter around us, come into existence?** All the elements, except hydrogen and most of helium, were *made* inside stars through the process of **nucleosynthesis**. The stars make elements during their life-time. Interestingly, all the stars produce the same elements which we find on the Earth. Further, we find the same elements everywhere in the universe and more or less in the same proportion. The relative proportion of these elements in the Universe is called **cosmic abundances** about which you will learn in Sec. 10.2. In Sec. 10.3, you will learn about various nucleosynthesis processes taking place inside the stars at different stages of their life. You will discover that the conditions for different processes are different. This provides a basis to track the evolution of stars along the main-sequence and afterwards. The low-mass and high mass stars evolve differently leading to different end products such as white dwarfs, neutron stars and black holes. You will learn about this in Sec. 10.4. In Sec. 10.5, you will learn that, when the entire nuclear fuel at the core of a star is exhausted, rapid gravitational collapse takes place which may result in a violent explosion, called **supernova**, of the stellar envelope.

Objectives

After studying this unit, you should be able to:

- list the various methods of determining cosmic abundances;
- list and explain various nucleosynthesis processes in the context of stellar evolution;

- describe where and how chemical elements are formed;
- explain the significance of stellar mass in respect of evolution of stars;
- estimate the lifetime of stars on the main sequence;
- describe the conditions for the formation of red giants, supergiants and white dwarfs; and
- discuss conditions for the supernova explosions and the fate of left over stellar cores.

10.2 COSMIC ABUNDANCES

You know that the atom is the smallest unit of an element and atoms of each element are unique. Atoms may be said to be the basic building blocks of matter. Molecules are formed when atoms combine due to electrical forces between them. More complex substances are formed when there is chemical reaction between elements.

In school chemistry, you must have learnt about elements, atoms and molecules. Elements are the simplest substances of ordinary matter. Scientists recognise 93 elements as *natural*. Besides these, there are 20 elements which can be *manufactured* in the laboratory by bombarding nuclei with α-particles or other high energy particles. These 20 artificial elements are not found in nature because they are *unstable* and live for extremely short times.

Almost all the natural elements are found on the Earth. A few elements which are not found on the Earth are found in other bodies of the solar system. You may be surprised to know that the same 93 elements are also found elsewhere in the universe and their proportion is more or less the same as their proportion in the solar system. The **chemical composition of the universe** refers to the presence of different types of elements and their proportions in the universe. Since the chemical composition of the universe and that of the solar system are similar, it is one and the same whether we talk of the chemical composition of the universe, or the chemical composition of the solar system. Further, the relative proportions of elements in the universe are called **cosmic abundances**.

Determination of Cosmic Abundances

Now, the question is: **How do we determine abundances in the solar system, that is, how do we determine cosmic abundances?** Some of the important methods to obtain information about abundances are as follows:

i) In the solar system, the immediate source for obtaining such information is obviously the Earth. Samples from many locations on the Earth are analysed in the laboratory. Care is taken that these locations are as diverse as possible.

ii) The next obvious source is the Sun. You may recall from Unit 5 that the dark lines in the **solar spectrum**, called **Fraunhofer lines**, are actually **absorption** lines due to elements present in a slightly cooler layer above the photosphere. Each line in the spectrum is checked against the sample spectra of elements and the elements are identified. *The intensity of a particular line gives the abundance of the corresponding element*. You may also recall from Unit 5 that the higher layers of the solar atmosphere, the **chromosphere** and the **corona**, are at relatively higher temperatures than the solar surface. The spectra of these layers show **emission lines** due to elements present in these layers. Analysis of these lines also helps in determining solar system abundances.

iii) The Sun also emits streams of particles in the form of **solar wind**. Occasionally, the Sun emits very high energy particles, called the **solar cosmic rays**. The compositions of the solar wind and the solar cosmic rays are directly determined by instruments on-board many spacecrafts orbiting the Earth.

iv) The spectrum of other objects in the solar system such as the moon and planets are other sources of information about abundances in the solar system. Samples of dust brought from the moon and chemical analysis of the Martian surface has added significantly to this information.

v) You must be aware that small rocky pieces wandering in the solar system, called **meteors**, occasionally enter the atmosphere of the Earth. If meteors are not burnt completely by the heat generated due to atmospheric friction, they reach the Earth. These pieces are called **meteorites**. Analysis of their composition provides valuable information about abundances. The spectra of comets are yet another source of information about the solar system abundances.

vi) Outside the solar system, spectra of other stars and interstellar clouds are important sources of information about the cosmic abundances.

Cosmic abundances of various elements have been determined using a variety of methods including those discussed above. Refer to Fig. 10.1 which depicts the variation of cosmic abundances with mass number of elements.

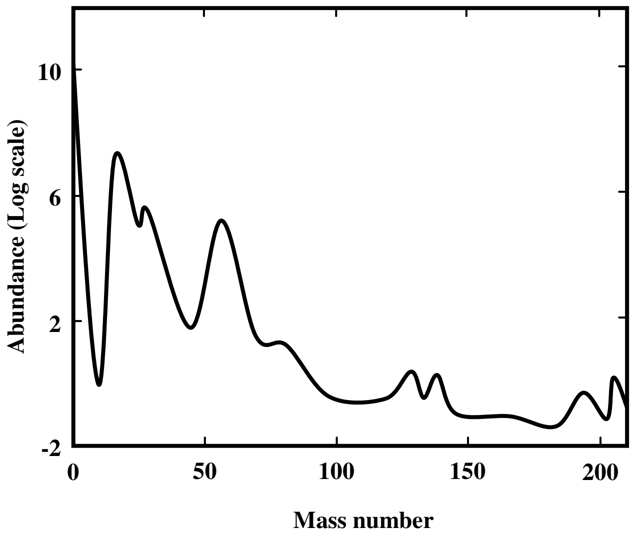


Fig.10.1: Abundances of various elements in the universe as a function of mass number

The same data is shown in greater detail in Fig. 10.2. The abundances have been expressed in terms of a unit in which the abundance of silicon (Si) is exactly 10^6. This is because the abundance of Si is very close to this number.

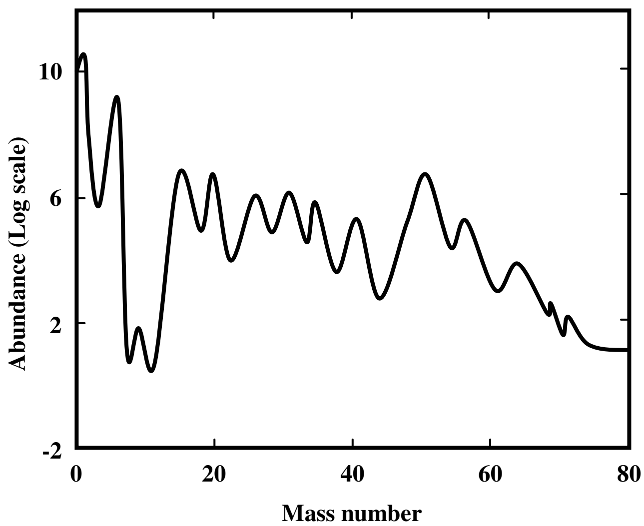


Fig.10.2: A detailed version of Fig. 10.1 for elements up to mass number 80

The salient features of Figs. 10.1 and 10.2 are as follows:

1. *Hydrogen* (H^1) *and helium* (He^4) *are the most abundant elements in the universe.* About 90% of the particles in the universe are hydrogen atoms. Helium is the next most abundant element, accounting for *about* 10% of all the particles.

2. *Heavier elements* constitute less than 1% of the total matter in the universe.

In the language of astronomy, any element heavier than He^4 is called a **heavy element**.

3. If we leave out H^1 and He^4, we observe that *abundances generally increase with mass number up to the mass number around 60*. This is in the neighbourhood of iron (Fe^{56}). Around this mass number, there is a broad peak.

4. Beyond the mass number 60, the abundances decrease. At first, the decrease is faster and then it gradually tapers off.

5. There are peaks of abundances corresponding to elements with mass numbers 12, 16, …. and so on (multiples of 4). Moreover, elements with mass numbers, 14, 18, … and so on (multiples of 2) are more abundant as compared to those with odd mass numbers.

On the basis of these features of cosmic abundance data, we can conclude that:

a) The origins of hydrogen and helium are perhaps different from the origin of heavier elements in the universe.

b) Peaks of abundances at mass numbers that are multiples of four could involve a particle such as the α-particle or the helium nucleus, which has mass equal to 4 atomic mass unit (amu).

Spend 5 min.

SAQ 1

On the basis of relative number of atoms of hydrogen and helium in the universe, calculate the fractional mass of the matter in the universe contributed by hydrogen and helium.

Having learnt about the cosmic abundances, a logical question that may come to your mind is: **Where and how are these elements formed?** *Astronomical studies tell us that all the elements, except hydrogen and helium, have been synthesised in the stars during their evolution.* This is also reinforced by the observation that the older stars in our Galaxy contain much less heavier elements than the younger stars. Thus, we can visualise the following roadmap for creation of elements and how the process is related with the evolution of stars:

a) Elements are formed inside the stars. Since the birth and death of stars is a continuous process, the formation of elements is also an on-going process.

b) The oldest stars in the Galaxy, called **Population II stars**, were formed from the original matter of the Galaxy which was mostly hydrogen. These stars had to manufacture their own heavy elements. Therefore, they are relatively poor in heavier elements.

c) At the end of their life, some of these stars explode and return the heavier elements formed by them to the interstellar medium.

d) From this enriched interstellar material, new stars are formed. These relatively younger stars, also called **Population I stars**, are rich in heavier elements. In addition, they also manufacture elements in their cores which constitute the raw material for the subsequent generations of stars.

The hypothesis that elements are made inside the stars gets support from the detection of elements like **technetium** in the spectra of some stars. This element is not found in the solar system. Where could this element have been formed except in the stars in which it is observed?

Now, the question is: **What is the origin of the major constituents, namely hydrogen and helium, of interstellar medium?** An acceptable theory in astronomy tells us that hydrogen and helium were formed in a different process (see Unit 15). You could question this theory since you have learnt earlier that He^4 is formed from H^1 in the core of the Sun and the other main-sequence stars. *The fact is that if we take account of all the helium that could have been formed in the stars in all the galaxies, it falls much short of the total helium estimated to be present in the universe (about 30% by mass).* To appreciate this statement, solve the following SAQ.

SAQ 2

Spend 10 *min.*

The atomic weights of hydrogen and helium are 1.0079 and 4.0026, respectively. In the fusion reaction converting hydrogen into helium, one gram of hydrogen produces about one gram of helium and approximately 6×10^{18} ergs energy is released. Given that the luminosity of the Sun is 4×10^{33} erg s^{-1} and its estimated age is 5×10^{9} years, show that only about 5% of its mass has been converted into helium. Take the solar mass as 2×10^{30} kg.

Having solved SAQ 2, you might conclude that only a small fraction of the total helium present in the universe has been manufactured in the stars. It is, therefore, reasonable to believe that light elements like hydrogen, helium, deuterium (D^2), He^3, and Li^7 did not form inside the stars. You may ask: **Do we have any clue about the origin of these elements?** According to one theory about the origin and evolution of the universe, *these elements were formed in the first minute after the birth of the universe*. *At that time*, *the universe was hot and dense and the conditions were suitable for the formation of light elements*. (This issue is discussed in detail in unit 15 of this course.) This theory is supported by the fact that the abundances of light elements predicted by it in the early universe agree very well with the observed abundances. **The coincidence is considered a very strong evidence supporting the idea that the early universe was very hot and dense and that it was born in a violent event called the Big-Bang**.

A clue to support the hypothesis that heavier elements are *manufactured* inside the stars was provided by Bethe (in US) and Weizsacker (in Germany) in 1938.They showed the possibility of converting hydrogen into helium through nuclear reactions which would take place at high temperatures and high densities. Such conditions are readily available in the interior of stars such as the Sun, which also has plenty of hydrogen. The work of Bethe and Weizsacker gave birth to the field of nuclear astrophysics and subsequently, scientists were able to show that other heavier elements could also have been formed in stars through the process of nucleosynthesis involving a variety of nuclear reactions. Would you not like to know about nucleosynthesis? We discuss this in the next section.

10.3 STELLAR NUCLEOSYNTHESIS

You may recall from your school physics that nuclear fusion is the process of coming together of two or more light nuclei to form a new nucleus. Since a fusion reaction involves coming together of charged particles, it requires that they have sufficient energy to overcome the Coulomb repulsion. Such energies are readily available in the form of thermal energy in stellar interiors. The nuclear reactions taking place in such environments are called **thermonuclear reactions**. The process of creation of new elements in such reactions is called **nucleosynthesis**.

A variety of nuclear reactions can take place depending upon the elements present, temperature and density in the interior of stars. The information about these reactions helps us understand stellar evolution better because on the basis of this information, The temperature inside the stars is very high. Therefore, all the atoms are ionised. The nuclear reactions take place between nuclei and the products are also nuclei. In this context, therefore, whenever we talk of atoms or elements, we really mean nuclei.

we can determine the age of the stars as well as their future. Let us now discuss the major processes by which elements are synthesised in the stellar core.

1) Hydrogen Burning

The first stage of nucleosynthesis is the fusion of hydrogen nuclei and consequent formation of helium. You have already learnt in Unit 5 about the chain of reactions, called the **pp-chain**, which causes fusion of four hydrogen nuclei (protons) to form helium. This is the process by which the Sun and other similar stars generate their energy:

$$H^1 + H^1 \rightarrow H^2 + e^+ + \nu_e$$

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

$$He^3 + He^3 \rightarrow He^4 + 2H^1$$

Another chain reaction has helium as its end product and it produces energy in the main sequence stars. It starts with carbon and is called the **carbon-nitrogen cycle (CN-cycle)**. Obviously, for this reaction, it is necessary that the stars have some carbon to begin with. Such stars are called the **second generation stars**. The stars which start life with only hydrogen and helium are called **first generation stars**.

The temperature required for CN-cycle is higher than the temperature required for the pp-chain. The nuclear chain reactions involved in the CN-cycle are given below:

$$C^{12} + H^1 \rightarrow N^{13} + \gamma$$

$$N^{13} \rightarrow C^{13} + e^+ + \nu_e$$

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

$$N^{14} + H^1 \rightarrow O^{15} + \gamma$$

$$O^{15} \rightarrow N^{15} + e^+ + \nu_e$$

$$N^{15} + H^1 \rightarrow C^{12} + He^4$$

You may note that the end result of the CN-cycle is to combine four hydrogen nuclei to form helium; carbon merely acts as a catalyst for the reaction and is not consumed in the process. You may ask: **If we know that CN-cycle is active in a star, what information can we obtain about that star?** Recall from Unit 7 that, as we go up in the H-R diagram, the luminosity increases. Since luminosity of a star is proportional to some power (generally 3.5) of its mass, the mass also increases upwards. Further, the internal temperature of a star is generally proportional to its mass. Therefore, the stars in which energy is generated by the CN-cycle are generally found in the upper region of the main sequence. They have high internal temperature and were formed from material enriched in heavy elements.

Spend 2 min.

SAQ 3

On the main sequence in the H-R diagram, where would you find stars which have internal temperatures lower than that of the Sun?

2) Helium Burning

When all the hydrogen in a stellar core has been used up, pp-reactions and CN-cycle are no longer possible. As a result, the energy generation stops and the pressure in the core decreases. It is no longer able to match the inward gravitational pull of the particles and the core contracts. In some stars, the contraction continues till the temperature has risen to about 2×10^8 K. When the core temperature of a star attains this value, it is possible for helium nuclei to fuse together and produce carbon.

If you look at the periodic table carefully, you will find that at mass number eight, there is a gap. This means that the element at this position is unstable. The question is: **How do reactions between helium nuclei overcome this gap?** The two He^4 nuclei (or α-particles) combine to form Be^8. Since Be^8 is unstable, it disintegrates into two α-particles in a very short time. In the presence of to and fro reactions of this kind, the stellar core becomes a sea of He^4 nuclei with a few Be^8 nuclei floating. *These floating Be^8 nuclei combine with α-particles to form C^{12}* nuclei. Despite very low population of Be^8 nuclei, C^{12} is formed because the reaction between α-particle and Be^8 has a very high probability of occurrence. So, carbon is formed when three α-particles combine according to the following reactions:

$$He^4 + He^4 \rightarrow Be^8 + \gamma$$

$$Be^8 + He^4 \rightarrow C^{12} + \gamma$$

The above nuclear reaction is also called the **triple-α reaction**. Once carbon is formed in the stellar core, formation of heavier nuclei becomes possible. You may recall that carbon and some other heavier elements are absolutely essential for the origin of life. Thus, it can be argued that we are here and discussing nucleosynthesis today because **triple-α reactions** took place in some stellar cores in the distant past!

SAQ 4

Spend 5 min.

a) Why are three α-particles needed to initiate helium reactions?

b) Explain the importance of triple-α reaction in the formation of heavy nuclei. In what way is triple-α reaction related to the origin of life on the Earth?

3) Burning of Carbon and Heavier Nuclei

Once carbon is formed, it can combine with an α-particle and form oxygen (O^{16}). Afterwards, O^{16} can react with an α-particle to form Ne^{20}. When all the helium has been converted into carbon in the core of the star, helium reactions stop and energy generation is terminated once again. This leads to further gravitational contraction of the core and temperature of the interior of the star increases. At the enhanced temperature, it becomes possible for two carbon nuclei to combine and form Mg^{24}.

By now, you must have noted that every time a particular type of nuclear fuel is used up completely, core contraction due to gravitation takes place. As a consequence, there is a rise in the temperature of the core. When the temperature has risen to the required level, yet another nuclear reaction becomes possible. *This cycle continues till all the nuclei in the core have become iron nuclei.*

You may ask: **Why does the series end at iron?** To answer this question, refer to Fig. 10.3 which depicts the binding energy curve for nuclei. Note that the average binding energy per nucleon increases with mass number till we reach the mass number of iron. This means that with increasing mass number, the nuclei are more tightly bound and are more stable. *It also means that iron is the most stable element. It cannot combine with other nuclei to produce still heavier nuclei.* The binding energy curve also gives us a clue for understanding why energy can be derived by fusing light elements as well as by splitting (**fission**) the nuclei of heavy elements.

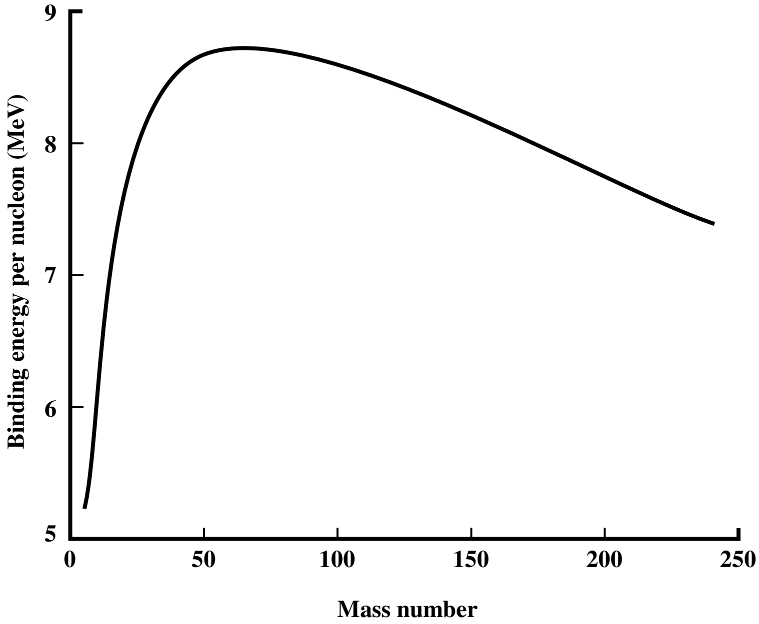


Fig.10.3: Average binding energy per nucleon as a function of mass number

It is, therefore, understandable why elements heavier than iron cannot form as a result of thermonuclear fusion reaction. However, the fact of the matter is that elements heavier than iron do exist in nature. The question, therefore, is: **How did they form?** It is believed that such heavier elements formed in some special types of nuclear reactions called s- and r-processes.

4) s- and r- processes

The elements heavier than iron are probably synthesized by the absorption of one neutron at a time. For example, let us consider the nucleus of atomic number Z and mass number A. It is written as (Z, A). When it absorbs one neutron, its mass number increases by one and it becomes $(Z, A+1)$. If the new nucleus absorbs yet another neutron, it becomes $(Z, A+2)$. If this nucleus emits a β-particle before it can absorb another neutron, it becomes $(Z+1, A+2)$. The last one, nucleus $(Z+1, A+2)$, may absorb another neutron to become $(Z+1, A+3)$. **In this way, all the elements up to Bi^{209} are formed**. This process of absorption of one neutron at a time is a **slow process** and is named as **s-process**. The neutrons required for this process are produced as a by product of reactions of the following types:

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

$$O^{16} + O^{16} \rightarrow S^{31} + n$$

Well, you can further ask: **Why does the s- process stop at Bi^{209}?** It is because the elements heavier than Bi^{209} are unstable and emit β-particles before they can absorb a neutron. However, if neutrons become available in large numbers, then these nuclei can absorb neutrons rapidly. Due to this **rapid process**, or the **r-process**, elements right up to uranium are synthesized in stars.

So far, you have studied about cosmic abundances and stellar nucleosynthesis. You now know that all the heavy elements are formed in stars due to thermonuclear reactions. The relative proportion of heavier elements in stars tells us whether it is a first or a second generation star. The various types of nuclear reactions are associated with different stages in the life of a star and also with the location of the star on the HR-diagram. You will now learn about the evolution of stars.

10.4 EVOLUTION OF STARS

You may recall from Unit 9 that gravitational collapse of a gas cloud gives birth to stars. A stable star is formed and finds its place on the main sequence only when it attains hydrostatic equilibrium, that is, when the pressure inside the star balances the gravitational force acting inwards. In the following, we shall discuss the **life of stars** on the main sequence and afterwards.

10.4.1 Evolution on the Main Sequence

For most of their lives, stars live on the main sequence on the H-R diagram. We would, therefore, like to know: i) **How long does a star live on the main sequence?** and **ii) What happens in the core of a star while it is on the main sequence and when it departs from the main sequence?**

When a star arrives on the main sequence, it is said to have been born. That is why the main sequence is called **zero-age main sequence** (ZAMS). While the star is on the main sequence, it burns hydrogen either through pp-chain or through CN-cycle. There is little change in its luminosity. The best example of the main sequence star is the Sun. It is known that the luminosity of the Sun has not changed much during its lifetime of 5 billion years. You may ask: **How do we estimate the life of a star on the main sequence?** Fortunately, for the Sun, we have enough data to make an intelligent guess. It is estimated that the core of the Sun has about 10% of its total mass and from SAQ 2, we know that so far it has burnt only about half of this (hydrogen) mass to make helium. Therefore, it is estimated that the Sun would stay on the main sequence for another 5 billion years.

Let us now ask ourselves a more general question: **How long does a star live on the main sequence?** To address this question, we need to look critically at the mass-luminosity relation of stars. *We know that the ultimate source of energy for a star is its mass. When it is burning hydrogen to form helium, it is actually converting its mass into energy*. The relation between luminosity (L) and mass (M) of a main sequence star is given by:

$$L \propto M^{3.5} \qquad (10.1)$$

Since luminosity is the energy radiated by a star per second and M is its total mass which can be converted into energy, the time for which it will stay on the main sequence can be written as:

$$\tau \approx M / L. \qquad (10.2)$$

From Eqs. (10.1) and (10.2), we can write:

$$\tau \propto M^{-2.5} \qquad (10.3)$$

The constant of proportionality is determined by the expected lifetime of the Sun. Eq. (10.3) shows that the *more massive a star is,* the *shorter is its life on the main sequence*. To get a feel of the numerical values of the age of stars on the main sequence, you should solve the following SAQ.

SAQ 5

Spend 5 min.

The estimated lifetime of the Sun on the main sequence is ~ 10^{10} years. Calculate the main sequence lifetime of a star of mass (i) 10 M_Θ and (ii) 0.5 M_Θ.

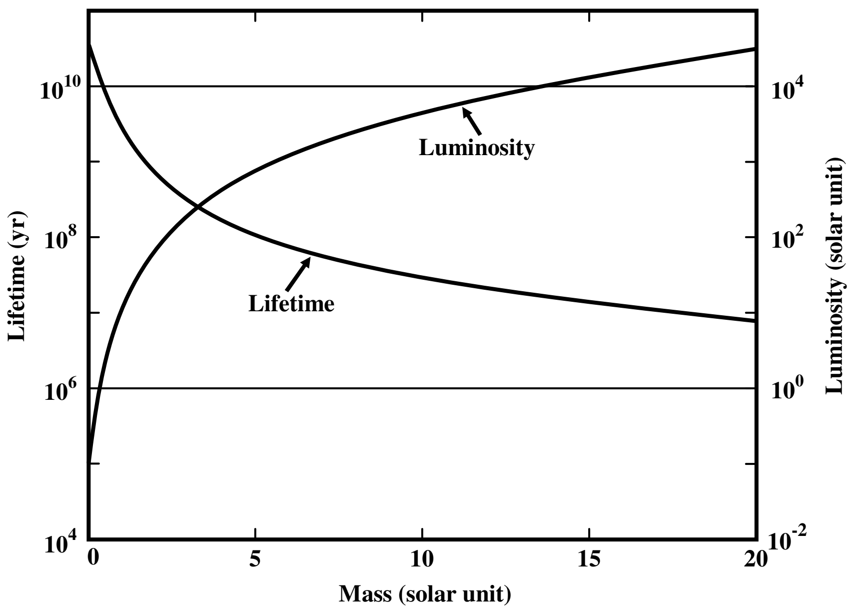


Fig.10.4: Lifetime and luminosity of stars on the main sequence as function of mass

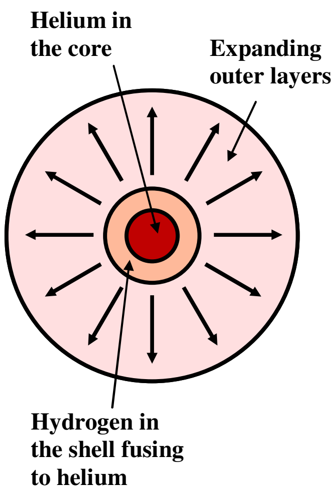


Fig.10.5: When hydrogen in the core of a star is exhausted, the core contains pure helium and hydrogen burns in a thin shell around the core

Refer to Fig. 10.4 which shows the lifetime of stars on the main sequence as a function of the stellar mass. You may note that a star of mass 10 $M_{\odot}$ will stay on the main sequence for about 3×10^7 years and a star of mass 0.5 $M_{\odot}$ will stay on the main sequence for about 6×10^{10} years. You may ask: **How come a more massive star which has more nuclear fuel has shorter lifetime on the main sequence?** Recall that massive stars must burn their fuel at a faster rate to emit more energy from their surfaces per second. Thus, they run out of fuel sooner. By the same token, lower mass stars burn fuel at a slower rate. In this context, it is interesting to note that the estimated age of the universe is ~ 1 to 2×10^{10} years, a time period much shorter than the estimated lifetime of low mass stars on the main sequence!

Having got a fairly good idea about lifetimes of stars of different masses on the main sequence, you may like to know: **How does the core of a main sequence star evolve?**

While a star is on the main sequence, its core becomes progressively richer in helium. When the core consists only of helium, no nuclear reaction takes place because the temperature is not high enough for the next stage of nuclear reactions. As a result, the pressure in the core decreases and the core must contract under its own weight. The gravitational energy released due to contraction raises the temperature of hydrogen in a thin shell around the core so much that it starts burning (Fig. 10.5). The helium made in the shell adds to the mass of the core whose contraction is accelerated. The energy produced in the shell and the gravitational energy due to the contracting core push out the envelope of the star due to radiation pressure. As a result, the star expands in size. Its surface becomes cooler but its luminosity increases enormously because of increased surface area. It becomes a giant star.

Spend 3 min.

SAQ 6

It is estimated that after its life on the main sequence, the Sun will swell to 200 times its present radius. If, at that time, its surface temperature is half of its present temperature, calculate the luminosity of the Sun in terms of its present luminosity.

Let us now look at the events that take place in the life of a star when it leaves the main sequence.

10.4.2 Evolution beyond the Main Sequence

When a star leaves the main sequence, it becomes a giant star because of its increased size. Since the surface temperature of these stars is low, they appear red and are also known as **red giant stars**. The more massive (> 10 M_Θ) stars become so huge because of expansion that they are called **supergiant stars**. The time taken by a star to travel from the main sequence to the giant or supergiant branch is much shorter than its stay on the main sequence. *The Sun will also become a giant star after about 5 billion years.*

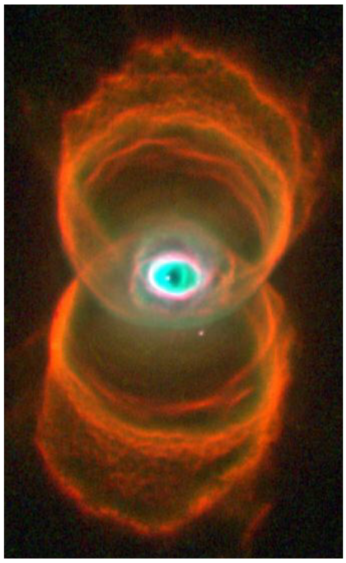


Fig.10.6: A planetary nebula

Meanwhile, the cores of these stars continue to contract and their temperatures rise further. When the temperature of the core is about 2×10^8 K, triple α - reactions become possible. The energy released in these reactions builds up the pressure in the core and further contraction of the core is halted. Further details of evolution depend on the mass of the star. Let us discuss some illustrative cases now.

Mass of the star is ~ 1 M_Θ

If the mass of the star is approximately 1 M_Θ, the helium burning is rather abrupt and a large amount of energy is suddenly released. This phenomenon is called a **helium flash**. Several circumstances, some not yet completely understood, combine at this stage to force the star to throw away its outer envelope. The ejected matter surrounds the star. This object is called a **planetary nebula** (Fig. 10.6). In a small telescope, it appears like a planet, hence the name planetary nebula.

Within a short time, the gas surrounding the star vanishes due to interaction with the interstellar medium. Simultaneously, the core again begins to contract and becomes very dense and the matter in the core becomes a **degenerate gas.**

Degenerate gas is a particular configuration of a gas composed of fermions (electrons, neutrons, etc.) whose behaviour is regulated by a set of quantum mechanical laws, in particular, Pauli's exclusion principle (explained in the physics electives PHE-11 entitled Modern Physics). This configuration of a gas is usually reached at high densities. Recall that according to Pauli's exclusion principle, **no more than two fermions (of opposite spin) can occupy the same quantum state of a system**. As the density of electrons in the core of a star increases in a fixed volume, these particles progressively fill the lower energy states. The additional electrons are forced to occupy states of higher and higher energy.

This process of gradually filling in the higher-energy states **increases the pressure** of the electron gas. The pressure of the degenerate gas depends only on the density of the gas and is independent of its temperature. Since degeneracy occurs when the density is high, the pressure of the degenerate gas is high. The equation of state of such a gas is independent of temperature unlike the normal gas.

In stars of mass ~ 1 M_Θ , only the electron component of the matter becomes degenerate. The pressure of degenerate electrons is sufficient to halt the contraction of the star. A state of equilibrium is established. The star is then called a **white dwarf** star. *The maximum mass of a white dwarf star is* ~ 1.4 M_Θ. This limit on the mass of a white dwarf star was predicted theoretically by S. Chandrasekhar, an Indian astrophysicist. It is, therefore, called the **Chandrasekhar limit**.

In the H-R diagram, the white dwarf stars occupy the left bottom corner, much below the main sequence as shown in Fig. 10.7. The numbers above the lines in Fig. 10.7 indicate the mass of white dwarf stars in terms of solar mass.

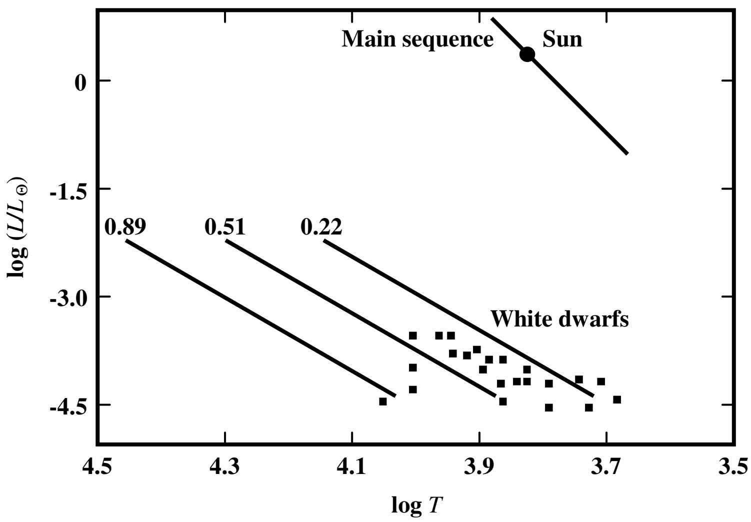
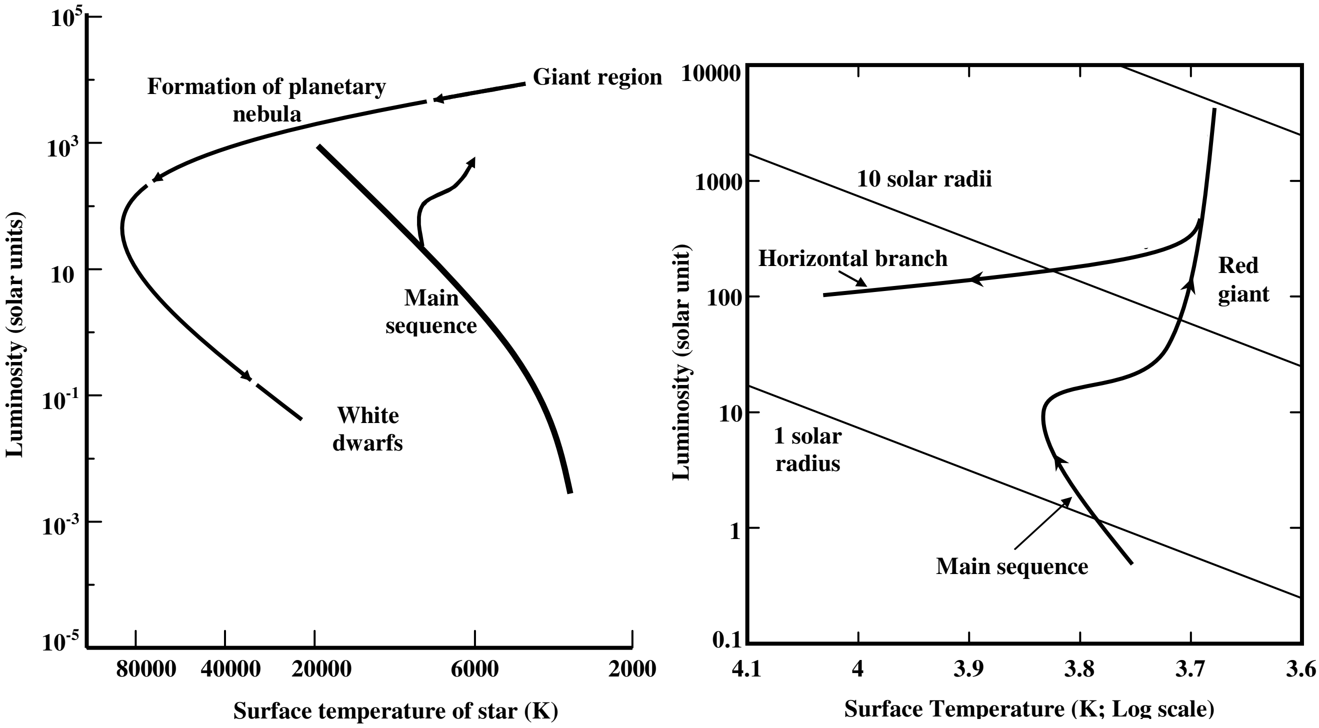


Fig.10.7: Location of white dwarf stars on the H-R diagram

There is no source of nuclear energy inside a white dwarf star. It is a **dead star**. It just utilises the thermal energy of its particles to radiate from its surface. It can live like this for several billion years and, afterwards, it becomes a cold object. The path of evolution of such stars on the H-R diagram is shown in Fig. 10.8a. Note that, after the star leaves the main sequence, it swells and heads towards the giant region. Subsequently, depending upon its mass, it may become a white dwarf star.



(a) **(b)**

Fig. 10.8: a) Evolutionary track of a general mass star; and b) evolutionary track of a star of a few solar mass

Mass of the star is ~ 5 M_Θ

After becoming a giant star, a star having mass approximately equal to 5 M_Θ traces its path back on the H-R diagram towards the main sequence along a horizontal line, called the **horizontal branch** (see Fig. 10.8b). This happens because of the commencement of the helium fusion (also called triple alpha process). As helium is exhausted and the next set of nuclear reactions involving carbon starts, the star changes its evolutionary course backwards towards the giant branch. It wriggles several times between the giant and the horizontal branch. During this time, it also sheds a lot of mass. Eventually, it also becomes white dwarf after passing through the planetary nebula phase.

Mass of the star is > 10 M_{Θ}

If the initial mass of the star is several times the solar mass, the helium reactions start gradually. When helium in the core is exhausted, the core contracts once again. The helium reactions are now ignited in a thin shell around the core. The temperature of the contracting core rises and becomes high enough for carbon-carbon reactions to occur. The cycle of core contraction and burning of the next heavy element continues till the core consists of iron. No more fusion reactions are possible now.

SAQ 7

Spend 3 min.

Why do fusion reactions stop at iron?

Let us pause for a moment and think of what we have learnt about the evolution of stars. We have traced the evolution of stars and simultaneous formation of elements. Depending upon its mass, a star can take different evolutionary courses. Well, you can further ask: **What happens after all the nuclear reactions have stopped and the stellar core consists of iron only?** We have seen from the binding energy curve (Fig. 10.3) that iron has the highest binding energy per nucleon. It cannot, therefore, burn to give off energy. Thus, the core is forced to contract. *The gravitational energy heats the core resulting in the disintegration of iron nuclei into nuclei of helium*. The break up of iron is an **endothermic process**, that is, the reaction absorbs energy rather than giving it out. To feed this process, the only source of energy is the gravitational collapse. As a result, the collapse of the core is accelerated. Faster release of gravitational energy due to collapse gives rise to further break up of iron nuclei into helium nuclei. This, in turn, accelerates the collapse. As the density of the core continues to increase, even the helium nuclei cannot remain intact as nuclei. They break up into protons and neutrons.

In the nuclear reaction taking place in the core of stars, a large number of **neutrinos** are also produced. *You may be aware that the neutrino has no charge and very small mass, if at all*. These particles react with matter extremely weakly. So, their mean free path is very large and these were considered to be the carrier of energy from the core to the envelope. It has, however, been found now that at the extremely high densities developed in the core, the mean free path of neutrinos is shorter than the size of the core. So, they cannot transfer energy to the envelope. A different process is now proposed for the transfer of energy from the core. *When the density of matter approaches the nuclear density* (~ 10^{15} gcm^{-3}), *the short range nuclear forces come into play. The particles repel one another strongly and rebound. A* ***bounce*** *is said to travel from the core and into the envelope*. It is the bounce that is thought to transfer energy to the envelope.

Coming back to the evolution of the collapsing star, let us first consider its envelope. Due to transfer of energy from the core to the envelope, very high temperatures are produced in the envelope and nuclear reactions in various layers of the envelope are ignited. The energy released due to these reactions heats the envelope so much that it becomes prone to explosive disintegration in a matter of seconds. *In this short time before explosion, nuclear reactions produce heavy nuclei all the way up to the iron group*. In addition, the large numbers of neutrons released in the nuclear reactions participate in the r-process and heavy nuclei beyond Bi^{209} are produced. Finally, **the envelope explodes**. The explosion is called a **supernova**. *The elements built inside the star over hundreds of millions of years of its life are thrown into the interstellar medium.* The new stars born from this enriched medium contain a small proportion of heavy elements and these stars are called the **second generation stars**. It has been suggested that the interstellar material from which the solar system was formed contained heavy elements released in a supernova that took place nearby.

Well, the envelope explodes but what happens to the core? **The core keeps collapsing**. According to our present knowledge, *if the initial mass of the star is up to about 12 M_{Θ}, then the core is left with a mass of about* 2 M_{Θ} *to* 3 M_{Θ}. The matter in such stars is mostly neutrons. Like electrons, neutrons also obey Pauli's exclusion principle. At the extremely high density which exists in the core, neutrons become degenerate. The pressure exerted by the degenerate neutrons is sufficiently high to halt the collapse of the core. The core stabilises in the form of a **neutron star**.

If the initial mass of the exploding star is close to 15 $M_\odot$ or more, the core that is left behind has a mass more than 3 $M_\odot$. A core of this mass cannot attain equilibrium of any kind. It keeps contracting. Eventually, its gravitational field becomes so strong that even light cannot escape it. It becomes a **black hole**.

10.5 SUPERNOVAE

Supernovae are extremely violent and bright stellar explosions. The energy released in one such explosion is equivalent to the conversion of 1 $M_\odot$ into energy, or about 10^{47}J! *The luminosity of a supernova is of the order of the luminosity of a whole galaxy*. In all supernova explosions, the brightness reaches a peak within a few days of the explosion. During the short time of its maximum brightness, it shines as a very bright object. Thereafter, its brightness decreases, first rapidly and then slowly. The variation of the brightness of an object with time is called the **light curve** of the object.

Light curves of supernovae have been studied extensively because of their importance in many areas of astronomy. Based on the type of light curves, supernovae have been classified as type I and type II. Fig. 10.9 shows the light curves of type I and type II supernovae. You may note that the light curve of type I supernova reaches higher brightness but show a rapid decline. On the other hand, the light curve of type II supernova shows a lower maximum brightness but slower decline. *The difference in the light curves of the two types of supernovae indicates differences in the stars which explode*.

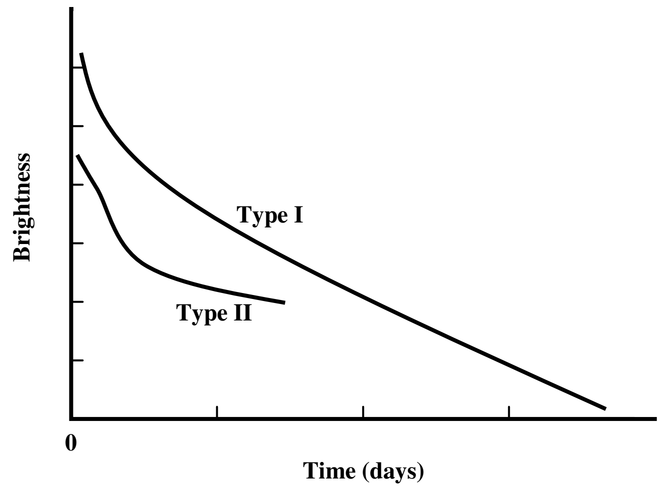


Fig.10.9: Schematic light curves of supernovae of type I and type II

You may argue: **Since supernovae are so bright, it must be easy to observe them.** Surprisingly, it is not so; observations of only four supernovae in our Galaxy have been recorded in the last two thousand years! The most famous supernova occurred in the year 1054 A.D. and was observed by the Chinese astronomers in the constellation Taurus.

Type I supernovae are further subdivided into two classes: Ia and Ib. The light curve for a supernova of type Ia is shown in Fig.10.10. Again, note that the brightness of the supernova is maximum at the time of explosion and it drops drastically afterwards. The light curves of supernovae of type Ia are almost identical. *These supernovae are believed to be caused due to the explosion of white dwarf stars*. You may ask: **How can a white dwarf give rise to a supernova explosion because its mass cannot be greater than 1.4 $M_\odot$?** This would be possible if we imagine a white dwarf star in a binary system with a main sequence or a giant star as its **companion**. Because of its strong gravitational field, the white dwarf star sucks matter from the companion. As its mass increases beyond 1.4 $M_\odot$, it explodes as a supernova. Since all stars have the same mass at the time of explosion, it is possible that supernovae Ia reach the same brightness or absolute magnitude. Further, the observed apparent magnitude of a supernova can be used to determine its distance using its **distance modulus** (defined as $m - M$) because all type Ia supernovae have the same absolute magnitude at the time of the maximum brightness. In recent years, type Ia supernovae have been used successfully to find distances of distant galaxies. This has been very useful in understanding the nature and the ultimate fate of the universe.

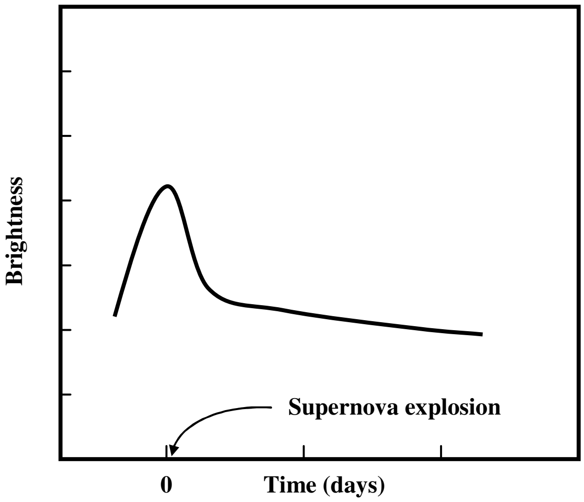


Fig.10.10: Schematic diagram of the light curve of type Ia supernova

Type Ib supernovae are thought to be due to carbon burning in the degenerate core of a star. Carbon burning in this situation is abrupt and very rapid. It is called a **carbon flash**. It generates so much energy that the star explodes.

The stars which explode to become supernovae of type II have usually masses higher than 10 $M_\odot$. Their light curves are all distinct. These supernovae leave behind neutron stars or black holes, which are detected several years after the explosion.

You may ask: **How do we know all that we have said above about supernovae?** At the time of explosion, a star throws a cloud of gas which travels into the interstellar medium with speeds of the order of 10,000 kms^{-1}. The cloud expands and merges gradually into the interplanetary medium. It seeds the interplanetary medium with heavy elements. The explosion also generates ripples in the surrounding medium which create conditions favourable for the formation of new stars. An example of the what remains behind a supernova explosion is the Crab Nebula. It is the remnant of the supernova of 1054 A.D. A neutron star is located at the centre of the nebula which was formed as a result of the explosion.

Now, let us summarise what you have learnt in this unit.

10.6 SUMMARY

- **Chemical composition of the universe** refers to the presence of different types of elements and their proportions in the universe. The chemical composition of the universe is the same as that of the solar system.

- Relative proportions of elements in the universe are called **cosmic abundances**. Observed abundances of elements show that (i) hydrogen and helium are the most abundant elements in the universe, (ii) there is a broad peak of abundances near

$A = 56$ (iron group of elements), and (iii) there are peaks at mass numbers which are multiples of 4.

- All elements except hydrogen and helium are formed inside the stars due to thermonuclear reaction and creation of new elements in such reactions is called **nucleosynthesis**.
- Depending upon the elements present, density and temperature in the interior of stars, nucleosynthesis takes place through one of the three major processes, namely **hydrogen burning**, **helium burning** and **burning of carbon and heavier nuclei**. As long as a star stays on the main sequence, it burns hydrogen.
- The **life span** of a star on the main sequence depends on its mass: $\tau \propto M^{-2.5}$. Also, the evolution of a star away from the main sequence **depends on its mass**. Low mass stars become **white dwarfs** at the end of their lives.
- Massive stars (> 10 M_Θ) explode as **supernovae** at the end of their lives leaving behind neutron stars or black holes.

10.7 TERMINAL QUESTIONS

Spend 30 *min.*

1. List the major processes of formation of elements inside stars. Why can elements beyond iron not be formed by fusion?

2. Suppose that a supernova explosion takes place at the distance of Proxima Centauri (~ 3 pc). If its luminosity equals the luminosity of our galaxy (~10^{12} L_Θ), show that it would appear about as bright as the Sun. Take the absolute magnitude of the Sun as 5 and its apparent magnitude as – 27.

3. For stars having more mass than 10 M_Θ, the luminosity is directly proportional to their masses. Show that their lifetime on the main sequence is independent of their masses.

4. Aldebaran (α-Tauri, *Rohini* in India) is a red giant star of spectral class K5. Its radius is 22 times the radius of the Sun. Its surface temperature is 3800 K. Calculate its luminosity (in units of solar luminosity) and its absolute magnitude. The absolute magnitude of the Sun is 5.

10.8 SOLUTIONS AND ANSWERS

Self Assessment Questions (SAQs)

1. 90% hydrogen and 10% helium by number implies that the universe comprises 90 units of mass of hydrogen and 40 units of mass of helium because the mass of a helium atom would be 4 units if mass of a hydrogen atom is taken as 1 unit.
   So, out of 130 units of mass, 90 units is hydrogen and 40 units is helium.

   Thus,

   $$\text{Percentage of hydrogen} = \frac{90}{130} \times 100 \sim 70$$

   $$\text{Percentage of helium} = \frac{40}{130} \times 100 \sim 30$$

   That is, approximately 70 percent of the mass of the matter in the universe is contributed by hydrogen and remaining by helium.

2. Total energy radiated by the Sun during its lifetime

$$= \text{Luminosity of the Sun} \times \text{Age (in s) of the Sun}$$

$$= (4\times10^{33}\text{erg s}^{-1}) \times (5\times10^{9}\times3\times10^{7}\text{s}) \qquad [\because \quad 1 \text{ yr} = 3\times10^{7} \text{ s}]$$

$$= 6\times10^{50} \text{ erg}$$

Now, this energy was generated in the nuclear reactions within the Sun converting hydrogen into helium. So, to produce this much energy, mass of hydrogen

consumed $= \dfrac{6\times10^{50}\text{ erg}}{6\times10^{18}\text{ erg g}^{-1}} = 10^{32}\text{ g}$

Therefore, percentage of the total mass of the Sun which has been converted into

helium till date $= \dfrac{10^{32}\text{ g}}{2\times10^{33}\text{ g}}\times100$

$= 5\%$

3. The internal temperature of a star is roughly proportional to its mass. Since luminosity of a star is proportional $\sim M^{3.5}$, the stars with lower internal temperature than the Sun have lower luminosities than the Sun. So, these stars will be found in the H-R diagram to the right of the Sun and lower than the Sun.

4.a) Since the nucleus with mass number 8, which nucleosynthesis of two α-particles will produce, is unstable, three α-particles are needed to produce stable nuclei beyond mass number 8.

b) If triple - α reaction could not take place, carbon and heavier nuclei would not have been synthesized. Further, since carbon is essential for the origin of life, without triple - α reaction, life on the Earth would not have been possible.

5. The lifetime of a star on the main sequence is given by (Eq. (10.3)):

$$\tau \propto M^{-2.5}$$

Thus, for the Sun, we have:

$$\tau_{\Theta} \propto M_{\Theta}^{-2.5}$$

On the basis of above expressions for τ, we can write:

$$\tau = \tau_{\Theta}\left(\frac{M}{M_{\Theta}}\right)^{-2.5}$$

i) For a star whose mass is $10M_{\Theta}$, we can write its lifetime on the main sequence as:

$$\tau = 10^{10}\text{ yr}\left(\frac{10M}{M_{\Theta}}\right)^{-2.5}$$

$$= 10^{10}\times10^{-2.5}\text{ yr}$$

$$= 10^{7.5}\text{ yr} = 10^{7}\sqrt{10}\text{yr}$$

$$\cong 3\times10^{7}\text{ yr}$$

ii) For a star whose mass is $0.5M_\Theta$, we can write:

$$\frac{M}{M_\Theta} = \frac{1}{2}$$

Thus,

$$\tau = 10^{10}\left(\frac{1}{2}\right)^{-2.5} \text{ yr}$$
$$\cong 6 \times 10^{10} \text{ yr}$$

6. We know that the luminosity of a star is given as:

$$L = 4\pi R^2 \sigma T^4$$

So, we can write for the Sun:

$$L_\Theta = 4\pi R_\Theta{}^2 \sigma T^4$$

After the Sun has expanded, we have, as per the problem:

$$R = 200\, R_\Theta$$

and

$$T = \frac{T_\Theta}{2}$$

Thus, the luminosity of the expanded Sun is:

$$L = 4\pi (200 R_\Theta)^2 \sigma \left(\frac{T_\Theta}{2}\right)^4$$
$$= \frac{4\pi \times 4 \times 10^4 R_\Theta{}^2 \sigma T_\Theta{}^4}{16}$$

$$\frac{L}{L_\Theta} = \frac{4\pi \times 4 \times 10^4 R_\Theta{}^2 \sigma T_\Theta{}^4}{16 \times 4\pi R_\Theta{}^2 \sigma T_\Theta{}^4}$$
$$L = 2.5 \times 10^3 L_\Theta$$

7. Fusion reaction stop at iron because iron is the most stable atom/nucleus. It cannot combine with any other nucleus to produce heavier nuclei.

Terminal Questions

1. See text.

2. As per the problem, luminosity of the supernova, $L = 10^{12} L_\Theta$.

   If the absolute magnitude of supernova is M and that of the Sun is M_Θ, we can write:

$$\frac{L}{L_\Theta} = 10^{-0.4(M - M_\Theta)}$$
$$10^{12} = 10^{-0.4(M - M_\Theta)}$$

$$12 = -0.4\,(M - M_{\Theta})$$
$$M = -30 + 5$$
$$= -25$$

If m is the apparent magnitude of the supernova, we can write:

$$m = M + 5\ \log\ r - 5$$
$$= -30 + 5 \times (\log\ (3)) \qquad (r = 3\text{pc})$$
$$= -30 + 5 \times 0.48$$
$$\approx -27.5$$

The value (−27.5) of apparent magnitude of the supernova is approximately same as that of the Sun. So, the supernova will be as bright as the Sun.

3. As per the problem,

$$L \propto M$$

Now, the lifetime of a star can be approximated as:

$$\tau \sim \frac{M}{L}$$

or $$\tau \propto \frac{M}{M}$$

$$= \text{Constant.}$$

So, the life time of such stars is independent of their masses.

4. You have seen in SAQ 2 of Unit 5 that, using Stephan - Boltzmann law, we can express the luminosity of a star as

$$L = 4\pi R^2\, \sigma T^4$$

where R is the radius of the star and T is its temperature.

We can, therefore, write the luminosity of a star like Aldebaran as:

$$L_{Ald} = 4\pi R^2\, \sigma T^4$$
$$= 4\pi \times (22 R_{\Theta})^2\, \sigma (3800\,\text{K})^4$$

And, the luminosity of the Sun can be written as:

$$L_{\Theta} = 4\pi \times R_{\Theta}{}^2\, \sigma (6000\,\text{K})^4$$

Thus, we have:

$$\frac{L_{Ald}}{L_{\Theta}} = \frac{484 \times (3.8)^4}{6^4}$$
$$= 95$$

Further, the ratio of luminosity of Aldebaran and the Sun can be expressed in terms of their absolute magnitude M_{Ald} and M_{Θ}, respectively, as:

$$\frac{L_{Ald}}{L_{\Theta}} = 10^{-0.4(M_{Ald} - M_{\Theta})}$$

Thus, we get:

$$95 = 10^{-0.4(M_{Ald} - 5)}$$

because M_{Θ} is 5. Taking logarithm on both sides, we get:

$$\log 95 = -0.4\,(M_{Ald} - 5)$$

$$1.98 = -0.4\,(M_{Ald} - 5)$$

or,

$$M = -4.95 + 5$$

$$= 0.05$$