UNIT 7 STELLAR SPECTRA AND CLASSIFICATION

Structure

7.1 INTRODUCTION

In Unit 5, you have studied about the Sun and in Unit 6, you have learnt about the solar system. You also learnt the characteristic features of the solar atmosphere and solar activity. You now know that the Sun is the nearest and the only star in our solar system. All the stars, including the Sun are located at very large distances from the Earth. Thus, a logical question is: How do we obtain information about the stars? All the information about stars is obtained by analysing their spectra and this is the subject matter of the present Unit.

You may recall from Thermodynamics and Statistical Mechanics (PHE-06) course that the radiation emitted by an object at a given temperature covers a range (spectrum) of wavelengths with a characteristic peak wavelength. The value of the characteristic wavelength depends on temperature of the object. Therefore, by a careful analysis of the radiation emitted by a star, we can estimate its temperature. In addition, we can also obtain useful information regarding composition, pressure, density, age etc. of a star on the basis of its spectrum. In Sec. 7.2, we briefly recapitulate the atomic origin of emission and absorption spectra and explain how the temperatures and luminosities of stars can be inferred from their spectra.

One of the earliest uses of stellar spectra was to classify stars on the basis of strength of certain spectral lines. Later on, it was discovered that the relative strengths of spectral lines depend basically on the star's temperature. The spectral classification has been discussed in Sec. 7.3. The most comprehensive classification of stars was done on the basis of the correlation between their luminosities (an observable parameter of stars) and temperatures. This classification gave rise to Hertzsprung-Russell (H-R) diagram about which you will learn in Sec. 7.4. This diagram is of utmost importance in astronomy. In Sec. 7.5, you will learn yet another classification of stars, called luminosity classification, which tells us about the size of a star.

Objectives

After studying this unit, you should be able to:

- explain the atomic origin of emission and absorption spectra;
- discuss the correlation between the strength of spectral lines of an element and the temperature of the region containing the elements;
- list the spectral types of stars and their characteristic features;
- discuss the salient features of different groups of stars on the H-R diagram;
- describe the need for luminosity classification of stars; and
- estimate the size of a star on the basis of its luminosity class.

7.2 ATOMIC SPECTRA REVISITED

To appreciate the relation between the physical parameters of an object and the radiation emitted by it, let us imagine heating an iron bar. First, the iron bar begins to glow with a dull red colour. As the bar is heated further, the dull red colour changes to bright red and then to yellowish-white. If we can prevent the bar from melting and vaporising with further increase of temperature, it would glow with a brilliant bluish colour. This simple experiment reveals how the intensity and colour of light emitted by a hot object varies with temperature. Similar is the situation with stars. You must have noticed, while looking at night sky, that all stars do not look the same in terms of their brightness or colour: the differences are determined by their surface temperatures.

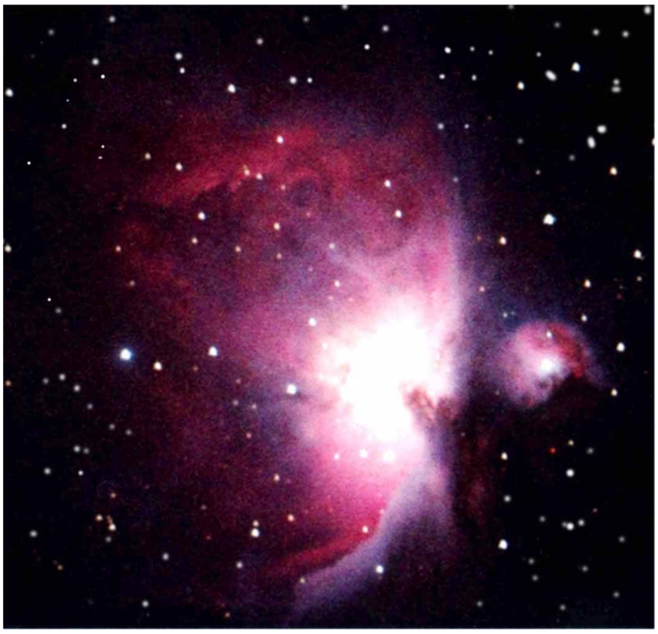
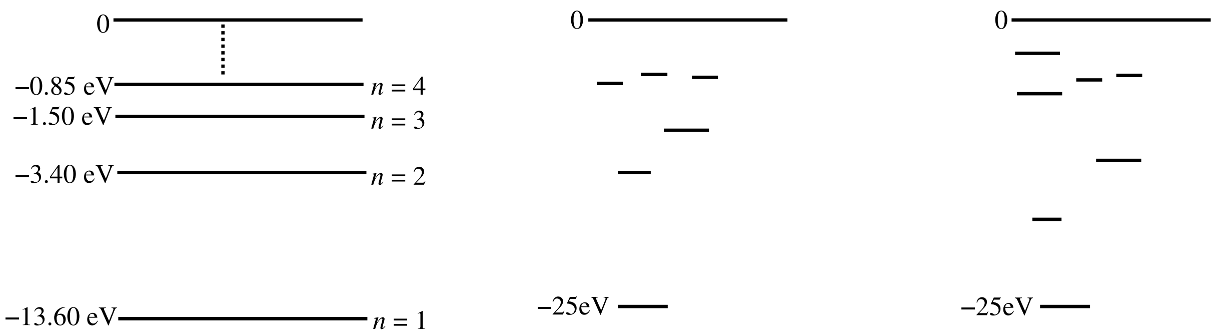


Fig.7.1: The Orion nebula

If you happen to look at Orion nebula (Fig. 7.1), it has not only blue stars but also some red stars. Similarly the brightest visible star to the naked eye – Sirius (*Vyadh*) – looks whitish; Canopus (*Bramhahrudaya*) is yellowish and Aldebran (*Rohini*) is reddish.

From Unit 3, you know that spectroscopy refers to the analysis of light in terms of its wavelength and it is extensively used to obtain information regarding temperature, composition etc. of stars. Such analyses provide valuable information. But, the question is: **How do we analyse the light from a star?** To answer this, we need to recapitulate the atomic origin of emission and absorption of light. Recall from the Modern Physics (PHE-11) course that:

i) **Electrons in an atom exist in certain allowed energy states**. Each element has a characteristic set of energy levels (see Fig. 7.2).



(a) (b)

Fig.7.2: Energy level diagram of a) hydrogen atom; and b) helium atom

ii) **When an electron makes a transition from a higher energy level to a lower energy level, radiation is emitted.** An electron goes from a lower energy level to a higher energy level when it absorbs energy and vice-versa (Fig. 7.3). Such transitions follow certain selection rules and are always accompanied by the emission/absorption of radiation. You know from Unit 9 of the PHE-11 course that t**he wavelength (or frequency) of the emitted/absorbed radiation is determined by the difference in the energies of the two atomic energy levels:**

$$\Delta E = E_2 - E_1 = h\nu \tag{7.1}$$

where E_1 and E_2 are the energies of the levels involved in transition, h is Planck's constant , ν is the frequency of the emitted/absorbed radiation and ΔE is the energy of the corresponding photon.

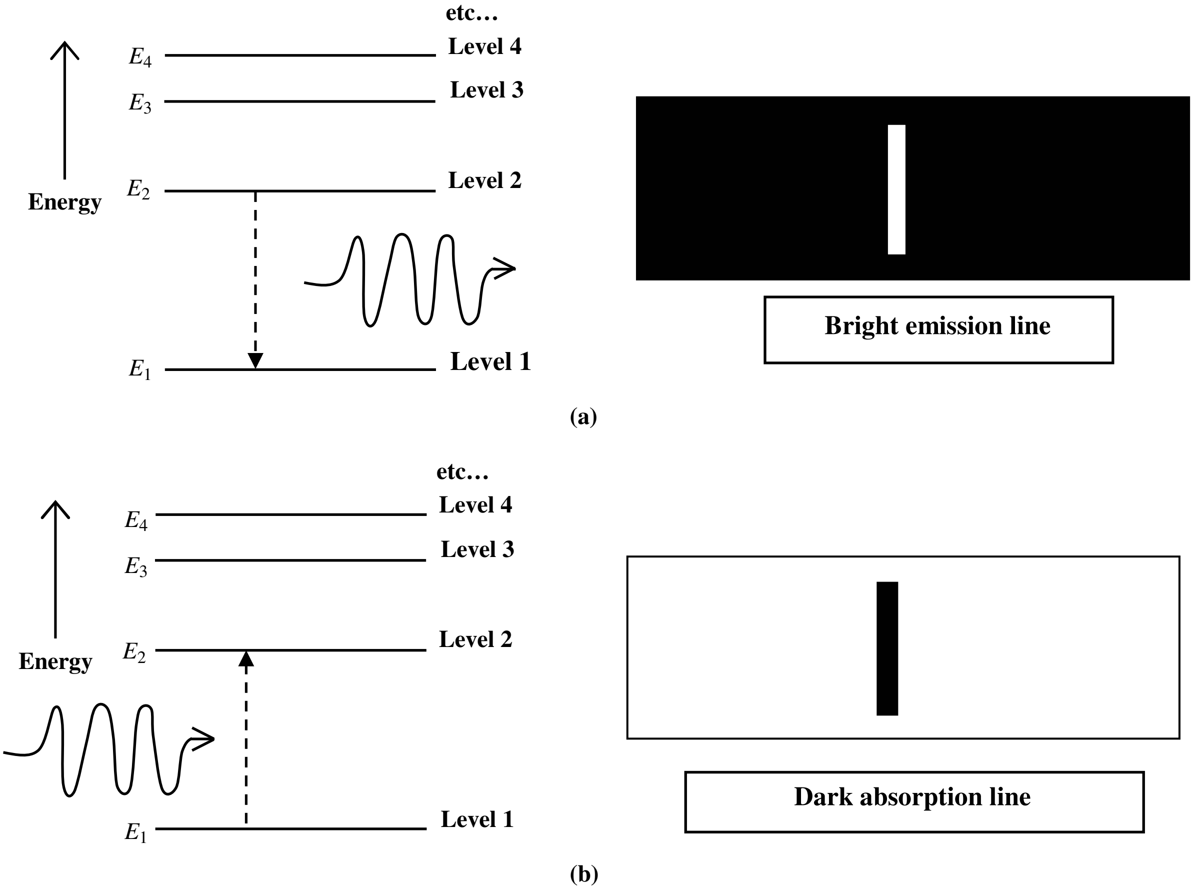
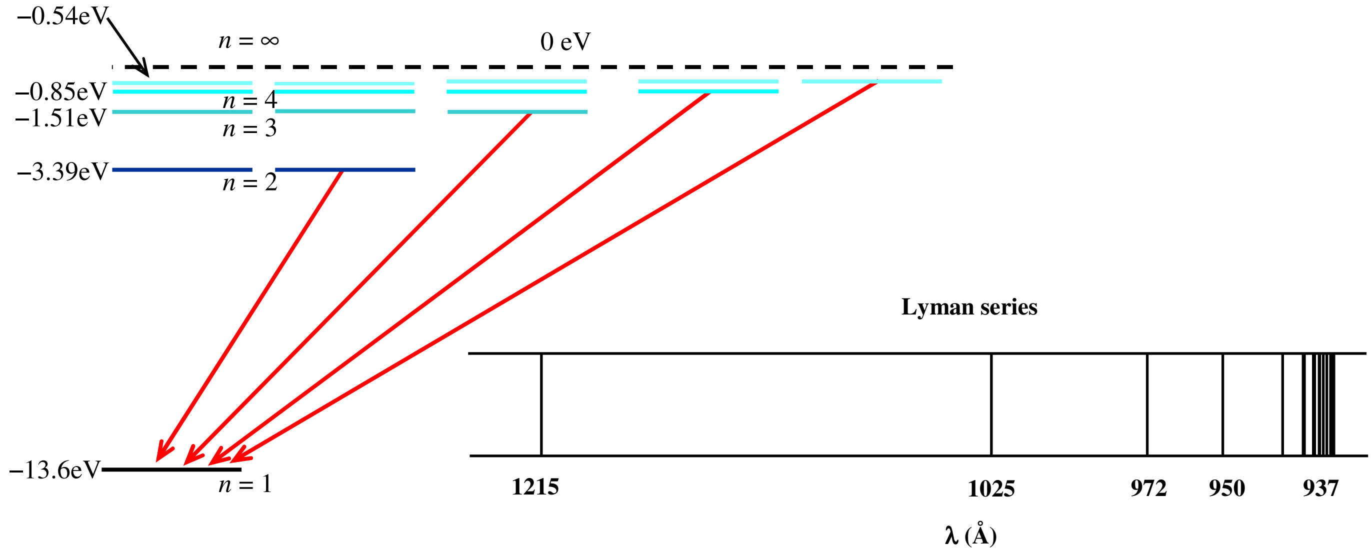


Fig.7.3: The atomic electron a) emits radiation when it makes a transition from a higher energy level to a lower energy level giving rise to emission spectrum; and b) makes a transition to a higher energy level on absorbing radiation giving rise to absorption spectrum

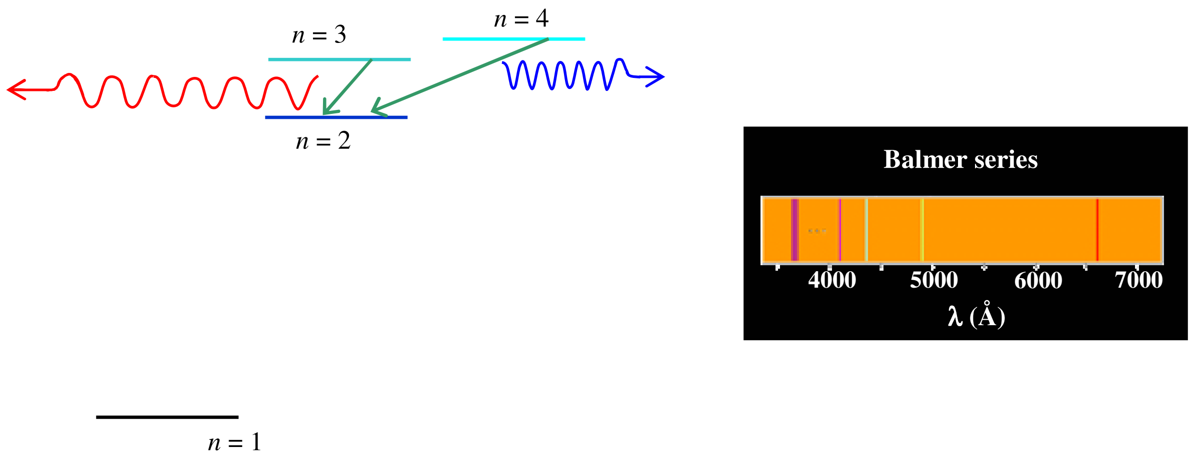
To understand the origin of atomic spectra, refer once again to Fig. 7.3 which shows the energy level diagram and transition of electron between these levels for a hydrogen atom. In Fig. 7.3(a), a hydrogen atom makes a transition from the 2nd energy level to the 1st, giving off light *with an energy equal to the difference of energy between levels 2 and 1*. This energy corresponds to a specific colour or wavelength of light -- and thus we see a bright line at that *exact* wavelength! This is an **emission spectrum**.

On the other hand, what would happen if we tried to reverse this process? That is, what would happen if a photon of the same energy was incident on a hydrogen atom in the ground state? The atom could absorb this photon and make a transition from the ground state to a higher energy level. This process gives rise to a **dark absorption line in the spectrum** as shown in the figure. This is an **absorption spectrum**.

If light from a star with a *continuous* spectrum is incident upon the atoms in its surrounding atmosphere, the wavelengths corresponding to possible energy transitions within the atoms are absorbed. Thus, an observer will see an absorption spectrum.



(a)



(b)

Fig.7.4: Emission of radiation by hydrogen atoms corresponding to Lyman and Balmer series: a) Transitions to level n=1 gives Lyman series; and b) Transitions to n=2 level gives Balmer series

On the basis of above, we can understand the genesis of atomic spectra. Let us take the simplest example of the spectrum of hydrogen atom. In Fig. 7.4 we show the various spectral series for the hydrogen atom. The transition of electrons from higher energy levels to the lowest (n = 1) energy level gives rise to emission of a series of characteristic wavelengths known as **Lyman series.** Similarly, transition of electrons from higher energy levels to the first excited (n = 2) energy level results into the emission of another series of characteristic wavelengths called the **Balmer series**. You may note that some of the spectral lines in Balmer series fall in the visible region of the electromagnetic spectrum (Fig. 7.4b). This makes them very useful spectral lines for spectroscopic analysis. Further, transitions to the second excited (n = 3) energy level give rise to the **Paschen series**.

Emission Spectrum

Now, let us consider the nature of emission of radiation by hydrogen gas (a collection of many hydrogen atoms) kept at a **high temperature**. Each atom in the gas can absorb thermal energy as well as the energy due to collisions with other atoms. As a result, each atom would absorb a different amount of energy. Therefore, the electrons in the lowest energy level of various atoms get excited to different higher energy levels (Fig. 7.5). The question is: **What kind of emission spectrum would we obtain in such a situation?**

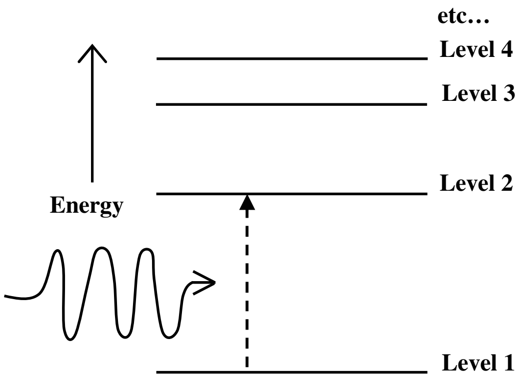


Fig.7.5: At high temperatures, electrons in hydrogen atoms get excited to various higher energy levels; transitions to levels 2 and 3 are shown here as examples

To answer this, let us consider a hydrogen atom in this *hot* gas whose electron has been excited to the second excited energy level (Fig. 7.6). This electron can return to the lowest energy level either directly (Fig. 7.6a) or in steps. For example, it can go to the first excited energy level and then to the lowest level (Fig.7.6b). In the two cases, the energies of the emitted photons would be different. Thus, in a gas of hydrogen atoms at high temperature, electrons can be excited to many possible levels and can make transitions to any of the lower levels emitting radiations of the corresponding frequencies. This implies that photons of different frequencies will be emitted and we will observe more than one emission line in the emission spectrum of a hot gas.

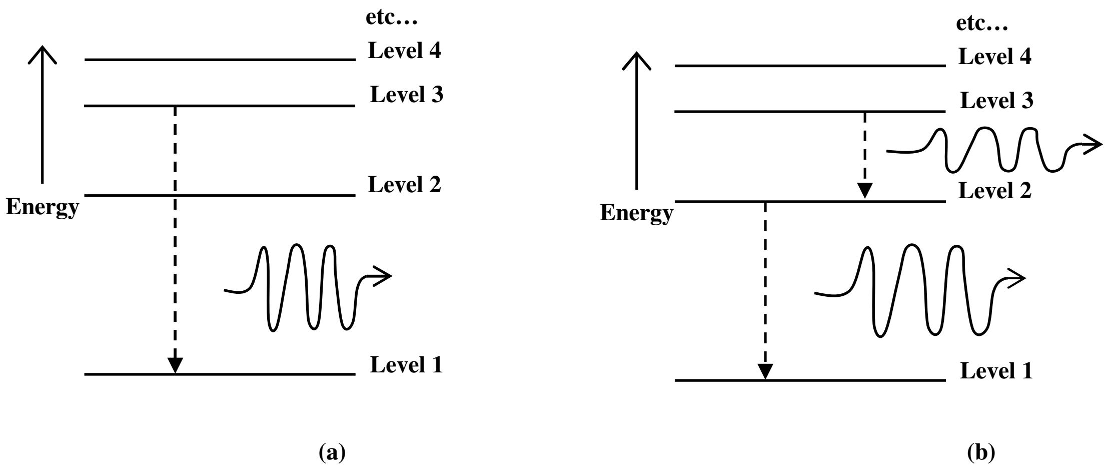


Fig.7.6: Different ways of transition of electron in a hydrogen atom from an excited energy level to the lowest energy level

However, you must remember that the spectrum of hydrogen gas is not continuous, that is, not all frequencies will be emitted; radiations of only those frequencies will be emitted whose energies are equal to the difference in energy between the allowed energy levels. Therefore, the **emission spectrum** of hydrogen gas contains bright lines of certain definite frequencies.

The frequencies contained in the emission spectra of each element are unique: no two elements have the same type of emission spectra because each one of them has a characteristic set of allowed energy levels.

Absorption Spectrum

Let us assume now that the hydrogen gas is not at a high enough temperature to excite the electrons to higher energy levels. In such a situation, there is no emission of radiation. If white light (continuous spectrum) is passed through this *cool* hydrogen gas, it will absorb light of only those frequencies which give electrons just enough energy to make a transition to one of the excited energy levels (see Fig. 7.3b). Therefore, just as photons of certain energies are emitted by hydrogen gas at a high temperature, photons of the same energies are absorbed by the *cool* hydrogen gas.

You can argue that atoms absorbing photons and giving rise to absorption spectrum will eventually re-emit photons of the same frequencies. Thus, it should cancel out the effect of absorption and we could not observe any absorption spectrum! The question, therefore, is: **How to explain the observed absorption spectrum?** The re-emitted photons are repeatedly absorbed by the atoms of the cool gas before they finally escape it. These re-emitted photons escaping from the gas travel along different directions. Thus, the photons of certain frequencies, which were originally coming towards the spectroscope as a part of white light, are ***scattered*** by the atoms of the cool gas. As a result, the intensities of the light corresponding to these frequencies are very low and we observe an absorption spectrum.

Thus when white light passes through a *cool* hydrogen gas, we obtain a series of dark lines and such a spectrum is called the **absorption spectrum**.

Do remember that for any element, the dark lines of absorption spectrum occur at exactly the same frequencies (or wavelengths) where we observe bright lines in its emission spectrum.

Now, before proceeding further, you should answer an SAQ to fix these ideas.

SAQ 1

Spend 5 min.

a) Why do the spectra of different elements have different sets of lines?
b) What do you understand by a continuous spectrum? Under what condition do we observe it?

Let us pause for a moment and think: **How does the knowledge about the origin of spectral lines help in analysing stellar spectra**? Firstly, you have learnt that each element produces a unique set of spectral lines. Therefore, observing the spectrum of a star, we can tell which element(s) are present in its atmosphere. Secondly, the nature of spectrum — emission or absorption — depends on the temperature prevailing in the atmosphere through which star light passes. Thus, the nature of spectrum gives us an idea about the temperature of the star's atmosphere.

Strictly speaking, the stellar spectra tell us about the composition of the star's atmosphere. However, it is generally believed that the composition of the atmosphere reflects the composition of the star itself.

In addition, stellar spectra also provide information about the density of the star's atmosphere and the motion of stars with respect to the Earth. Whether a star is moving towards or away from the Earth can be inferred on the basis of Doppler effect:

According to the Doppler effect, there is an apparent change in the wavelength of radiation emitted by a star due to its (star's) motion; if the star is moving away from the Earth, the wavelengths are shifted towards longer wavelengths (the phenomenon is known as red shift) and if the star is moving towards the Earth, the wavelengths are shifted towards shorter wavelengths (the phenomenon is known as blue shift).

With this background information, you are now ready to study stellar spectra. In this context, it is useful to remember a set of empirical rules of spectroscopic analysis given below:

i) A hot and opaque solid, liquid or highly dense gas emits a continuous spectrum; Fig. 7.7a (you have learnt about optically thin and thick media in Unit 4).
ii) A hot gas produces emission spectrum and the number and position of the emission lines depends on the composition of the gas (Fig. 7.7b).
iii) If light having continuous spectrum is passed through a gas at low temperature, an absorption spectrum consisting of dark lines is produced (Fig. 7.7c). Again, the position and number of dark lines are characteristic of the elements present in the gas.
iv) When light with continuous spectrum passes through a very hot, transparent gas, a continuous spectrum with additional bright lines is produced.

Fig. 7.7 shows some of these situations.

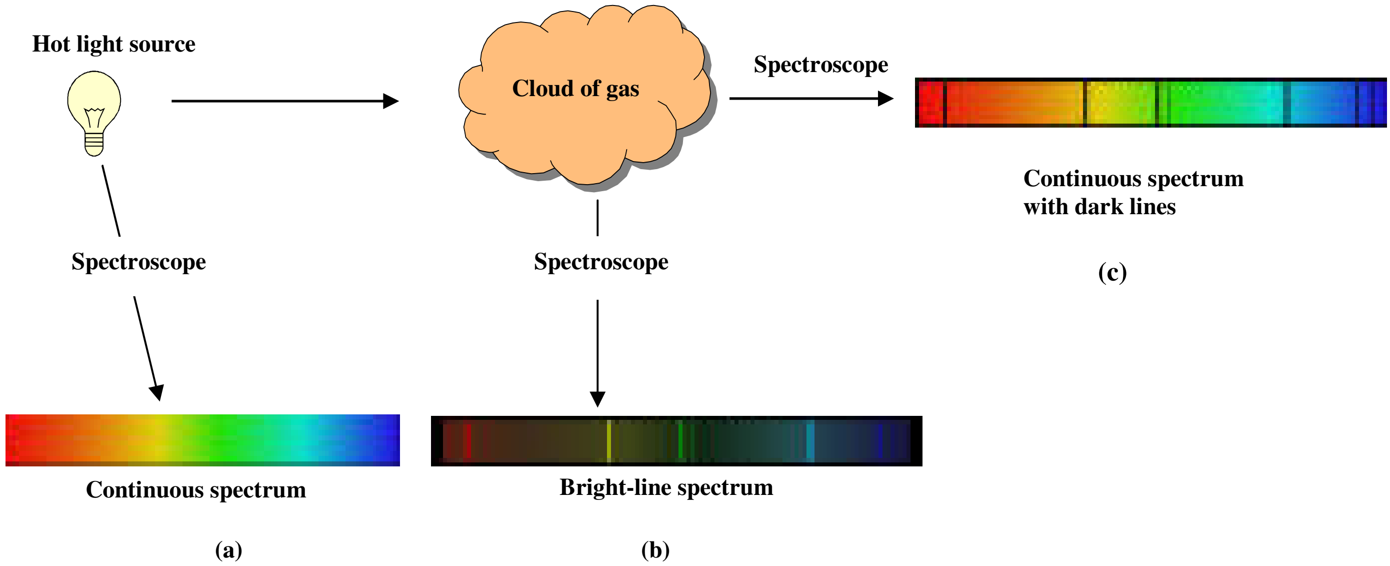


Fig.7.7: Diagrammatic representation of empirical rules for spectroscopic analysis of stellar spectra

7.3 STELLAR SPECTRA

Before discussing stellar spectra, you may like to know how they are obtained using a spectroscope. Refer to Fig. 7.8 which shows how to obtain a spectrum using a spectroscope. Light from the telescope (pointing towards the star) is passed through a slit, a collimating lens, through the prism of the spectroscope to obtain the spectrum. The resulting spectrum is focussed by another lens and can either be viewed directly or photographed.

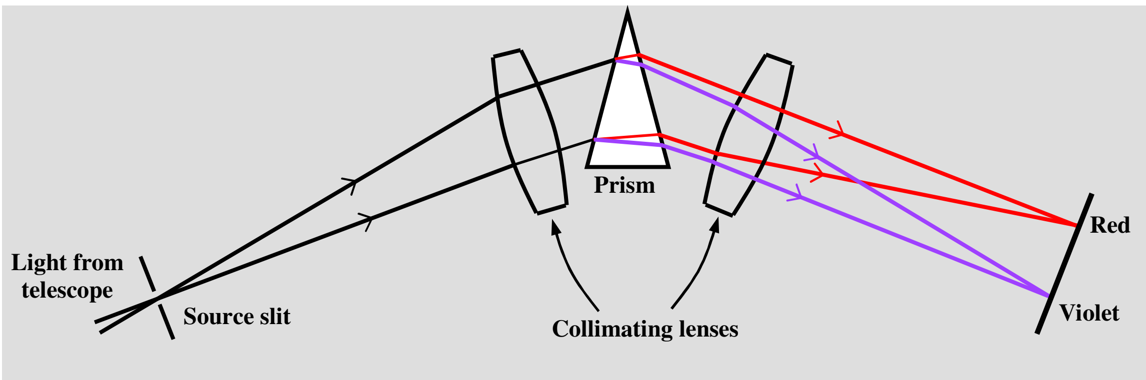


Fig.7.8: Schematic diagram of a spectroscope

For a casual observer, all stars look alike. But, if observed carefully, some stars appear bright and some faint. It is usually difficult to make out the colours of stars if they are fainter than the second magnitude. This is due to poor colour sensitivity of the human eye to fainter light. Stellar spectra, however, show that individual stars differ widely from one another in brightness and spectral details. While spectra of some stars contain lines due to gases like hydrogen and helium, others show lines produced by metals. Some stars have spectra dominated by broad bands of molecules such as titanium oxide.

Stellar Spectra and Classification

In earlier times, the spectrum was exposed on a photographic film. The film was then developed in the usual way and scanned for intensity at each point of the film. The data so obtained was plotted to obtain the spectrum. Now-a-days, with the advent of modern detectors like the CCDs (about which you have studied in Unit 3), the spectrum can be directly stored in a computer and plotted.

A typical spectrum of a star consists of a continuum, on which are superposed dark absorption lines. Sometimes emission lines are also present. An example of a typical stellar spectrum is the solar spectrum (Fig. 7.9). Solar spectrum can be easily obtained by passing a narrow beam of sun light through a prism. It consists of a continuum background superposed by dark lines.

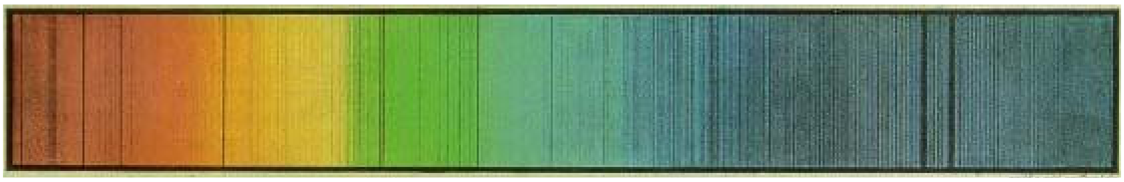


Fig.7.9: Solar spectrum

The dark lines in the solar spectrum are called **Fraunhofer lines**. You know that the intensities of spectral lines indicate the abundance of various elements to which the lines belong. The important lines in stellar spectra are due to hydrogen, helium, carbon, oxygen, neutral and ionised metal atoms. Bands in the spectra are caused by the molecules such as titanium oxide, zirconium oxide, CH, CN, C_3 and SiS_2.

You have learnt in Unit 1 that the brightness of stars is expressed in magnitudes.

Similarities in stellar spectra provided the basis for classification of stars into certain categories. The earliest classification was done by Annie J. Cannon. She classified more than 2, 50,000 stars by observing the strength of absorption lines, particularly, the hydrogen Balmer lines. In this way stars have been classified into seven major spectral types, namely, O, B, A, F, G, K and M.

For greater precision, astronomers have divided each of the main spectral types into 10 sub-spectral types. For example, spectral type A consists of sub-spectral types A0, A1, A2.... A8, A9. Next come F0, F1, and so on. Thus there are 70 sub-spectral types possible. However, in practice, all 70 types have not been observed. The advantage of the finer division is to estimate the star's temperature to accuracy within about

5 percent. The Sun, for example, is not just a G star, but a G2 star, with a surface temperature of about 5800 K.

7.3.1 Spectral Types and Their Temperature Dependence

Fig. 7.10 shows a set of spectra of seven main types of stars: O, B, A, F, G, K and M (hottest O-type to coolest M-type). It was shown by M.N. Saha, an Indian scientist, that Cannon's spectral classification can be explained primarily on the basis of the temperatures of stars because the intensities of spectral lines depend on the surface temperature of a star. To elaborate this argument, let us take the case of spectral lines of hydrogen Balmer series as an example.

M.N. Saha

M.N. Saha's conclusion that Cannon's spectral classification is based on surface temperature of stars is based on the fact that ionisation of atoms is a process similar to chemical reaction. This means that at a given temperature, relative number of atoms in various stages of ionisation which are in equilibrium, is fixed. Further, the intensity of an absorption line is a function of the number of atoms which can absorb radiation corresponding to this line and this number itself is a function of temperature.

You know that 50 to 80 percent of the mass of a typical star is made of hydrogen. However, only a small fraction of the stars show Balmer lines in their spectra! It is so because most of the stars do not have sufficient surface temperature to raise the electrons in hydrogen atoms to the second and higher energy levels. And, as you know, for production of Balmer lines, electrons in the hydrogen atoms make transitions from the higher energy levels to the first excited energy level. For example, a M type star whose surface temperature is about 3000 K, does not have enough energy for production of Balmer lines. Therefore, even though there is an abundance of hydrogen in the stars, Balmer lines may not be observed in the spectra of all of them: the surface temperature prohibits the formation of Balmer lines of hydrogen.

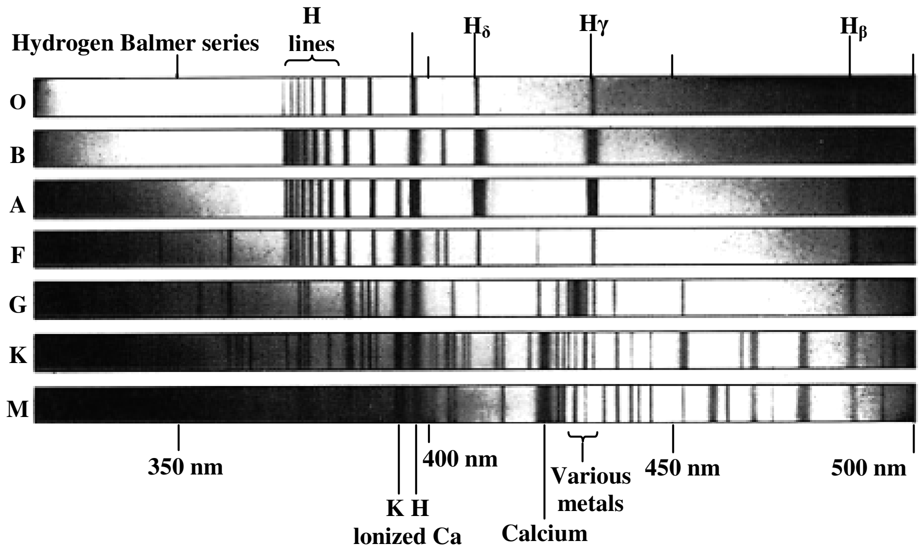


Fig.7.10: Examples of spectra of various types of stars (O to M type)

On the other hand, very hot stars with surface temperatures higher than 25000 K also do not contain Balmer lines in their spectra. **Can you guess why is it so?** It is because such stars are so hot that electrons of the hydrogen atoms are ripped off and the atoms are ionised. Such ionised atoms cannot produce spectral lines. *It is only when the surface temperature of a star is between 7500* K *and 11000* K *that the conditions are favorable for the production of Balmer lines. Therefore, surface temperature of a star determines which spectral lines would be formed and what their intensities would be.*

After hydrogen, the second most abundant element in stars is helium. A helium atom has two electrons which are held very tightly together in their lowest states. Hence, helium absorption lines are seen in the spectra of relatively hot stars with surface temperatures in the range 11000 K to 25000 K. In stars hotter than 25000 K, one of the two electrons in helium atoms is torn away. The question is: **Are the spectral lines produced by singly ionised helium atoms similar to those produced by un-ionised helium atom**?

The spectral lines produced by singly ionised helium are different from those produced by neutral or un-ionised helium. Further, stars with temperatures in excess of 40000 K are so hot that helium is completely ionized which cannot produce any spectral lines.

In some stars, conditions are favourable for a molecule to produce spectral lines. Very cool stars with temperatures less than 3500 K show very strong, broad bands of titanium oxide (TiO). Table 7.1 shows the values of the temperature and some other important parameters of seven main spectral types.

Table 7.1: Spectral types and their parameters

Spectral class	Approx. temp. (K)	Hydrogen Balmer lines	Other spectral features	Naked-eye example (Star)	Color
O	40,000	Weak	Ionised He	Meissa (O8)	Blue
B	20,000	Medium	Ionised and Neutral He	Achenar (B3)	Blue/White
A	10,000	Strong	Ionised Ca weak	Sirius (A1)	White
F	7,500	Medium	Ionised Ca weak	Canopus (F0)	Yellow/White
G	5,500	Weak	Ionised Ca medium	Sun (G2)	Yellow
K	4,500	Very weak	Ionised Ca strong	Arcturus (K2)	Orange
M	3,000	Very weak	TiO strong	Betelgeus (M2)	Orange/Red

There is an alternative method to determine the temperature of a star on the basis of its spectrum. This method is based on the principle of black body radiation and you will learn it now.

7.3.2 Black Body Approximation

As you know, the colour and brightness of a star is different from other stars. You also know that these parameters depend on temperature. **Does it, therefore, mean that we can estimate the temperature of stars on the basis of their observed colour and brightness?**

It can indeed be done if we consider a star as an ideal object called *black body*. Refer to Fig. 7.11 which shows a set of black body spectra at various temperatures. Note that hotter bodies radiate most of their total energy in the shorter wavelength part of the spectrum. On the other hand, the cooler bodies have the peak of their radiation at the longer wavelength side of the spectrum and the total energy radiated by them is relatively low.

It has been observed that the outer envelope of a star's spectrum is quite similar to a black body spectrum at a certain temperature. Thus, a stellar spectrum can be approximated to a black body spectrum. You should, however, note that the absorption features of stellar spectra distinguish it from the black body spectrum. Therefore, the main spectral types, namely O to M, can be considered as referring to different temperatures. In other words, we can say that spectral type directly refers to the effective temperature of the star (see Table 7.1).

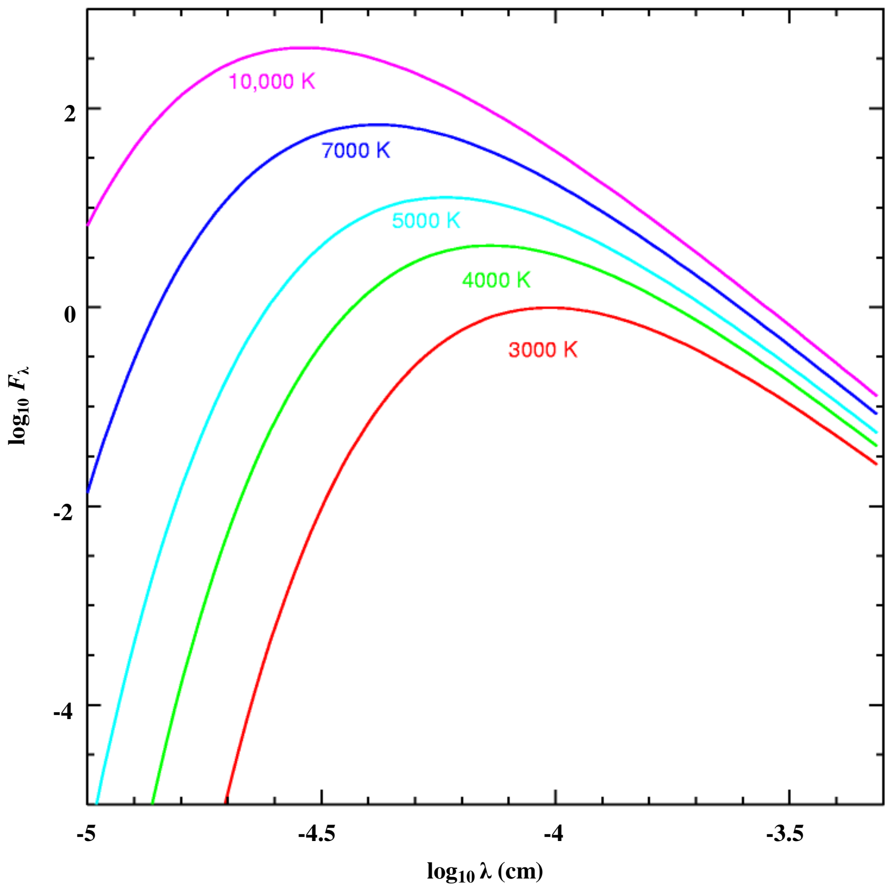


Fig.7.11: Black body radiation curves for various temperatures

To estimate the temperature of an astronomical object such as a star on the basis of black body approximation, go through the following Example carefully.

Example 1

An astronomical object named Cygnus *X*-1, a strong *X*-ray source, is found to radiate like a black body with peak wavelength at 1.45 nm. Calculate its temperature. Assume that the constant for Wien's displacement law is equal to 2.9×10^{-3} mK.

Solution

You may recall from Thermodynamics and Statistical Mechanics (PHE-06) course that the Wein's displacement law is given by:

$$\lambda_{peak}\, T = \text{constant}$$

where λ_{peak} is the value of wavelength corresponding to the peak of the black body spectrum and T is the temperature of the black body. For Cygnus *X*-1, we have

$$\lambda_{peak} = 1.45 \times 10^{-9}\text{m}$$

and

$$\text{value of the constant} = 2.9 \times 10^{-3}\text{mK.}$$

Thus, temperature of Cygnus *X*-1,

$$T = \frac{2.9\times10^{-3}\,\text{mK}}{1.4\times10^{-9}\,\text{m}} \cong 2\times10^{6}\,\text{K}\,.$$

As you know, the temperature of a star is not a directly measured quantity; rather, we infer this parameter on the basis of black body approximation. *Would it not be better to classify stars on the basis of a parameter, say luminosity, which is more easily measurable?* This is what was attempted by Ejnar Hertzsprung and Henry Norris Russell and their classification of stars resulted in a graph known as **H-R diagram**. You will study about it now.

7.4 H-R DIAGRAM

H-R diagram is a graph which enables us to simultaneously classify stars on the basis of their temperatures and their luminosities. Since H-R diagram involves parameters such as temperature, luminosity and radius, it would be advisable to first recapitulate these terms and their interdependence in the context of stars.

The luminosity (L) of a star is defined as the total energy radiated by it, in one second, consisting of radiations of all wavelengths. On the other hand, you may recall from Unit 1 that the absolute visual magnitude refers only to the visible range of the electromagnetic radiation. Therefore, corrections need to be applied for the radiations emitted at other wavelengths. The required extent of correction depends upon the temperature of the star. This correction is called **Bolometric Correction** (B.C.) and for medium temperature stars like our Sun, its value is small. After making necessary correction, we obtain the **absolute bolometric magnitude**: for the Sun it is + 4.7 and for Arcturus, it is – 0.3.

Thus, the expressions for the apparent magnitude as well as the absolute magnitudes of a star are written as:

$$m_{bol} = m_v + \text{B.C.} \tag{7.2a}$$

and

$$M_{bol} = M_v + \text{B.C.} \tag{7.2b}$$

where m_{bol}, m_v, M_{bol} and M_v are respectively the apparent bolometric magnitude apparent visual magnitude, absolute bolometric magnitude and absolute visual magnitude of a star. Further, the absolute bolometric magnitude of a star can be calculated from the following relation:

$$M_{star}^{bol} - M_{\Theta}^{bol} = -2.5 \log \left(\frac{L_{star}}{L_{\Theta}} \right) \qquad (7.3)$$

You have already learnt that a difference of 5 in absolute magnitude implies a ratio of 100 in luminosity. So, the luminosity of Arcturus is $100\,L_{\Theta}$. The most luminous stars can have luminosities of the order of $10^5\,L_{\Theta}$, whereas the least luminous ones have luminosities ~ $10^{-4}\,L_{\Theta}$.

Thus, if we can measure the parallax of a star, we can find its distance, calculate its absolute visual magnitude, calculate the bolometric correction and obtain absolute bolometric magnitude. As a result, we can estimate the luminosity of a star in terms of the Sun's luminosity. How about solving an SAQ to check your understanding of the terms discussed above?

You have learnt in Unit 1 how the parallax of a star is measured.

SAQ 2

Spend 5 min.

The absolute visual magnitude of a star is 8.7 and for its temperature, the bolometric correction is – 0.5. Calculate the absolute bolometric magnitude and the luminosity of the star.

You know that one of the fundamental parameters of a star is its diameter and it is related to the star's luminosity and temperature. To appreciate the relation amongst these parameters, consider a normal candle flame which has a low surface area. The candle flame, despite being very hot, cannot radiate much heat and its luminosity is low. However, if the candle flame were 25 cm long, it would have larger surface area. In this case, despite being at the same temperature, it would radiate more heat and would have high value of luminosity.

In the same way, a star's luminosity is affected by its surface area and temperature. To obtain a relation between the luminosity and diameter of a star, we can assume the star to be spherical in shape having surface area $4\pi R^2$, where R is the radius. Further, from basic thermodynamics (PHE-06 course), you know that, the total energy radiated by a black body per second per unit area is σT^4 (Stefan's law). Assuming that the star radiates like a black body, we can express its luminosity (L) as the product of its surface area and the energy radiated by it per unit area per second, i.e.,

$$L = 4\pi R^2 \sigma T^4 \qquad (7.4)$$

Thus, by comparing the luminosity L of a star, with L_{Θ}, the luminosity of the Sun, we get:

$$\frac{L}{L_{\Theta}} = \left(\frac{R}{R_{\Theta}} \right)^2 \left(\frac{T}{T_{\Theta}} \right)^4 \qquad (7.5)$$

where R_{Θ} and T_{Θ} are the radius and temperature of the Sun.

Let us now refer to Fig. 7.12 which shows a H-R diagram for all known stars in our solar neighbourhood. Note that the H-R diagram is a plot between absolute magnitude or luminosity (along y-axis) and temperature (along x-axis).

The H-R diagram contains quite a lot of information about stars. Since the absolute magnitude or luminosity refers to the intrinsic brightness of a star, H-R diagram relates the intrinsic brightness of a star with its temperature. Moreover, the H-R diagram separates the effects of temperature and surface area on the luminosity of the stars because the brightness of two stars at the same temperature is proportional to their radii. This feature enables us to classify stars in terms of their diameters.

Further, you must remember that the location of a star on the H-R diagram is in no way related to its location in space: a star located near the bottom of the diagram simply means that its luminosity is low and similarly, a star in the right indicates that its temperature is low (because the temperature decreases away from the origin) and so on. Another interesting feature of the H-R diagram is that the position of a star on *it changes with time*. This implies that the star's luminosity and temperature change with its age. Again, this change in position of a star has nothing to do with the star's actual motion.

The stars have been divided into different types/groups on the basis of their location on the H-R diagram. In Fig. 7.12, you may note that the distribution of stars follows a pattern such that a majority of stars fall along a central diagonal called the **main sequence**. The main sequence stars account for nearly 90 per cent of all stars. The other types of stars such as *giants*, *supergiants*, *white dwarfs* populate other regions. The **giant stars** (named so because of their big size) located at the top right of the H-R diagram have low temperature but high luminosity.

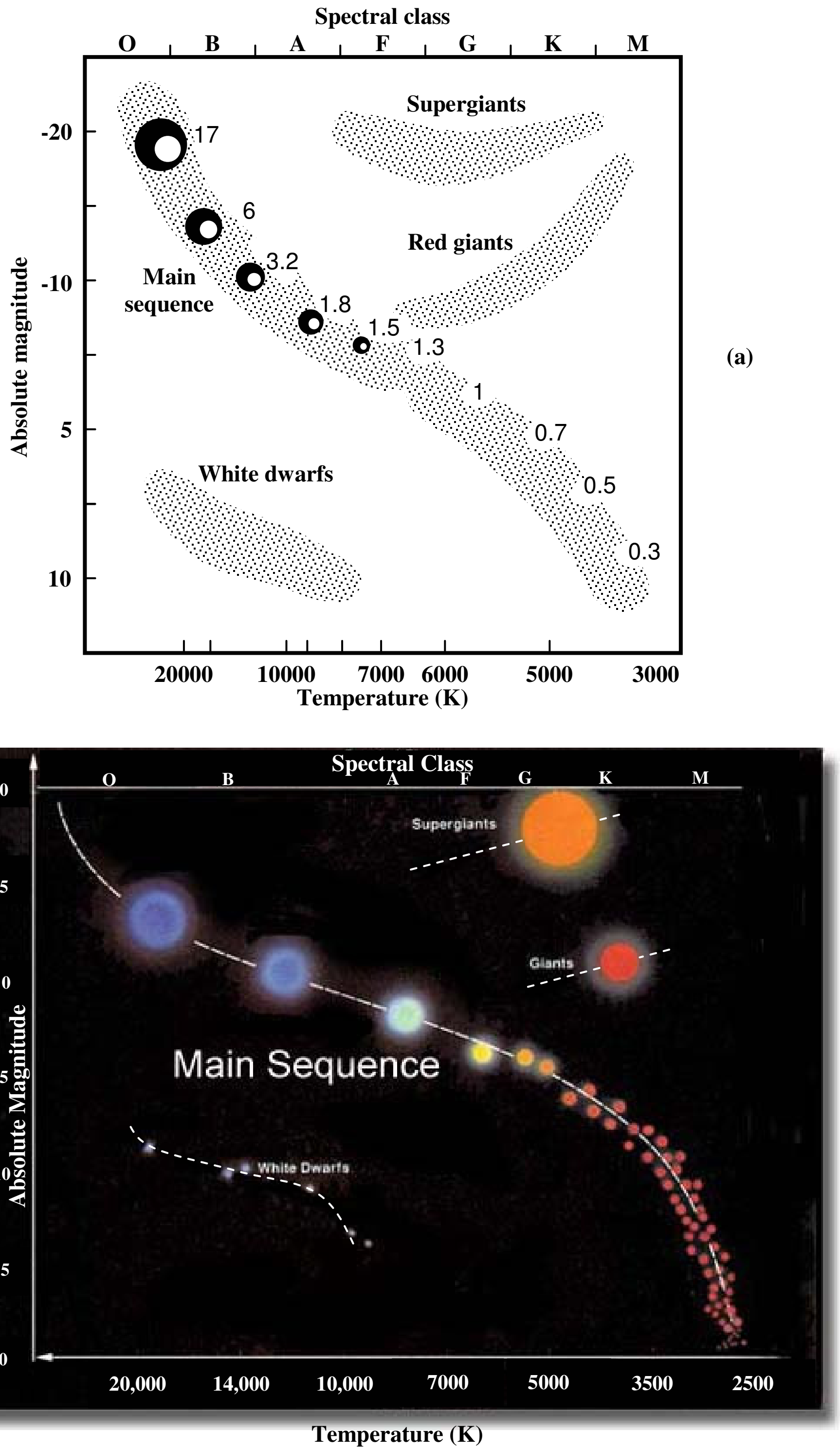


Fig.7.12: a) A schematic H-R diagram (Note that on the main sequence, masses of the stars are indicated in units of solar mass.); and b) magnified version of the H-R diagram

When we move further up in the H-R diagram (Fig. 7.12), we find **super giants**. These high luminosity and low temperature stars must be extraordinarily big in size. It has been estimated that the *diameters of super giants are roughly 100 to 1000 times the diameter of the Sun*! Further, when we come to the bottom left (below the main sequence), we come across stars known as **white dwarfs** — stars which are very hot but their luminosity is very low. Obviously, white dwarf stars must be very small in size compared to the Sun to have such low luminosities.

Example 2

A bright star in Orion constellation, Betelgeuse, has a surface temperature of 3500K and is 10^5 times more luminous than the Sun. Calculate its radius in terms of R_Θ, the radius of the Sun. What kind of star could it be on the basis of the H-R diagram?

Solution

We have

$$T_B = 3500\text{K}; \quad T_\Theta = 5800\text{K}; \quad \frac{L_B}{L_\Theta} = 10^5$$

From Eq. (7.5), we have

$$\frac{L_B}{L_\Theta} = \frac{R_B^2 T_B^4}{R_\Theta^2 T_\Theta^4}$$

or,

$$10^5 = [3500/5800]^4 (R_B/R_\Theta)^2$$

or,

$$R_B \approx 1000 R_\Theta$$

The luminosity and surface area of Betelgeuse is much higher than the Sun whereas its temperature is lower than the Sun. These characteristics, as per the H-R diagram, indicate that Betelgeuse is a super giant.

To fix the ideas expressed above, you should answer the following SAQ.

SAQ 3

Spend 8 min.

a) Suppose that the surface temperature of two stars *A* and *B* is the same and the luminosity of *A* is higher than *B*. Which of the two stars is bigger in size? Why?

b) Choose a typical giant star in Fig. 7.12 and estimate its radius.

Although the basic H-R diagram depicts stars in terms of their temperatures and absolute magnitudes, we can have its many other representations as well depending upon the extent of information we wish to incorporate in it. Fig. 7.13 shows a composite H-R diagram incorporating several parameters such as luminosity, absolute magnitude, temperature, and spectral type.

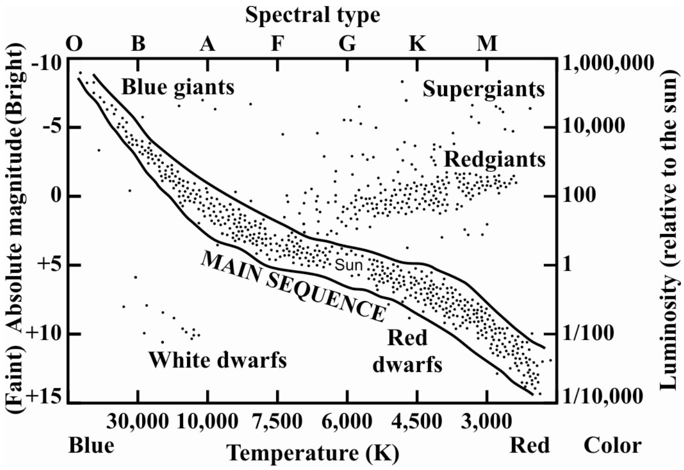


Fig.7.13: A composite H-R diagram showing various parameters of the stars

Spend 5min.

SAQ 4

a) In which part of the main sequence are the less massive stars located?

b) A main sequence star has a luminosity of 400 L_{Θ}. What is its spectral type?

Thus, on the basis of above discussion, you will agree that the H-R diagram provides information about the following parameters of stars:

a) size
b) luminosity
c) mass
d) spectral type, and
e) absolute magnitude

It is because of this reason that the H-R diagram is so important in astronomy. So far, you have studied about stellar spectra and classification of stars on the basis of their temperature. You have also learnt that, on the basis of H-R diagram, one can get an idea about the size of a star. However, to get a better idea about the size of a star, we can use the correlation between the sharpness of spectral lines and luminosity. This gives rise to luminosity classification. You will learn about it now.

7.5 LUMINOSITY CLASSIFICATION

We have discussed earlier in this unit that the luminosity of a star predominantly depends on its size: the bigger the star is, the higher is the value of its luminosity. Detailed study of the stellar spectra helps in ascertaining the density and size of a star which give a fairly good idea of its luminosity. You may ask: **Which features of the stellar spectra provide such information?** Recall that the spectrum of an isolated atom differs from that of the gas of such atoms. The difference is manifested in the form of broadening of spectral lines of the atom in the latter case due to collision between atoms.

The next logical question is: **Under what conditions can collisions readily take place?** For frequent collisions, a denser gas provides a better environment than a rarer gas. Therefore, if the spectral lines in stellar spectra are broadened, we can safely conclude that the density of the star is high. Examples of such stars are the main sequence stars. On the other hand, giant stars have very low densities. As a result, their spectral lines are fairly narrow compared to the main sequence stars.

Thus, sharp lines in the stellar spectra clearly indicate that the size of the star is large and hence its luminosity is high. The converse is also true. Thus, looking at the width of spectral (absorption) lines, we can obtain a fairly good idea about its luminosity.

As such, stars have more or less continuous range of luminosities. Still, on the basis of the width of their spectral lines, they are categorized into various **luminosity classes**. Table 7.2 gives the various luminosity classes denoted by Roman numerals I to V with the supergiants further subdivided into classes Ia and Ib.

Table 7.2: Luminosity classes

Ia	Bright supergiant
Ib	Supergiant
II	Bright giant
III	Giant
IV	Subgiant
V	Main-sequence star

The star Rigel (β Orionis) is a bright supergiant (class Ia) and Polaris, the North star is a regular supergiant (class Ib).The star *Adhara* (ε Canis Majoris) is a bright giant (Class II); Capella (α Aurigae) is a Giant (III) and Altair (α Aquilae) is a subgiant (IV). The Sun is a main-sequence star (V). *Thus, the complete spectral classification for the Sun is* G2V. This complete classification is also called the **spectro-luminosity classification**. The spectro-luminosity class of star Vega is A0V.

Refer to Fig. 7.14 which shows the position of luminosity classes on the H-R diagram. You must remember that the lines corresponding to each class is just an approximation; star of a particular class may lie just above or below the line corresponding to that class.

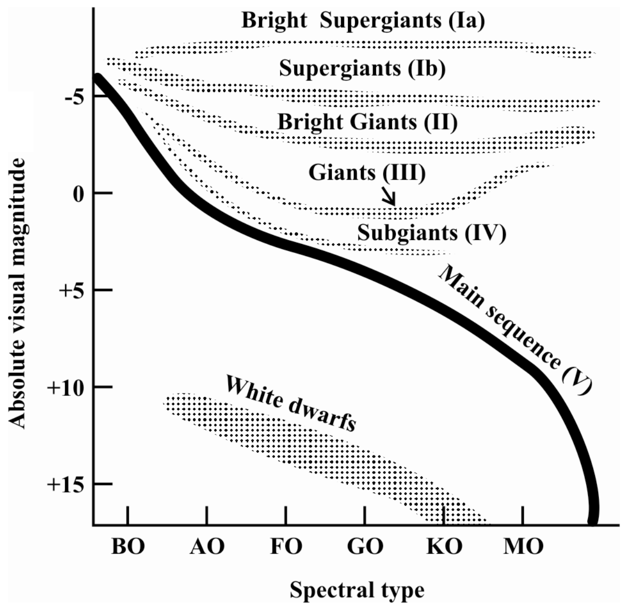


Fig.7.14: H-R diagram depicting the location of luminosity classes

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

7.6 SUMMARY

- **Emission** and **absorption** of radiation is caused due to transition of electrons in atoms between allowed energy levels. Analysis of stellar spectra provides information about the temperature and size of a star.
- On the basis of the strength of spectral lines, particularly Balmer lines, in stellar spectra, stars were classified into seven main **spectral types** namely O, B, A, F, G, K and M. It was shown by M N Saha that this classification essentially refers to the temperatures of stars.
- **H-R diagram** enables us to classify stars on the basis of their temperatures and luminosities.

- **Luminosity** of a star is defined as the total energy rediated by it in one second consisting of radiations of all wavelengths. The relation between luminosity, radius and temperature of a star is given by:

$$\frac{L}{L_\Theta} = \left(\frac{R}{R_\Theta}\right)^2 \left(\frac{T}{T_\Theta}\right)^4$$

- On the basis of H-R diagram, stars are grouped into four categories namely **main sequence, giants, super giants** and **white dwarfs**. Stars of each group have characteristic temperatures, sizes and luminosities.
- The density of a star affects the sharpness of its spectral lines. This fact is used for **luminosity classification** of stars.
- According to the luminosity classification, stars are classified into **five classes**: I, II, III, IV and V with class I further sub-divided into Ia and Ib.

7.7 TERMINAL QUESTIONS

Spend 25 *min.*

1. Assign spectral class to each of the objects whose characteristics are given below:
   a) Temperature ~ 40,000K
   b) Weak Balmer lines but moderately strong Ca lines
   c) Strongest hydrogen lines
   d) Molecular bands of T_iO
   e) Neutral helium lines

2. A star has luminosity ~ 100 L_Θ and apparent bolometric magnitude, $m_{star}^{bol} = 9.7$. If Sun has $M_\Theta^{bol} = +4.7$, calculate the distance of the star.

3. Calculate the radius of a star which has the same effective temperature as the Sun but luminosity 10,000 times larger.

4. In the following table, which star is a) the brightest; b) the most luminous; c) the largest; and d) the smallest?

Star	Spectro-luminosity type	m_v
1.	G2V	5
2.	B1V	8
3.	G2Ib	10
4.	M5III	19
5.	White Dwarf	15

7.8 SOLUTIONS AND ANSWERS

Self Assessment Questions (SAQs)

1. a) Spectra of different elements have different lines because their atomic energy levels are different.

   b) A continuous spectrum contains all wavelengths. We get such a spectrum when the density of a system is high, as in a solid.

2. From Eq. (7.2b), we know that

$$M_{bol} = M_v + \text{B.C.}$$

Substituting the values of M_v and B.C., we get, $M_{bol} = 8.7 - 0.5 = 8.2$

Further, from Eq. (7.3), we have:

$$\frac{L_{star}}{L_\Theta} = 10^{-4\left(M^{bol}_{star} - M^{bol}_\Theta\right)}$$

$$= 10^{-0.4(8.2-4.7)}$$

$$= \frac{1}{25}$$

Thus, we get, $L_{star} = \frac{L_\Theta}{25}$.

3. a) Since $L_A > L_B$, the surface area of A is greater than the surface area of B. So, A is bigger.

   b) In Fig. 7.12, we find that the temperature of a typical giant star can be taken as 5000 K. So, we can write for a typical giant, $T = 5000$ K. Further, the luminosity of a typical giant can be written as, $L = 100\ L_\Theta$

   Thus, using Eq. (7.5), we get:

$$\frac{L}{L_\Theta} = \left(\frac{R}{R_\Theta}\right)^2 \left(\frac{T}{T_\Theta}\right)^4$$

   or,

$$\left(\frac{R}{R_\Theta}\right)^2 = \frac{L}{L_\Theta}\left(\frac{T_\Theta}{T}\right)^4 = 100 \times (6/5)^4$$

   or,

$$R = 14.4\ R_\Theta .$$

4. a) Lower part of the main sequence.

   b) From Eq. (7.3), we have

$$M^{bol}_{star} - M^{bol}_\Theta = -\ 2.5\ \log\left(\frac{L_{star}}{L_\Theta}\right) = -2.5 \log 400 = -6.5$$

   Thus,

$$M^{bol}_{star} = -6.5 + 4.7 = -1.8$$

   If we look at the H.R. diagram to identify the class of the star having this value of absolute magnitude, we find that its class should be B7, approximately.

Terminal Questions

1. (a) O (b) G (c) A (d) M (e) B

2. We have from Eq. (7.3):

$$M^{bol}_{star} - M^{bol}_\Theta = -2.5 \log\left(\frac{L_{star}}{L_\Theta}\right)$$

or,

$$M^{bol}_{star} = 4.7 - 2.5\ \log(100) \quad = -\ 0.3$$

Further, we have:

$$m_{star}^{bol} - M_{star}^{bol} = 5\log\left(\frac{d}{10}\right)$$

$$9.7 - (-0.3) = 5\log\left(d/10\right)$$

or,

$$d = 1000\,\text{pc}.$$

3. From Eq. (7.5), we have:

$$L_1/L_2 = R_1^2 T_1^4 \Big/ R_2^2 T_2^4$$

or,

$$10^4 = R_1^2 T_1^4 \Big/ R_\Theta^2 T_1^4;$$

or,

$$R_1 = R_\Theta \sqrt{10^4} = 100 R_\Theta$$

4. [**Hint:** Use Fig. 7.12 to determine the absolute magnitudes.]

   The answers are: a) 1; b) 3; c) 3; d) 5.