38A
STARS

38.1 INTRODUCTION

You are all familiar with stars. You have seen them as twinkling little lamps in the sky at night. It is a great experience to see the sky on a moonless, cloudless night from a place where there is no pollution and there are no bright city lights. But have you been curious to know what these really are? How they came into existence? Have they different colours and why?

Such curiority in ancient time lead people to speculate interesting ideas. They thought, for example, that the stars are little lamps fixed on a sphere, which revolves round earth. This is, after all. what they appear to be. Other built mythological stories around them and propagated the view that stars could determine human destiny. This created fear among people and they started worshipping stars in order to please them. You will study in this lesson, what does the modern science say about these questions.

38.2 OBJECTIVES

After Studying the lesson, you should be able to,

- *measure the distances of stars directly and explain the limitation of this method;*
- *estimate the masses of the stars;*
- *describe the meaning of apparent magnitude and define the absolute magnitude of a star; and derive relation between the apparent and the absolute magnitudes and use this relation to calculate distances of stars;*
- *define the luminosity of a star and estimate it from the absolute magnitude of the star;*
- *state the principle underlying the spectral classification of stars ; and explain the colours of stars;*
- *state the H.R. diagram and recognize various families of the stars on this diagram; and describe the importance of H.R. diagram for the study of stars;*
- *explain the evolution and death of stars and explain the end stages of stars.*

38.3 DISTANCES OF STARS

The distances of stars are so large that the ordinary units become useless. Even the **distance of the sun from the earth,** called an **astronomical unit,** is of no help. In an earlier lesson you might have learnt that an astronomical unit is = 1.5×10^{11}m. We have to think of some special units to express the distances of stars. One such unit is the light year. How much is the speed of light?

If you remember the speed of light then calculate the distance travelled by light in one year. How many seconds are there in an year?

Multiply the number of seconds in a year with the speed of light and you have unit called light year.

A light year $= 3 \times 10^{8} \times 365 \times 24 \times 3600$ **m**

$= 9.46 \times 10^{15}$ **m**

$= 6.324 \times 10^{4}$ **astronomical units**

Do you now realize why astronomical unit is not very useful in measuring distances of stars?

In astronomical literature we use another unit, called **parsec.** This unit comes naturally from the method employed to determine stellar distances. Let us look at this method.

One has to choose a base large enough so that the angle indicating the change in the direction of the star is measurable. The naturally available base is the diameter of the earth's orbit round the sun (Fig 38.1). Suppose that we wish to measure the distance of the star X. We assume that the objects behind the star represent an unchanging background. This is true to a very good approximation. We observe the star from position E_1 and then six months later from position E_2 on the earth's orbit round the sun S. The change in the direction of the star is noted. The half of this angle, denoted by θ, is called the **annual parallax** of the star.

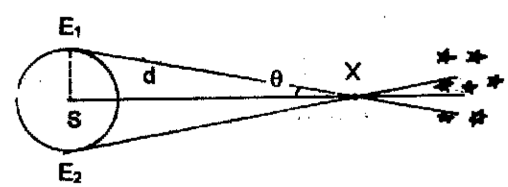

Fig. 38.1: Measuring distance of star X by parallex method, taking E_1E_2 as base line

Recall the simple rule of trigonometry that an angle is equal to the arc length divided by the radial distance. At the kind of distances at which stars are, the radius of the earth's orbit can be considered an arc of circle of redius XS (Fig, 38.1). The distance of the star from the sun is then,

$$d = \frac{\text{the radius of the earth's orbit}}{\theta}$$

$$\Rightarrow d = \frac{\text{astronomical unit}}{\theta} \quad \text{...(38.1)}$$

If the *angle* θ is equal to one second (1/3600 of a degree), then the distance of the star is called a parsec. **The value of one parsec = 3.086 x 10^{16}m.**

You might object that we have calculated the distance of the star from the sun and not from the earth. But in view of the fact that the distance of the earth from the sun is so small compared with the distance of the nearest star from the sun (about a parsec), does the difference between the two really matter?

The star nearest to us is called **Proxima Centauri.** Its distance is about 1.2 parsec.

Eq. (38.1) tells us that the smaller the angle p, the larger is the distance of a star from us. In fact, *the distance of a star in parsec is just the reciprocal of its annual parallax in seconds of arc.*

This method is simple only in principle. In practice, several observations spread over several years have to be taken to get a reasonable estimate of the distance of a star. The method of parallaxes is a direct method of getting stellar distances. But it works only for stars whose distances do not exceed a few hundred parsec. The reason is that the annual parallaxes of stars farther than this distance cannot be measured accurately. For stars farther than a few hundred parsec indirect methods are used. but it must be appreciated that all the indirect methods are based on the properties of stars deduced from accurate measurements of their distances by the method of parallaxes.

Table 38.1 given at the end of this lesson lists the twenty nearest stars. Indian names of some of these stars are also given. The Indian names of other stars are not known.

INTEXT QUESTIONS 38.1

1. *How many light years are there in a parsec? Find the distance in parsec of a star whose distance is given as 12.2 light year.*

   ....

2. *Express the distance between the sun and the earth in light years and parsec.*

   ....

38.4 MASSES OF STARS

In an earlier lesson you might have learnt how to find the mass of the Sun. Essentially, we find the centripetal force necessary to keep the Earth in its orbit round the Sun. This force is provided by the gravitational pull of the Sun. Equating the centripetal force with the gravitational force gives the mass of the Sun. It is 2 x 10^{30} kg. Most stars have masses of this order. Some are, however, much more massive, may be as much as 100 times the mass of the Sun.

How do we estimate the masses of other stars? Luckily, the process of star formation favours the formation of stars in groups of two, three or more.

Two stars revolving round each other are called ***binary stars.*** The orbits of these stars are ellipses around their common centre of mass in accordance with the laws of Kepler (Fig 38.2). In most cases what is observed is the ***relative orbit, which is the orbit of one of the stars round the other described in the plane of the sky*** (i.e. plane perpendicular to our line of sight). One of the most well known binary system consists of the star **Sirius** (known as Lubdhak in India), the brightest star in the sky, and its companion. The relative orbit of the companion is shown in Fig. 38.3. The time period for the relative orbit is the same as that for the actual orbit around their common centre of mass. It is denoted by T and is given by the third law of Kepler:

$$T^2 = \frac{4\pi^2}{G}\frac{r^3}{(M_1 + M_2)} \qquad \text{...... (38.2)}$$

where M_1 and M_2 are the masses of the two stars and r is their separation. Astronomers prefer to write this relation in the following form.

$$\boxed{(M_1 + M_2) = \frac{a^3}{T^2\, p^2}} \qquad \text{...(38.3)}$$

Here masses have been expressed in units of solar mass, time period T (Time) is in years, a is the angular separation of the two stars in seconds of arc and p is the annual parallax of the system in seconds of arc. Both T and a can be measured and then the combined mass of the system is obtained. The relative orbit can give only the combined mass of the system. In some cases the orbits of both the stars about their common centre of mass can be charted out with reference to the neighbouring stars. In that case the masses of individual stars can be found. Recall that the distance of each star from the centre of mass is inversely proportional to its mass. If r_1 and r_2 are the distances of the stars with masses M_1 and M_2 respectively from their connon centre of mass, then we have

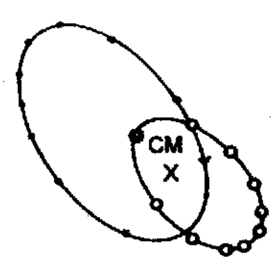

Fig. 38.2: Orbits of two stars around their common CM

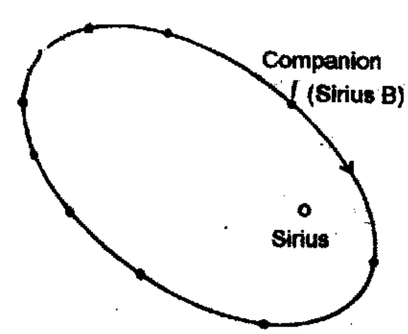

Fig.38.3: Orbit of Sirius

$$\boxed{\frac{M_1}{M_2} = \frac{r_2}{r_1}} \quad where\ r_1 + r_2 = r \qquad (38.4)$$

If a_1 and a_2 are angular distances of stars from their common C.M., then

$$\frac{M_1}{M_2} = a_2/a_1 \quad where\ a_1 + a_2 = a \qquad ...(38.5)$$

With the help of these relation we can find the masses of individual stars of binary groups from a knowledge of their combined mass. For those which are not members of binary groups, the mass has to be estimated by indirect methods. One of these methods will be explained later in this lesson.

INTEXTQUESTIONS 38.2

1. Prove Eq (38.5) that is $M_1/M_2 = a_2/a_1$.

   ....

2. *The following data was obtained for a binary system:*

   T = 1.7 years, a = 0.225" of arc, a_1 = 0.075" of arc, a_2 = 0.15" of arc, p = 0.157" of arc.

   Find the masses of the two stars.

   ....

38.5 BRIGHTNESS OF STARS

We have already noticed that some stars are very bright, some are less bright and many are so faint that they can be seen with great difficulty. Just go out at night and verify this fact for yourself. So, how do we distinguish the stars on the basis of their brightness?

When systematic observations of stars started about two thousand years ago, the observers assigned to each star a number from 1 to 6 to indicate its brightness. Remember that at that time the stars were observed only with the naked eye. There were no telescopes. (The telescope was first made for astronomical observations by Galileo in the beginning of the seventeenth century and used by him to observe the phases of Venus, the moons of Jupiter and mountains on the moon.) Lower numbers were assigned to brighter stars and higher numbers were given to fainter stars. Therefore, on this scale stars with number 6 were the faintest stars and those with number 1 were the brightest. The number assigned to a star is called its **apparent magnitude**, denoted by the letter *m* (do not confuse it with the mass). The brightest star in the sky, Sirius, and other stars of similar brightness were assigned magnitude *1*.

When it became possible to observe stars with the help of telescopes, stars fainter than magnitude 6 were found and numbers higher than 6 were added to the list. Similarly, negative numbers had to be assigned to very bright objects like the sun. Since the brightness of stars could be measured more accurately with the help of instruments used with the telescopes, it was found necessary to have fractional magnitudes. So, to day we have magnitudes accurate to one-tenth, or sometimes one-hundredth of a magnitude.

How faint is the star which the large telescopes of today can detect? The large optical telescopes of today can detect stars as faint as those of magnitudes 27. It may also be of interest for you to know that the apparent magnitude of the sun is about-27. Table 38.1 given at the end of this lesson shows the apparent magnitudes of the nearest stars.

But surely you would like to know how faint the star of ma itude 27 is compared with the sun. When accurate measurements of brightness of stars became possible it was found that on the overage the stars of magnitude 1 were about 100 times brighter than the stars of magnitude 6. To give a more precise meaning to a magnitude, therefore, it was decided to define that a difference of 5 in magnitudes would correspond to a brightness ratio of exactly 100. By this logic a star of magnitude 6 is 100 times brighter than a star of magnitude 11, 10 times brighter than a star of magnitude 8.5.

Example 38.1: *Find out how many times the sun is brighter than a star of magnitude 23.*

Solution : Since difference in magnitudes of two stars indicates ratio of their brightness, the relationship between the magnitudes is written as

$$\boxed{m_1 - m_2 = -2.5 \log \frac{b_1}{b_2}} \quad ...(38.6)$$

or,

$$\frac{b_1}{b_2} = 10^{0.4(m_2 - m_1)} \quad ...(38.7)$$

Where *b* denotes the brightness of a star. You can easily verify that a difference of 5 in magnitude indicates a brightness ratio of 100. The logarithmic laws like (38.6) are quite common in biology, where generally the intensity of a sensation is proportional to the logarithm of the stimulus producing it.

38.5.1 Stellar Luminosities

You must have noticed that a point source of light (e.g. a torch bulb) placed nearby appears brighter compared with the same source when it is seen from a larger distance. This means that the observed brightness of a source depends upon two factors, (1) its own, or intrinsic, brightness and (2) its distance from the observer. In the case of stars, their intrinsic brightness would obviously depend on the energy radiated by them. ***The total energy radiated normally by a star in one second is called its luminosity.*** It is denoted by L.

To compare luminosities of stars, we must first ensure that they are observed from the same distance. For this purpose we imagine a star to be placed at a distance of 10 parsec. The magnitude of a star at that distance is called its **absolute magnitude,** M. Let the brightness seen from that distance be denoted by B. Let the actual brightness of the same star be *b* and its apparent magnitude be m. We now use 38.6 to compare the star (at its actual distance) with itself when placed at 10 parsce. If we identify m_1 with M and B_1 with B, then we have from 38.6.

$$M - m = -2.5 \log \frac{B}{b} \quad \text{...(38.8)}$$

Recall now from your lesson in optics how the brightness of a source of light varies with distance.

If the distance of the star is r parsec then using the inversesquare law of brightness variation, we find that the ratio $B/b = r^2/100$ (remember B is measured when the star is placed at a distance 10 parsec). Eq (38.8) then becomes

$$\boxed{M = m + 5 - 5 \log r} \quad \text{.... (38.9)}$$

or, if we express distance in terms of the parallax p which is the reciprocal of r then,

$$M = m + 5 + 5 \log p \quad \text{.... (38.9a)}$$

The absolute magnitude is a measure of the true brightness or the luminosity of a star. In fact a relation similar to 38.6 can be written for two stars in terms of their absolute magnitudes and luminosities.

From (38.9) we get

$$M_1 - M_2 = m_1 - m_2 - 5(\log r_1 - \log r_2) = m_1 - m_2 - 2.5 \log \frac{r_1^2}{r_2^2}$$

Substituting (m_1-m_2) from (38.6) now we get

$$M_1 - M_2 = -2.5 \log \frac{b_1}{b_2} - 2.5 \log \frac{r_1^2}{r_2^2} = -2.5 \log \left(\frac{b_1 r_1^2}{b_2 r_2^2}\right)$$

Since $b \propto \dfrac{L}{r^2}$

$$\therefore \left(\frac{b_1 r_1^2}{b_2 r_2^2}\right) = \frac{L_1}{L_2}, \text{ we get}$$

$$\boxed{M_1 - M_2 = -2.5 \log \frac{L_1}{L_2}} \quad \text{....(38.10)}$$

This relation enables us to compare luminosities of stars by finding their absolute magnitudes from a knowledge of their distances and apparent magnitudes. Just as a difference of 5 in apparent magnitude corresponds to a brightness ratio of 100, a difference of 5 in absolute magnitudes means a ratio of 100 in luminosities. If we take Sun as one of the stars then the luminosities of other stars can be found in terms of the solar luminosity. The apparent magnitude of the Sun is about –26.8 its absolute magnitude found from (38.9) is about 4.8.

The relation between M and m is also important in another respect. There are several methods by which the absolute magnitude of a star can be estimated. Since the apparent magnitude is a directly measurable quantity, 38.9 leads to the determination of the annual parallax of the star. In this way, the distances of those stars for which direct measurement of parallaxes is not possible, can be measured.

To find luminosities of other stars by comparison with the Sun, we must first of all find the luminosity of the Sun. This is done by measuring the ***radiant energy falling on a unit area kept perpendicular to the Sun's rays in a unit time when the Earth is at its mean distance from the Sun.*** The measurement is carried out at the top of the atmosphere, (instruments can be placed in a spacecraft), otherwise the absorption in the atmosphere has to be taken into account. The quantity measured is called the **solar constant,** though strictly speaking it is not a constant. Very recent studies have shown that the solar constant varies by a very small amount when it is observed for several years. The value of the solar constant is 1.4×10^3 W/m^2. *This is the rate at which energy is flowing through a unit area of a sphere whose radius is equal to the mean distance of the Earth from* the Sun (Fig 38.4). It should now be possible for you to calculate the solar luminosity.

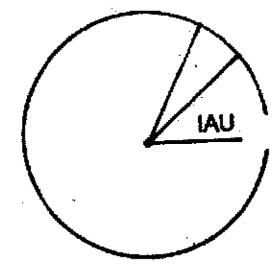

Fig. 38.4

Exercise 38.1 : *Given the mean distance of the Earth form the Sun as 1.5×10^{11} m and the solar constant as 1.4×10^3 W/m^2, show that the solar luminosity is 4×10^{26} Js^1.*

Intext Questions 38.3

1. *The brightest star in the sky, Sirius, has an apparent magnitude of −1.4. How much brighter is it than a star of apparent magnitude 23.6?*

   ....

2. *The apparent magnitude of the sun is given as −26.8. Show that its absolute magnitude is about 4.7.*

   ....

3. *The apparent magnitude of a star is 7.0. Its absolute magnitude is found to be 2.0. Find the distance of the star. Calculate also its luminosity.*

   ....

38.6 SURFACE TEMPERATURES OF STARS

Now that you have calculated the luminosity of the Sun, it is possible to calculate the surface temperature of the Sun knowing its radius to be 7×10^8 m. The way is to use Stefan-Boltzmann law which you have studied in an earlier lesson.

As you would recall the law says that the radiation flowing out through a unit area of the surface of a source is proportional to the fourth power of its absolute temperature. Using the Stefan-Boltzmann law we find that the surface temperature of the Sun is about 6000 K.

Exercise 38.2 : *Given that the angular radius of the Sun is 16 minutes of an arc, and distance is 1.5×10^{11} m, calculate the radius of the Sun.*

Solution : Once the radius and the luminosity of the Sun is known its surface temperature can be calculated as you have done above. In the case of other stars too the surface temperature can be calculated knowing their luminosities and radii. But their radii are not easy to find. So, how to find the surface temperatures of stars? But before we do that let us see why surface temperatures are so important.

You must have noticed the stars are of different colours. The colour of a star depends on its surface temperature. The stars which appear red have low temperatures, about 5000 K or less. The yellow stars like the Sun have surface temperatures of about 6000 K. White stars have surface temperatures of about 10000 K. The stars whose temperatures are much higher than 10000 K appear blue. To see how this change in colour takes place with the increase in the surface temperature of a star, You have only to recall your common experience of seeing burning coal. All this is in accordance with the Wien's displacement law, which you might have studied in your lesson on thermodynamics.

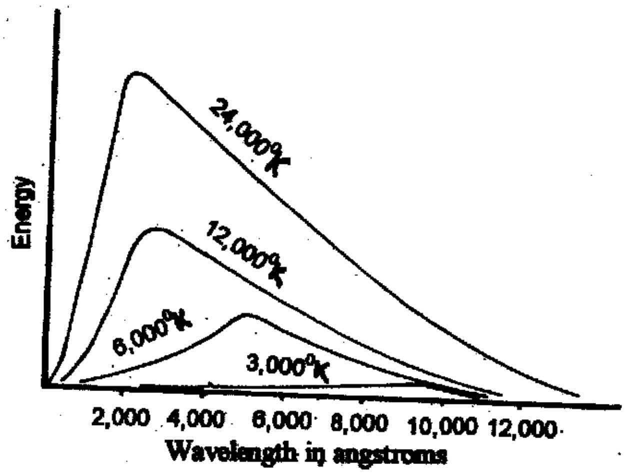

Fig. 38.5: Variation of intensity of radiation with wave length for stars at different temperature

As you learnt in thermodynamics that a hot body radiates at all wave lengths. The intensity of radiation varies with the wave length in the manner shown in Fig. 38.5. The colour of body is determined by the wave length at which the intensity is maximum.

If we raise the temperature of the body, the wavelength at which the maximum intensity occurs shifts towards shorter wavelengths (Fig 38.5), or towards blue colour. Now probably you can guess why the colour of a hot body changes when its temperature rises. The same argument applies to stars which are hot bodies and so their colours depend on their surface temperatures.

38.6.1 Stellar Spectra

Another indicator of the surface temperatures of the stars is their spectra. To see the solar spectrum, you can perform a simple experiment. Get hold of a glass prism, the one you use for splitting the colours contained in white light. Hold the prism in such a way that Sunlight falls on one of its faces through a narrow slit. Let the light emerging from the other face (Fig 38.6) fall on a white sheet of paper, or on a white wall. The prism breaks the

Sunlight into colours. The colours range from red to violet through orange, yellow, green, blue and indigo. (Remember VIBGYOR?). These colours form the spectrum of the Sun. The colours are not neatly separated from one another. To make the spectrum sharper, place a convex lens between the prism and the slit and another between the prism and the sheet of paper. Move the lenses to focus the colours on the sheet of paper. This will require that a parallel beam falls on the prism and the sheet of paper is in the focal plane of the second lens. If the Sun is bright and the colours on the sheet of paper are focused well, you may be able to see dark lines crossing the various coloured regions. These dark lines show what we call solar spectrum.

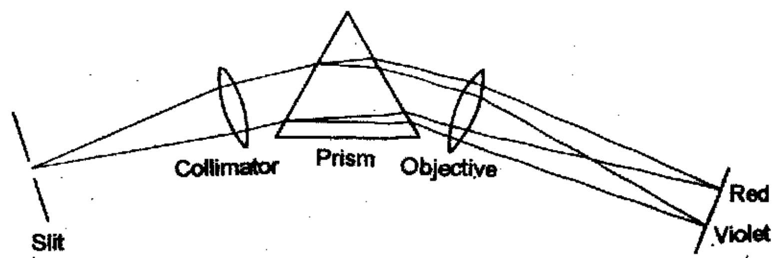

Fig. 38.6: Set up to produce pure spectrum by a prism

The dark lines in the solar spectrum were first observed by Fraunhofer and therefore the dark line spectrum is called Fraunhofer spectum. The dark lines are due to the absorption of light by atoms found in the solar atmosphere. The continuous light is emitted by the surface of the Sun, which as you have noted above, is at a temperature of about 6000 K. It is this light which shows bright colours. This layer on the solar surface which emits bright light is called the **photosphere.** The formation of dark lines in solar specturm has been described in 36.4.1.

The spectra of other stars arises in similar circumstances. On a continuous background there are number of dark lines like the Fraunhofer lines in the spectrum of the sun. Fig 38.7 shows a sample of such spectra. Notice the dark lines and their varying intensities. The dark lines show the type of atoms present in the atmospheric layers of stars. The intensity of a dark line shows the number of the particular star which produces it. Therefore, by analyzing the stellar spectra, we can find out the relative proportion, called the **abundance,** of the various atoms present in the atmosphere of the stars.

Fig. 38.7: Photograph of portion of sun's spectrum

It is interesting to know that no atom has been found in stars which we do not know on the Earth. Even proportion or abundance of these atoms is similar to that found on the Earth and in the solar system. In fact, it would be right to say that the chemical composition of the whole universe is similar to that found in the solar system.

38.6.2 Stellar Classification

In the sample of spectra shown in Fig.38.7 do you notice that the lines in the spectra are quite dissimilar in number as well in intensity? These systematic differences form the basis of stellar classification. A scheme of classification was proposed keeping in view the differences in spectra. The various classes were given the names: O, B, A, F, G, K, M. Later, it was realized that these classes were very broad and there was need to subdivide each class. So, each class was subdivided into ten classses. For example, classes between F and G are F0, F1, ..., F9. Many more improvements had to be made in the classification scheme, but we shall confine ourselves to the broad scheme outlined above. Since this classification is based on stellar spectra, it is called **spectral classification.**

When initially the differences in the spectra were noticed, it was thought that the stars differ in their chemical composition and the spectra reflect these differences. However, earlier in this century, an Indian astrophysicist, M.N. Saha, showed that the differences in spectra arise because of the different surface temperatures of the stars. He argued that at a given surface temperature only certain elements are ionized, the remaining elements remain unionized. So the spectrum of a star with that surface temperature will feature lines only due to certain ionized and unionized atoms. A star with a different surface temperature will show different lines since at that temperature certain other atoms will be found to be ionized and unionized.

The spectra of O type stars shows prominently lines due to ionized helium; there are very few other lines. Now helium is an element which can be ionized with great difficulty. At the temperature helium is ionized all other elements are already ionized. This is the reason O stars have very few lines of other atoms. This means that the surface temperature of O stars must by very high. It is around 50000 K. In B type stars, the prominent lines are due to neutral helium atoms, and very few other lines. So, the surface temperature of B stars is lower than that of O stars, not high enough to ionize helum, but high enough to ionize all other atoms. This temperature is about 25000 K for class BO. In A type stars, the helium lines are absent altogether, instead we have line due to hydrogen with maximum intensity. The surface temperature of A stars starts at about 11000 K. In the spectral class F the surface temperature is not high enough even to excite hydrogen atoms. So hydroghen lines become weak. The lines due to neutral metal atoms like calcium and iron start becoming strong. The temperature of stars belonging to the spectral class FO is around 7500 K. In stars of spectral class G (the Sun is classified as G2) the surface temperatures are around 6000 K and the prominent lines are due to ionized calcium and neutral metal atoms. As we go down the classification scheme, the temperatures are not high enough even to break the molecular bonds of some molecules. So, lines due to molecules start appearing in the spectra. The spectra of classes K (surface temperature for KO ~ 5000 K) and M (surface temperature for MO ~ 3500K) are dominated by lines due to molecules. In class M stars there are thousand of lines while in stars of classes O and B there are very few lines. In Table 38.2 given on last page of this lesson, we have given a summary of stellar classification.

38.6.3 H. R. Diagram

The two important characteristics of a star are its luminosity and its spectral class. But are they related to each other? Is it possible to find the luminosity of a star given its spectral class, or vice versa? These were some of the questions which astrophysicists asked themselves when they had collected considerable data on stars. The answers to these questions could obviously be found by plotting one characteristic against the other. This is what was done by Hertzsprung and Russell independently during the earlier years of the twentieth century. They plotted the absolute magnitude against the spectral class for stars. They found that on this graph the stars were not randomly distributed, but formed neat families. This meant that there was a significant relationship between the two characteristics of the stars. **Any diagram in which a measure of luminosity (such as absolute magnitude) is plotted against a measure of surface-temperature (such as spectral class) is called an H.R. diagram.** One such diagrams is shown in Figs 38.8. Notice that temperature as well as the spectral class. both are related. Above both are related. Along the y-axis in this diagram we have absolute magnitude decreasing upwards. Does it mean luminosity increasing upwards?

We notice in this diagram a band of stars running from top left to bottom right. These stars are called the **main sequence stars.** The Sun belongs to this category. The stars lying along horizontal bands towards the top of the diagram are called **giants.** Out of these which have very high luminosities are called **supergiants.** Well high surface temperature but have low luminosity. These stars are called the **white dwarf** stars.

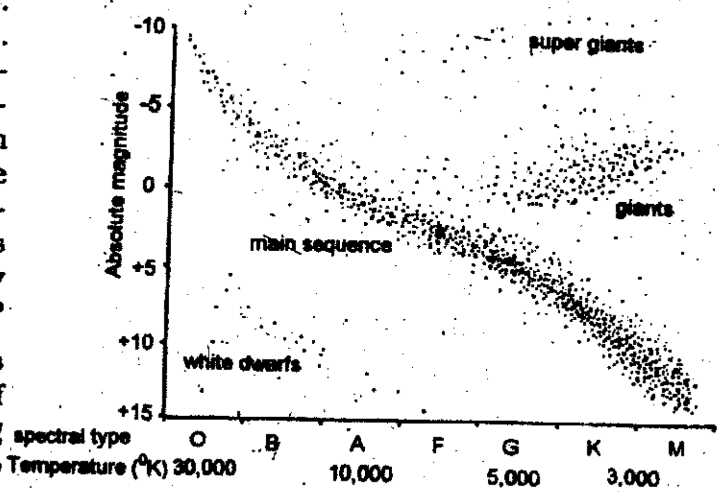

Fig. 38.8: H.R. diagram showing the absolute magnitudes of various stars against their surface temperature

The H.R. Diagrams give vary little hint about the relative number of stars of the various families in our **Galaxy.** The largest number of stars in our Galaxy belong to the **main sequence.** The next most populated family is that of **white dwarf stars.** There are very few supergiants.

The names giants and dwarfs really indicate their sizes. Consider white dwarf first. They are much less luminous than the stars of their spectral classes on the main sequence. The difference in absolute magnitude may be as large as 10. This means that the luminosity of the white dwarf stars is about 10^4 times less than the luminosity of the stars with the same surface temperature but on the main sequence. Now recall that the radiation given out by a star per unit area is proportional to T^4, where T is the surface temperature, and its surface area is $4\pi R^2$, where R is its radius. Then, its luminosity is given by

$$\boxed{L = 4\pi R^2 \sigma T^4,} \qquad (38.11)$$

where σ is the Boltzmann constant. Therefore, if for the same surface temperature white dwarfs have a much lower luminosity, it could only means that their radii are really very small compared to the radii of the stars of the same spectral class on the main sequence. Since their sizes are small the name dwarfs for them is quite right. The giant stars, you can now argue yourself, are very large in size and are aptly called giants.

The H.R. diagram is a very important tool for investigating the nature of stars in our Galaxy. Once the star has been located on the H. R. diagram, we can guess its mass, radius, surface temperature, luminosity, age, the source of its energy, its future life, and many more things. It may be thought of as a kind of horoscope *(janam patri)* for stars. No wonder that the astronomers spend so much effort in placing a star on the H. R. diagram.

You have learnt above that the Sun belongs to the spectral class G2. How do you indicate to your friend where it is located on the H.R. diagram? to make this task easier, a second classification scheme for stars has been devised. This is called *luminosity classification*. According to this scheme supergiant stars are assigned classes I and II, the giants are assigned classes III and IV, and the main sequence stars are called as belonging to class V. The white dwarf stars are indicated by the suffix wd. Taking this classification into account, the complete description of the Sun's class is G2 V.

INTEXTQUESTIONS 38.4

1. *The surface temperature of the Sun is about 5800 K. Assume that it radiates like a black body. Using Wien's displacement law, find the wavelength at which the intensity of its radiation is maximum.*

   ....

2. *The surface temperature of a star of spectral class K is 4500 K. Show that the star will appear red.*

   ....

3. *A white dwarf star has a surface temperature of 10000 K. Its absolute magnitude is 9.0. A main sequence star of the same spectral class has absolute magnitude —1.0. Calculate the ratio of their luminosities and the ratio of their radii.*

   ....

38.7 EVOLUTION OF STARS

The neat division of stars into families like the main sequence, giants, etc, prompts many questions. Does a star on the main sequence, for example, will always remain on the main sequence? Was a giant always a giant? Will it ever become a dwarf? When we say that a star belongs to the main sequence, or is a giant, or is a white dwarf, what does it mean in terms of the stage of development of the star? To answer these questions we have to find out how stars are born, how they become old and how they ultimately die. ***The sequence of birth, growing old, and death of stars*** is called their evolution.

38.7.1 Development of a Star

Most of the young stars in our Galaxy are found in places where there are huge gas clouds. Many objects which we know will ultimately become stars are found inside the gas clouds. This association indicates that stars are born in the gas clouds. Under certain circumstances, the very large gas clouds break up into smaller pieces. Each of these small pieces, called a **protostar**, then contracts because of mutual gravitational attraction of its particles. The contraction releases gravitational energy.

You can verify that after contraction the gravitational potential energy of a sphere of gas is less than what it was before contraction. Recall that the gravitational potential energy of two point masser is negative and is inversely proportional to their distance. Similarly, gravitational potential energy of all the molecules in a spherical gas cloud is also negative and inversely proportional to its radius. Thus decreasing radius results in decreasing potential energy (negative value increasing in magnitude) and hence a release of gravitational energy.

Gravitational energy is a very powerful source of energy. About half of this energy is used in heating the **protostar.** The other half is radiated out. When the temperature in the core of the protostar has risen to several million degrees the nuclear reactions can set in. the energy generation stops any further contraction of the protostar. The star is then said to have just been born. At that time it is on the main sequence. The age of the star is counted from that instant. That is why the main sequence is also called the zero age main sequence.

38.7.2 Energy Production in a Star

How long does a star stay on the main sequence? On the main sequence a star generates energy by fusing four protons into a helium nucleus (See equation below). The mass of the helium nucleus is slightly less than the combined mass of four protons. The loss in mass results in the production of energy in accordance with the Einstein's equation : $E = mc^2$, where c is the speed of light and m is the loss in mass. There are two ways in which the fusion of four protons can take place. If the temperature in the core of the star is abcut 15×10^6 K or less (as in the Sun), then most of the energy is produced by the following process, called the **PP-chain** :

$$_1H^1 + {}_1H^1 \Rightarrow {}_1H^2 + e^+$$

$$_1H^2 + {}_1H^1 \Rightarrow {}_2He^3 + \gamma$$

$$_2He^3 + {}_2He^3 \Rightarrow {}_2He^4 + 2\,{}_1H^1$$

Here e^+ is the positron and γ is the photon of energy released. The energy released in the formation of each helium nucleus is about 4×10^{-12} Joules. In case the temperature in the core of the star is higher than about 15×10^6 K, then most of the energy is generated by the **carbon nitrogen cycle**. This process runs as follows:

$$_6C^{12} + {}_1H^1 \Rightarrow {}_7N^{13} + \gamma$$

$$_7N^{13} \Rightarrow {}_6C^{13} + e^+$$

$$_6C^{13} + {}_1H^1 \Rightarrow {}_7N^{14} + \gamma$$

$$_7N^{14} + {}_1H^1 \Rightarrow {}_8O^{15} + \gamma$$

$$_8O^{15} \Rightarrow {}_7N^{15} + e^+$$

$$_7N^{15} + {}_1H^1 \Rightarrow {}_6C^{12} + {}_2He^4$$

In this chain of reactions the carbon nucleus is used as a **catalyst;** it is recovered at the end and is available for the next chain. The energy delivered per helium nucleus produced is roughly the same as in the PP-chain.

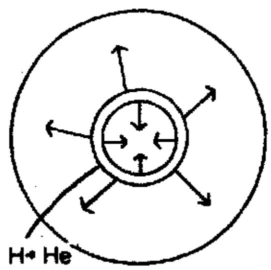

Fig. 38.9: The core of a star contracts while the hydrogen present in the rim burns to produce energy during red giant share of star

As long as the energy in the star is generated by the fusion of hydrogen into helium, also called **hydrogen burning,** the star stays on the main sequence. During this time it changes its position very little. For a star like the Sun this phase may last as much as eight billion years. For a star of mass 10 times the solar mass, this phase may last only for about 10^7 years.

38.7.3 Red Giant Phase

What happens when all hydrogen in the core has been converted into helium, no fusion is possible, because the temperatures are yet low for the next stage of fusion reaction. The core undergoes contraction, which releases gravitational energy. This heats up the core. The hydrogen which is present in the rim of the core (Fig 38.9) now produces energy more vigorously. Under the pressure of this energy, the shell of the star expands. The radius of the star increases enormously. The star heads towards

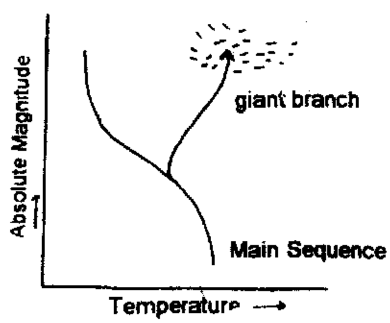

Fig. 38.10: After burning its hydrogen in the core the star (of 1 solar mass) heads towards the giant branch

the giant branch (Fig.38.10). The star of the mass of the Sun might take about 10^7 years to reach this. The core keeps contracting till its temperature rises to about 2×10^8 K.

38.7.4 End of a Sun-like Star

At this temperature three helium nuclei can fuse into a carbon nucleus and generate energy. After helium is exhausted in the core, the core once again starts contracting. In the stars of massses a few times the mass of the Sun, the core never gets heated to the stage where next set of fusion reactions can take place. In the absence of any energy generating process at the centre, the star contracts. Its size becomes more like that of a planet. At that stage the matter of the star becomes degenerate. Degeneracy is a quantum phenomenon and cannot be explained here. It is sufficient to know that the degenerate matter exerts enormous pressure which is able to stop further contraction. The star ends up as a white dwarf star.

You must have heard that the maximum mass of a white dwart star must be less than about 1.4 solar masses, called the *Chandrasekhar limiting mass*. So, what happened to the remaining mass of the star which became a white dwarf star? During the passage of the star to the white dwarf stage, it loses most of its mass so that as a white dwarf its mass is smaller than the limiting mass.

38.7.5 End Phases of Heavy Stars

All the stars do not have masses similar to that of the Sun. What happens to more massive stars? If the mass of the star is about 10 times the solar mass or more, the contracting core gets heated to a temperature at which the next set of reactions involving the fusion of carbon can take place. When carbon is finished in the core, another phase of contraction of the core takes place. When the temperature is appropriate the next set of fusion reactions takes place. This cycle of core contraction, energy production, core contraction....., continues till the whole of the core consists of iron nuclei. No more fusion is now possible because iron nuclei are the most stable of all muclei. The contraction of the core now sets in motion a chain of circumstances which result in the explosion of the star. The explosion produces such a huge amount of energy that the star becomes very bright for a short time. Such a star is called a **supernova**. The explosion sprays the matter of the star into the

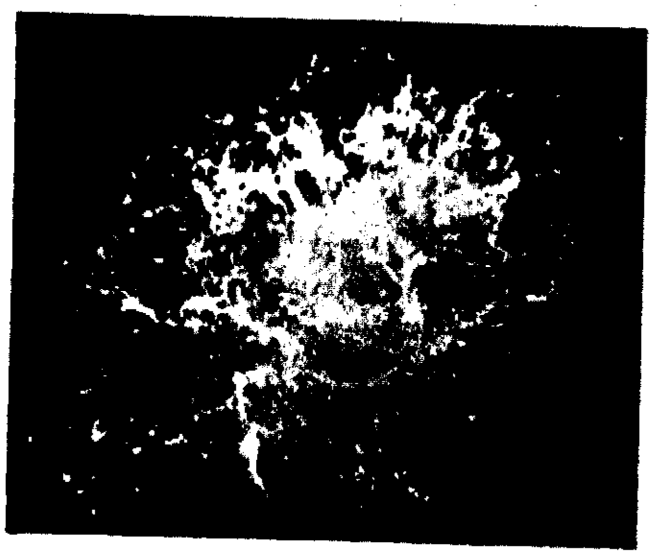

Fig. 38.11: Photo graph of crab nebula through a red filter

surrounding space with great speed. Eventually this matter mixes with the matter in the surrounding space and forms a slowly expanding cloud. Such clouds are called **Supernova remnants**. One such remnant is the well-known crab nebula (Fig 38.11). This is the remnant of the supernova explosion that took place in 1054 and was recorded by the chinese.

But, what happened to the core of the exploding star? The fate of the core depends on its mass. If the mass is less than 2-3 solar masses, then most of the matter of the core gets converted into neutrons. It is now the turn of the neutrons to become degenerate. The pressure of neutrons to become degenerate. The pressure of degenerate neutrons halts the contraction of the core and it becomes a **neutron** star. If the mass of the core is more than 2-3 solar mass, then the core contraction cannot be stopped and it becomes a **black hole**.

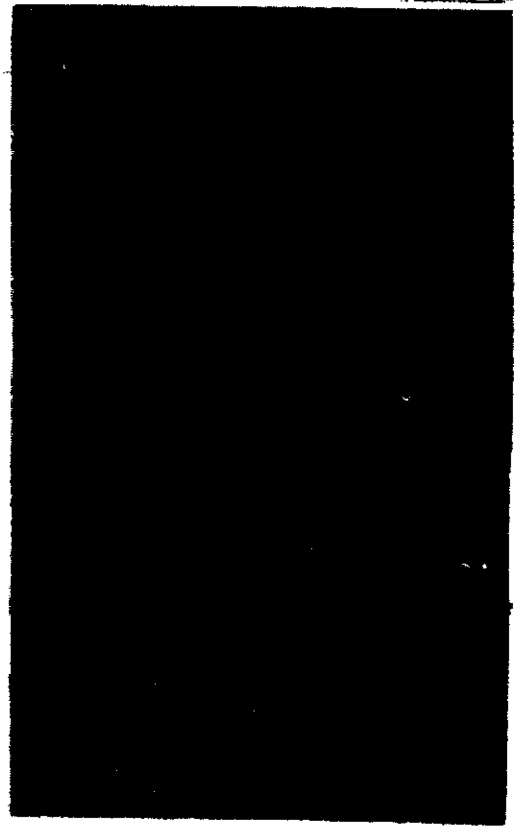

Fig. 38.12: Emission of radiation from a neutron star (pulsar)

A **neutron star** rotates very fast. It completes one rotation in a time of the order of a second, some in as short a time as a few milliseconds. Moreover, a neutron star possesses very strong magnetic field. The combination of magnetic field and fast rotation produces radiation of very high intensity. The radiation is confined to a rotating narrow cone (Fig 38.12), in much the same way as the rotating light beam from a light-house. On the Earth the radiation from a neturon star reaches in the form of regular pulses of short duration. That is why neutron stars are also called **pulsars**.

The core which cannot settle down as a neutron star keeps contracting. At some stage the radius of the star becomes so small that its strong gravitational field can prevent even light from escaping it. Since no light is received from the star it is said to have become a black hole (Fig 38.13 shows this process systematically). What happens to it after this stage is not known with any certainty and our story of stellar evolution must stop here.

INTEXT QUESTIONS 38.5

1. *If M is the mass of the star and L its luminosity, then its life time on the main sequence is roughly proportional to M/L because the ultimate source of energy of the star is its mass which it converts into energy. Suppose the luminosity of stars on the main sequence varies as $M^{3.5}$, find the life time of a star on the main sequence if its mass is 10 times the mass of the Sun. You are given that the life time of the Sun on the main sequence is alout 8 x 10^9 years.*

....

38.8 WHAT YOU HAVE LEARNT

- the distances of the stars are measured by the method of parallaxes
- the masses of stars are determined from the observations of binary stars
- apparent magnitudes measure the brightness of stars
- the relation between the apparent and absolute magnitudes can be used to measure distances of stars indirectly
- the luminosity of a star can be obtained from a knowledge of it absolute magnitude
- the colour of a star is given by its surface temperature
- stellar spectra is the basis of the spectral classification of stars
- the H.R. diagram is extremly useful for the study of stars
- the stars are born from gas clouds, produce their own energy from nuclear reaction and when these processes stop they die
- the end stage of a dying star could be (i) a white dwarf, (ii) a neutron star, or (iii) a black hole.

38.9 TERMINAL QUESTIONS

1. A star suddenly increases its brightness 45000 times. By how many magnitudes does it change?
2. The bright star Castor, which appears single to the naked eye, is found by telescopes to be a binary star. The magnitudes of the two stars are 1.99 and 2.85. What is the magnitude of the combination?
3. Two identical stars differ in magnitude by 5. Show that one of them is 10 times farther than the other.
4. If naked eye can see stars only up to a magnitude 6.2, at what distance should the Sun be placed compared to its present distance so that it just stops being visible? Assume that there is no absorption of light anywhere.

5. The mass of a proton is 1.0076 atomic mass units and that of a helium nucleus is 4.003 atomic mass units. Calculate the energy released for each helium nucleus made up of four protons. Atomic mass unit = 1.67 x 10^{-27} kg.

6. A star consists of pure hydrogen. Is the energy generation by the carbon-nitrogen cycle possible?

Table 38.1: Twenty nearest stars

No.	*Name*	*Parallax (")*	*Distance (parsec)*	*App. mag*	*Sp. Class*
1.	Sun (Surya)	—	—	−26.8	G2
2.	Alpha	0.760	1.32	0.1	G2
3.	Barnard's star	0.552	1.81	9.5	M5
4.	Wolf 359	0.431	2.32	13.5	M6e
5.	Lalande 21185	0.402	2.49	7.5	M2
6.	Sirius (Lubdhak)	0.377	2.65	−1.5	A1
7.	Luyten 726-8	0.365	2.74	12.5	M6e
8.	Ross 154	0.345	2.90	10.6	M5e
9.	Ross 154	0.317	3.15	12.2	M6e
10.	Epsilon Eridani	0.305	3.28	3.7	K2
11.	Luyten 789-6	0.302	3.31	12.2	M6
12.	Ross 128	0.301	3.32	11.1	M5
13.	61 Cygni	0.292	3.42	5.2	K5
14.	Epsilon Indi	0.291	3.44	4.7	K5
15.	Procyon	0.287	3.48	0.3	F5
16.	Σ 2398	0.284	3.52	8.9	M3.5
17.	Groombridge 34	0.282	3.55	8.1	M1
18.	Lacaille 9352	0.279	3.58	7.4	M2
19.	Tau Ceti	0.273	3.66	3.5	G8
20.	BD + 5° 1668	0.266	3.76	9.8	M4

Notes on Table 38.1

1. In the spectral class e indicates that the star's spectrum shows emission lines in addition to the dark lines.
2. Alpha Centauri is actually a triple star the nearest component of which is called Proxima Centauri.
3. Indian names wherever known are given in brackets.

Table 38.2: Major spectral classes and their characteristics

Spectral Type	*Surface Temp (K)*	*Prominent spectral lines*
O	50 000	He II, Si-IV, N III; hydrogen lines relatively weak
B0	25 000	He II absent; He I lines strong; Si III, O II; lines of H stronger
A0	11 000	He I absent; H at maximum; Mg II, Si II, strong; Fi II, CaII weak
F0	7 600	H weaker; Ca II strong; Fe II, Ti II reack maximum strength at A5; Fe I, Ca I about the same strength
G0	6 000	Ca II very strong; neutral metals like Fe I strong
K0	5 100	H weak; neutral atomic lines strong; molecular bands
M0	3 600	Neutral atomic lines like Ca I very strong; Ti II bands
M5	3 000	Ca I very strong, strong molecular bands

Note : Neutral atoms are denoted by I; singly ionized atoms by II; two-times ionized atoms by III, and so on. When conditions are suitable, emission lines appear in stars of all classes.

CHECK YOUR ANSWERS

Intext Questions 38.1

1. 1 parsec = $3.08 \times 10^{16}/9.45 \times 10^{15}$ light year
   = 3.26 light year

   Distance of the star in parsec = 12.2/3 26 = 3.74.

2. Distance between the Sun and Earth = $1.5 \times 10^{11}/9.46 \times 10^{15}$
   = 1.6×10^{-5} light year

   Distance between the Sun and Earth = $1.5 \times 10^{11}/3.086 \times 10^{16}$
   = 5×10^{-6} parsec.

3. The parallax of the star could lie between 0.098" and 0.102"
   Therefore the uncertainty in the distance, Δd, is
   Δd = 1/0.098 -1/0.102 = 0.4 parsec.

Intext Questions 38.2

2. $M_1 + M_2 = \alpha^3/(T^2 p^3) = 1.02$ solar mass
   $M_1/M_2 = \alpha_2/\alpha_1 = 0.15/0.075 = 2$
   So, $M_1 = 2M_2$. Thus, $3M_2 = 1.02$ solar mass, and $M_2 = 0.34$ M. where M. represents solar mass. This gives
   $$M_1 = 0.68 \text{ M.}$$

Intext Questions 38.3

1. Difference in magnitudes of two stars = 23.6 – (–1.4) = 25.0. Since a difference of 5 magnitudes = brightness ratio of 100 Diff of one magnitude = $(100)^{1/5} = 2.512$.

   Therefore diff. of 25 magnitudes = $(2.512)^{25} = 10^{10}$.

   Also remember

diff of 5 mag	=	brightness ratio $(10)^2$
..............10	=	..........................$(10)^4$
..............15	=	..........................$(10)^6$
..............20	=	..........................$(10)^8$
..............25	=	..........................$(10)^{10}$

2. Using eq. (38.9) where r is in parsec and remembering that distance between Sun and Earth ≈ 5 x 10^{-6} parsec (see answer to question 2 of Intext Questions (38.1)
   $$M = -26.8 + 5 - 5 \log (5 \times 10^{-6})$$
   $$\approx 4.7.$$

3. Using eq. (38.9)
   $2 = 7 + 5 - 5 \log r$
   so that
   $\log r = 2$, or $r = 100$ parsec.

   To calculate the luminosity, use (38.10) with $M_1 = M$, the absolute magnitude of the star and $M_2 = M.$, the absolute magnitude of the Sun. Then

   $M - M = -2.5 \log \frac{L}{L.}$ $M.$ was calculated as + 4.7 in the last problem,

   and L. was found earlier to be 4 x 10^{26} J. Using these values and putting M = 2, we find L = 5 x 10^{27} J.

Intext Questions 38.4

1. The Wien's displacement law says that the wavelength at which maximum intensity occurs, called λ max' is given by
   $$\lambda \text{ Max. } T = 0.29\text{cm} \quad K.$$
   Where the wavelength is expressed in cm. From the given data λ max' = 0.29/5800 cm = 0. 29/5800 x 10^8 Å = 5000 Å.

2. As in the above problem, λ max = 0.29/4500 x 10^8 = 6444 Å. This wavelength is in the red region of the spectrum, so the star appears red.

We shall use eq (38.10) : $M_1 - M_2 = 2.5 \log L_1/L_2$

Let 1 refer to white dwarf and 2 to main sequence star of same surface temperature. Substituting values of M_1 and M_2 :

$$9-(-1) = -2.5 \log L_1/L_2$$

$$\log L_1/L_2 = -4, \text{ i.e. } L_1/L_2 = 10^{-4}$$

Let R_1 and R_2 be radii of the white dwarf and main sequence stars respectively. Then from eq (38.11) for luminosity of a star :

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

$$\text{We get } L_1/L_2 = R_1^2/R_2^2 = 10^{-4}$$

$$\Rightarrow \quad R_1/R_2 = 10^{-2}$$

Hence white dwarf star has 10^{-4} times the luminosity and 10^{-2} times the radius as the main sequence star.

Intext Questions 38.5

1. If τ be the age of a star on the main sequence, then

$\tau \alpha M/L$

But $\quad L \propto M^{3.5}$, *therefore,*

$$\tau \propto M/M^{3.5} \; \alpha \; M^{-2.5}$$

Thus,

$$\tau/\tau_* = (M/M_*)^{-2.5} = 10^{-2.5}.$$

Substituting the age of the Sun, $\tau_* = 8\times10^9$ *year, we get*

$$\tau = 2.5\times10^7 \text{ years.}$$

TERMINAL QUESTIONS

1. We remember (refer Q. 1 of the Intext Questions 38.3) that for each difference in magnitude the ratio of brightness is $(100)^{1/5}$ or 2.512. Therefore, if the difference in magnitude of the two stars is X, then

$45000 = (100)^{x/5}$

This equation can be solved for X giving X = 11.6

2. The combined brightness of two stars is $b_1 + b_2$. Suppose the magnitude corresponding to this brightness is m, then from (6), we have

$(b_1 + b_2)/b_2 = 10^{0.4(m2-m)}$ $\quad$ $1 + b_1/b_2 = 10^{0.4(m2-m)}$

Substituting the values of b_1/b_2 and m_2, we get m = 1.58.

3. Since the two stars differ in magnitude by 5, the ratio of their brightness must be 100. As the brightness of an object is inversely proportional to the square of the distance, one must be 10 times farther than the other.

4. Suppose the sun would not be seen with naked eye if its magnitude is 6.2. The difference in magnitude is then 6.2 – (–26.8) = 33.0. The corresponding ratio of brightness is $(2.512)^{33}$. This means that the Sun must be moved to a distance which is $\sqrt{(2.512)^{33}}$ times its present distance. The square root has the value 4 x 10^6. So the sun must be moved to four million times its present distance to make it invisible with naked eye.

5. The difference between the mass of four protons and of helium nucleus is (4 x 1.0076 – 4.003) x 1.67 x 10^{-27} kg. The energy produced is this quantity multiplied by C. This gives 4.118 X 10^{-12} J

6. No, since the carbon-nitrogen cycle requires for its operation carbon as catalyst, which is not present if the star consists of pure hydrogen.