26

DISPERSION AND SCATTERING OF LIGHT

26.1 INTRODUCTION

In the previous lesson you have learnt about some properties of light like reflection and refraction. You have also learnt about the total internal reflection, mirrors and lenses.When a narrow beam of sunlight or light from an electric bulb is seen through a prism we find colour bands. This phenomenon is different from reflection and refraction. The *splitting of white light or polychromatic light into its constituent colours or wavelengths by a medium like prism is called* ***dispersion.***

In this lesson we will study about it. A fine example of this in nature is rainbow. Dispersion produces colour bands on the screen. This is called ***spectrum***. The spectrum can be studied by an instrument called ***spectrometer.*** Some of the spectra are extremely useful in the study of the nature and internal constitutions of the source of light. We will also learn about the blue colour of sky through another phenomenon called ***scattering*** in this very lesson. This lesson also contains a brief description of two major defects in the image formation by mirrors and lenses.

26.2 OBJECTIVES

After studying this lesson, you should be able to,

- *explain the dispersion of light;*
- *derive relation between angle of deviation (δ), angle of prism (A) and the refractive index of the material of the prism (μ);*
- *relate refractive index and colour of light and explain dispersion through the prism;*
- *describe spectrum and classify spectra into various types;*
- *explain the spectra produced by matter in different states;*
- *explain Fraunhofer lines;*
- *describe the spectrometer and its uses;*
- *recognise the defects in images formed by mirrors and lenses and suggest methods to minimise them;*
- *explain scattering of light and its applications;*
- *explain the formation of primary and secondary rainbows; and*
- *eliminate the defects in image formation by the lenses and mirrors.*

26.3 DISPERSION OF LIGHT

Natural phenomena like rings around planets, HALO, and rainbow formation cannot be explained by straight line propagation of light which you have read in earlier lesson. To understand such phenomena and many other events, light is considered to be having wave nature. Huygen dealt with the wave nature of light about which you will read in next lesson. As you know the light waves are electromagnetic transverse waves whose speed is same for all colours i.e 3×10^8 ms^{-1} in vacuum. Out of the long range of electromagnetic waves, visible light forms a small part. Even a small object will cast shadows and light appears travelling in straight lines. White sun light consists of seven prominent wave lengths corresponding to each colour. Thus, colours may be identified with their wave lengths. You have already learnt *that the speed and wavelength of waves changes when they go from one medium into another.* The speed of light waves and also their wavelengths change with the change in the medium. The speed of a wave having certain wavelength becomes less than its speed in free space when it enters an optically denser medium.

Refractive index μ has been defined as the ratio of speed of light in vacuum to the speed of light in the medium. It is but natural that the refractive index of a given medium will be different for waves having wavelengths 3.8×10^{-7} m and 5.8×10^{-7} m because these waves travel with different speeds in the same medium. This ***variation in the refractive index of a material with wavelength is known as dispersion.*** This phenomenon is different from refraction. In free space and even in air, the speeds of all waves of the visible light are the same so, they are not separated. Such a medium is called non dispersive medium. But in an optically denser medium the component wavelengths (colours) travel with different speeds and are thus separated. The medium is called *dispersive medium.*

26.3.1 Dispersion Through a Prism

The separation of colours by medium is not a sufficient condition to see dispersion of light, unless these are widely separated and are not allowed to mix up again after emerging from the dispersing medium. A glass slab (Fig 26.1) is unsuitable to show dispersion. The emergent waves are very close and parallel to the incident beam.

Newton used a prism to show dispersion of light. When a narrow beam of white light from a slit falls on the face AB of the prism, the emergent light from face AC is split into coloured beams. Coloured patches seen on the screen (Fig. 26.2) shows dispersion of light. Face AC increases the separation between the rays refracted at face AB. The incident white light PQ is split into its component seven colours. Each wavelength travelling with different speeds, is refracted through different angles and are thus separated. This splitting of white light is known as dispersion. The bending of rays is

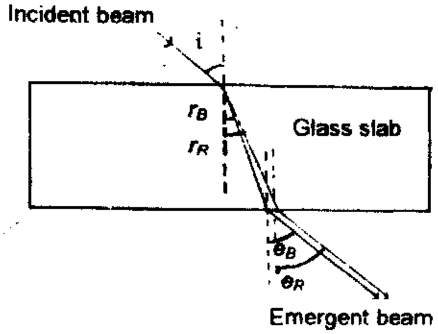


Fig. 26.1 : *Passage of light through a glass slab*

increased. MR and LV show the extreme coloured rays of red and violet light respectively. Violet, indigo, blue, green, yellow, orange and red colours are seen on the screen in this order. These colours on the screen make the *spectrum.*

The bending of original common beam PQN along MR, LV etc. is known as **deviation**. The angle between the emergent ray and the incident ray is known as angle of deviation. Thus δ_v represent the angle of deviation for violet light and δ_r for red light. The prism helps us in viewing the dispersion of light.

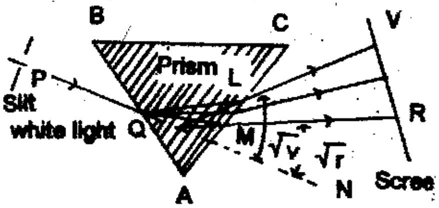


Fig. 26.2: *Dispersion of light by a prism.*

The following example shows variations of refractive index with the wavelength of light.

Example 26.1: *A beam of light of average wavelength 600 nm on entering a glass prism is divided into three coloured beams of wavelengths 384 nm, 589 nm and 760 nm respectively. Determine the refractive indices of the material of the prism for these wavelengths.*

Solution : The refractive index of the material of the prism is given

by $\mu = \frac{c}{\upsilon}$ where c = speed of light in vacuum, and

υ = speed of light in the medium (prism)

Now velocity of wave = frequency × wavelength

Hence, $c = \nu\lambda_a$ and $\upsilon = \nu\lambda_m$

where λ_a and λ_m are wavelengths in air and medium respectively and υ is the frequency of the light wave.

Thus, $\mu = \frac{\nu\lambda_a}{\nu\lambda_m} = \frac{\lambda_a}{\lambda_m}$

For wavelength 384 nm, the refractive index is

$$\mu_1 = \frac{600 \times 10^{-9}\,\text{m}}{384 \times 10^{-9}\,\text{m}} = 1.56$$

For wave length 589 nm

$$\mu_2 = \frac{600 \times 10^{-9}\,\text{m}}{58.9 \times 10^{-9}\,\text{m}} = 1.02$$

and for wavelength 760 nm

$$\mu_3 = \frac{600 \times 10^{-9}\,\text{m}}{760 \times 10^{-9}\,\text{m}} = 0.8$$

Note: The wavelength of light is measured in the following units

(a) in metres in powers of 10(eg. 3.8×10^{-7}m)

(b) in angstrom units (Å), 1 Å = 10^{-10} m

(c) in nanometers (nm) eg. 600 nm = 6000 Å

1 nm = 10^{-9} m

We have seen that the refractive index of a material depends on

(i) *the nature of the material, and*

(ii) *the wavelength of the light.*

An interesting outcome of the above example is that the variation in wavelength ($\Delta\lambda = \lambda_2 - \lambda_1$) causes variation in the refractive index ($\Delta\mu = \mu_2 - \mu_1$). The ratio $\frac{\Delta\mu}{\Delta\lambda}$ is known as the *dispersive power* of the prism material.

(a) Angle of Deviation and Angle of Incidence

We would like to find a relation between angle of incidence i, angle of deviations δ and the angle of prism A. Let a monochromatic beam of light PQ be incident on face AB of the principal section of the prism ABC. On refraction it goes along QR inside the prism and emerges along RS from face AC. Let $\angle A \equiv \angle BAC$ be the refracting angle of the prism, $\angle NQP = \angle i$, $\angle N'RS = \angle e$, $\angle RQO = \angle r_1$, and $\angle QRO = \angle r_2$ be the angle of incidence, angle of emergence and angles of refraction at faces AB and AC respectively (See Fig 26.3). The angle between emergent ray RS and the incident ray PQ at D is known as the angle of deviation (δ). NQ and M'R extended meet at O.

Angle MDR = $\angle\delta$ is the external angle of triangle QDR so that

$$\angle\delta = \angle DQR + \angle DRQ = (\angle i - \angle r_1) + (\angle e - \angle r_2)$$

or $$\angle\delta = (\angle i + \angle e) - (\angle r_1 + \angle r_2) \qquad ......(26.1)$$

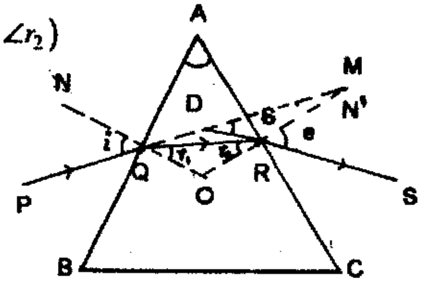


Fig. 26.3: *Refraction through a prism*

The sum of the internal angles of a quadrilateral is four right angles and in quadrilateral AQOR, $\angle AQO = \angle ARO = 90^0$, so

$$\angle QAR + \angle QOR = 180^0 \qquad ......(26.2)$$

But in Δ QOR

$$\angle QOR + \angle OQR + \angle QRO = 180^0$$

or $$\angle r_1 + \angle r_2 + \angle QOR = 180^0 \qquad .....(26.3)$$

Comparing equations (26.2) and (26.3) we have

$$\angle r_1 + \angle r_2 = \angle A \qquad \text{.....(26.4)}$$

Substituting for r_1 and r_2 from eq.(26.4) in eq.(26.1) we have

$$\angle\delta = (\angle i + \angle e) - \angle A$$

or

$$\angle i + \angle e = \angle A + \angle\delta \qquad \text{......(26.5)}$$

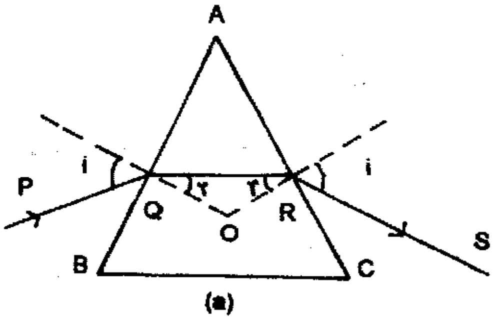


Fig. 26.4(a): *In minimum deviation* $\angle r_1 = \angle r_2 = \angle r$ *and* $\angle i = \angle e = \angle i$

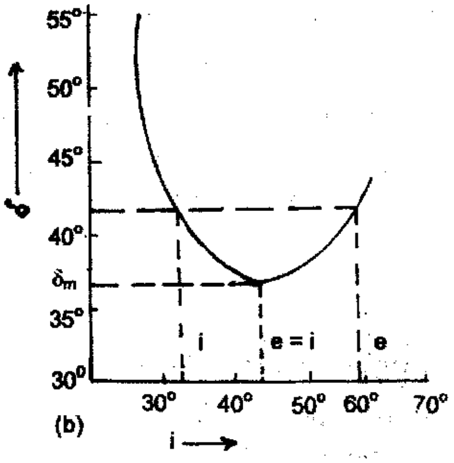


Fig.26.4(b): *Curve between* angle of incidence i and angle of deviation δ,

(b) Angle Of Minimum Deviation

Let us vary the angle of incident ray from 30^0. As i is increased, the angle of deviation δ decreases, becomes minimum for a certain value of i and again starts increasing as i is increased (Fig. 26.4(b)). The minimum value of angle of deviation is called angle of minimum *deviation* (δ_m). It depends on the material of the prism and the wavelength of light used. In fact corresponding to an angle of deviation there are two values of angles of incidence. Using the principle of reversibility of light we find the second angle of incident corresponds to the angle of emergence (e). In the minimum deviation position there is only one value of angle of incidence so that

$$\angle e = \angle i$$

using this fact in eq.(26.5) and replacing δ by δ_m we have

$$\angle i = \frac{\angle A + \angle\delta_m}{2} \qquad \text{......(26.6)}$$

The same fact also gives

$$\angle r_1 = \angle r_2 = \angle r$$

which on substitution in eq. (24.4) yields

$$\angle r = \frac{\angle A}{2} \qquad \text{......(26.7)}$$

The light beam inside the prism becomes parallel to the base (Fig 26.4(a)) The refractive index of the material of the prism is now given by

$$\mu = \frac{\sin i}{\sin r} = \frac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin\frac{A}{2}} \qquad (26.8)$$

μ can be found by eq(26.8) using a monochromatic or a polychromatic beam of light.The value of δ_m is different for different colours. It gives a unique value of the angle of incidence and the emergent beam is brightest for this incidence.

For a small angled prism keeping i and r small, we can write

$$\sin i = i,\ \sin r = r, \text{ and } \sin e = e \text{ etc.}$$

consequently,

$$\mu = \frac{\sin i}{\sin r_1} = \frac{i}{r_1} \quad \text{or} \quad i = \mu r_1$$

Also $$\mu = \frac{\sin e}{\sin r_2} = \frac{e}{r_2} \quad \text{or} \quad e = \mu r_2$$

Therefore,

$$\angle i + \angle e = \mu\,(\angle r_1 + \angle r_2)$$

using eqs (26.4) and (26.5) we have

$$\mu A = A + \delta \quad \text{or} \quad \boxed{\delta = (\mu - 1)A} \qquad (26.9)$$

We have seen that μ depends on the wavelength or colour of light so does δ as is evident from eq(26.9). That is why δ_v is different from δ_r. Since velocity of red ray is more than the velocity of violet ray in glass, red is deviated less than violet .

Therefore, $\delta_v > \delta_r$.

From eq.(26.9) we find $\mu_v > \mu_r$.

The change in refractive index of the material with wavelength of light, thus, explains the dispersion.

26.4.2 Angular Dispersion and Dispersive Power

The difference between the angles of deviation for any pair of wavelengths (colours) is known as *angular dispersion* i.e. angular dispersion for violet-red pair = $\delta_v - \delta_r$

The angular dispersion for blue- red pair of rays is

$(\delta_b - \delta_r)$.

In the visible part of the spectrum, the wavelength of yellow colour is nearly the average wavelength of the spectrum. The deviation for this colour is say δ_y.

Now the ***ratio of the angular dispersion to the mean deviation is known as the dispersive power*** (ω) of the material of the prism. Therefore,

$$\omega = \frac{\delta_v - \delta_r}{\delta_y}$$

By using eq. (26.9) we find

$$\omega = \frac{(\mu_v - 1)A - (\mu_r - 1)A}{(\mu_y - 1)A}$$

or $$\boxed{\omega = \frac{\mu_v - \mu_r}{\mu_y - 1}} = \frac{\Delta\mu}{\mu - 1} \qquad (26.10)$$

Example 26.2 : *The refracting angle of a prism is 30′ and the refractive index 1.6. Estimate the deviation caused by the prism.*

Solution: Since, $\delta = (\mu - 1)\ A$

$$\delta = (1.6 - 1) \times \frac{1^\circ}{2} = \frac{0.6}{2} = 0.3^\circ = 18'$$

Example 26.3: *The refractive index of water for colour A is 1.40 and for another colour B it is 1.32. Find the dispersive power of water.*

Solution : $\mu_A = 1.40, \quad \mu_B = 1.32$

So the average refractive index, $\mu = \dfrac{\mu_A + \mu_B}{2}$

or $$\mu = \frac{1.40 + 1.32}{2} = 1.36$$

Now $$\omega = \frac{\mu_A - \mu_B}{\mu - 1} = \frac{1.40 - 1.32}{1.36 - 1} = \frac{0.08}{0.36}$$

So $\omega = 0.22$

INTEXT QUESTIONS 26.1

1. *How can dispersion be shown in graphite or carbon?*

   ....

2. Most ordinary gases do not show dispersion withe visible light, why?

   ....

3. *With your knowledge about the relative values of μ for the component colours of white light, state which out of red or violet is deviated more from their original direction?*

   ....

4. *Does dispersion depend on the (a) size and (b) angle of the prism?*

   ....

5. *Find the angular dispersion produced by a thin prism of angle 4°; its* refractive indices for red and violet light are 1.56 and 1.68 respectively *Also calculate the dispersive power of the material of the prism.*

   ....

6. *Name the media whose dispersive powers are (a) $\omega = 0$, (b) $\omega \approx 0$ and (c) $\omega > 0$. Can ω have* a negative value?

....

7. *A prism produces both dispersion and deviation. Can you suggest some means so that one can get (a) dispersion but no deviation and (b) deviation without dispersion?*

....

26.5 SPECTROMETER AND ITS USES

Spectrometer is a versatile instrument used in the study of dispersion of light and spectra. It has helped in knowing not only the structure of molecules and atoms but also the atmosphere and tempreature of the planets and stars. It is used to obtain pure spectrum in the laboratory. You have read in Bohr's theory that excited atoms emit light containing several wavelengths. Similarly when light is incident on a substance the atoms may absorb it and the electrons may change their orbits. The spectrometer is a device to find the absorption or emission of the light waves which are characteristic of the atom. So, it is a device used to analyse the spectrum.

26.5.1 Impure and Pure Spectra

Spectrum, in simple words may be defined as follows:

A ray of white light entering a glass prism is split up or dispersed into its component wavelengths red, orange, yellow, green, blue, indigo and violet. The colours are collectively, taken on screen, called the **spectrum** *of white light. Any polychromatic beam has its own spectrum.*

If the boundaries of the colours overlap and are not clear the spectrum is called an *impure spectrum* as shown in Fig. (26.5(a)). On the other hand if the colours are distinctly separate on the screen the spectrum is known as *pure spectrum* (Fig. 26.5(b). A pure spectrum cannot be modified by a second prism.

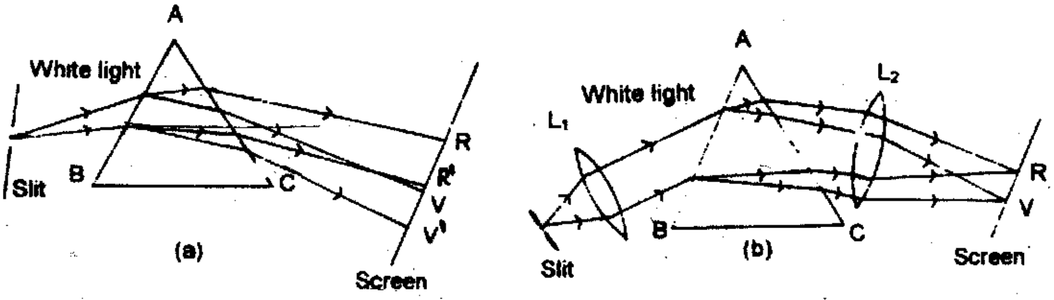


Fig. 26.5: *(a) Overlapping of colours in the region R' V shows an impure spectrum. (b) Each colour is distinctly separate, gives a pure spectrum.*

26.5.2 Spectrometer

This instrument consists essentially of three components

(a) a *collimator* to render a parallel beam of polychromatic light ,

(b) a *prism table* on which prism is placed to disperse light and produce spectrum, and

(c) a *telescope* to receive and focus parallel beam of light (see figure 26.6).

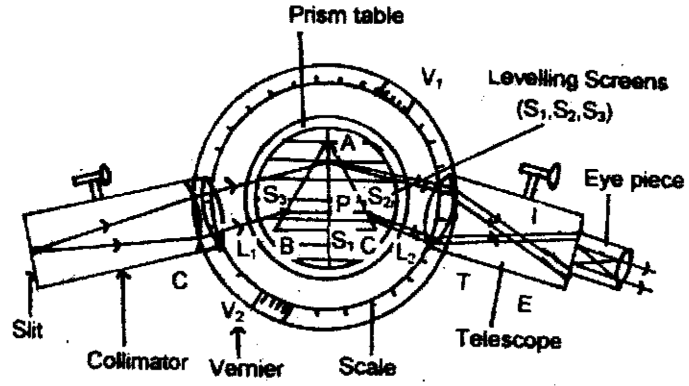
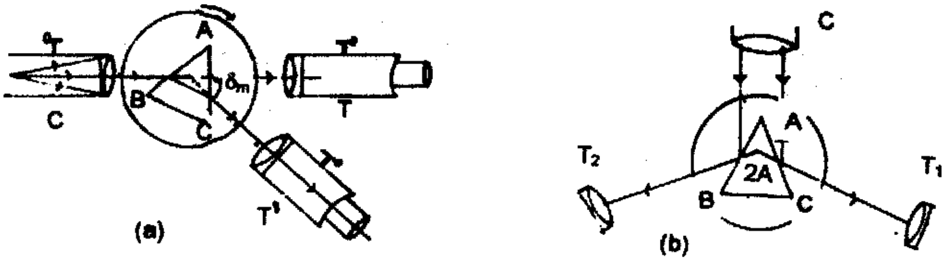


Fig. 26.6: *A spectrometer*

All the three components are mounted on a heavy metal base fitted with levelling screws and a circular scale moves concentric with the prism table. The circular scale moves with the movement of the telescope. A vernier scale moves with the movement of prism table on the circular scale. The horizontal axis of the collimator, horizontal axis of the telescope and the vertical axis of the prism table intersect at a single point. In a normal adjustment of the spectrometer this point lies at the centre of the prism One end of the collimator carries an adjustable slit and the other a lens such that the slit may be kept at the focus of the lens with the help of adjusting screw. The prism table has three levelling screws. It also has concentric circles and straight lines parallel to the line joining two screws.The eyepiece (E) of the telescope may be adjusted with an adjusting screw to receive parallel rays (Fig. 26.7 (a), (b)) clamping and fine motion screws are provided with the prism table and telescope in the base of the instrument. Heavy base provides stability to the apparatus. It is levelled with the levelling screws and spirit level. An intense monochromatic or polychromatic beam of light is used to illuminate the slit.



(a) (b)

Fig. 26.7 : *Line diagram of spectrometer determination of (a)minimum angle of deviation, (b) angle of prism.*

26.5.3 Use Of Prism Spectrometer

The prism spectrometer is used for several types of measurements. It is used to produce pure spectrum, determine refractive index of the material of the prism, find resolving power and to study the phenomenon of diffraction.

(a) Production of Pure Spectrum: The polychromatic beam of light used to illuminate the slit is rendered parallel by collimator lens L_1. This parallel beam is dispersed by the prism placed on optically levelled prism table with its centre coinciding with the centre of the prism table. The dispersed parallel beam is received by an adjusted telescope by directing it towards the second face AC of the prism (Fig. 26.7(a)) and pure spectrum can be seen through the telescope eyepiece.

(b)Determination of Refractive Index: The refractive index of the material of a prism (solid or hollow) may be determined for a given colour or monochromatic beam of light by measuring the angle of minimum deviation (δ_m) for the given light and the angle of prism using the spectrometer.

The angle of prism is determined by placing the edge A of the prism coinciding with the centre of the prism table. The base (BC) of the prism is now perpendicular to the incident light from the collimator (Fig.26.7(b)). The light is incident on both faces AB and AC of the prism. The reflected images of the slit from the two faces are taken on the cross-wire of the telescope in positions T_1 and T_2. The angle between T_1 and T_2 position gives 2A. It can be proved geometrically that this angle between the reflected rays from AB and AC is twice the angle of the prism A.

Then by putting the values of A and δ_m so using eq.(26.8) we can find the refractive index of the material of the prism as

$$\mu = \frac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin(A/2)} \qquad \text{......(26.8)}$$

Example 26.4 : *For a prism of angle A, the minimum angle of deviation is A/2. Find its refractive index. when monochromatic light is used. Given A= 60⁰.*

Solution : The refractive index is given by $\mu = \dfrac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin(A/2)}$

Now $\delta_m = A/2$ so that

$$\mu = \frac{\sin\left(\frac{A+A/2}{2}\right)}{\sin(A/2)} = \frac{\sin\left(\frac{3}{4}A\right)}{\sin(A/2)} = \frac{\sin\left(\frac{3}{4}\times 60\right)}{\sin\left(\frac{60}{2}\right)} = \sqrt{2} = 1.4$$

INTEXT QUESTIONS 26.2

1. *Calculate the refractive index of an equilateral prism if the angle of minimum deviation is equal to the angle of the prism.*

   ....

2. *Using following data determine the angle of incidence i for an angle of prism= A, e = 90° and refractive index = μ.*

   ....

3. *Why should the slit be narrow in the spectrometer?*

   ....

4. *Can you study the spectrum with a spectrometer without coinciding the centre of the prism table and the centre of the prism?*

   ....

5. *Why a dense glass (flint glass) prism is used with a spectrometer?*

   ....

6. *Distinguish between an impure and a pure spectrum.*

   ....

7. *A 60° prism is placed in minimum deviation position on a spectrometer. If angle of incidence is 50°, find angle of deviation.*

   ....

26.6 TYPES OF SPECTRA

We have gone through the definition of spectra earlier which may be stated as the cumulative band of colours received on a screen after dispersion of a polychromatic beam of light. An examination of the spectra produced by different sources such as red and white hot iron, a candle flame, a gas or carbon arc, a light bulb and sodium and mercury vapour lamps, reveal that the spectra are not similar in nature and colour distribution. The spectra are produced either by emission of light from a hot source or by absorption of light by a relatively cooler substance when light from hot source passes through it.

The spectra are thus classified as *emission* and ***absorption*** spectra. Each one of them are further classified into (a) continuous, (b) band and (c) line spectrum, according to their appearance.. A brief description of the types of spectra is given below.

26.6.1 Emission Spectra

Hot incandescent substances give emission spectra which are characteristic of the emitter. Same substances under varying physical conditions give a different spectrum which, in turn, reveals, different characteristics of the substance. Even though some lines may be common yet no two spectra are alike. For example, sodium on bunsen flame and sodium spark produce different spectra.

The emission spectra are of three types as stated below.

(a) Continuous Spectrum: A continuous emission spectrum contains all wavelengths from one end to the other without any perceptible demarcation from one colour to another (Fig.26.8(a). These are produced by hot incandescent matter in bulk such as white hot iron, carbon arc, bunsen flame, electric bulb and tube light. Hot dense mass of gas also gives it. These spectra are temperature dependent and give no specific charater of the emitter.

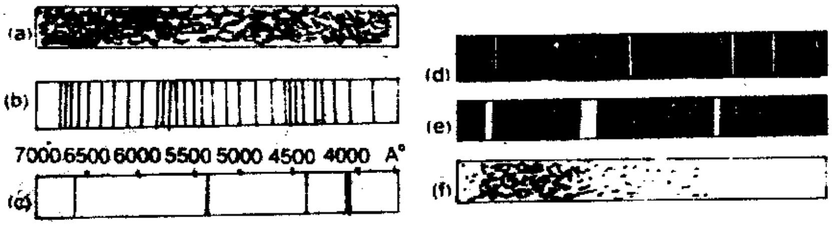


Fig. 26.8: Illustrative emission spectra (a) (b), (c), and absorption spectra (d), (e), (f).

(b) Band or Molecular Spectrum: Such a spectrum is produced by substances in molecular state. Here bands of colours intense on one edge and fading at the other end are obtained (Fig. 26.8b)). Eah band is distinct from the other. A close look reveals that at one end lines of the colour are closely packed making this end more bright. Chemical compounds in vapourous form such as CO_2, HCL, O_2, CO, AlO, N_2 give molecular spectra provided these are not heated too much.

(c) Line or Atomic Spectra: As the name suggests these spectra are emitted by substances in atomic state. For example sodium and mercury discharge lamps produce line spectrum. Characteristic isolated bright lines are observed in the spectrum. Each line corresponds to a specific wavelength and is chracteristic of the emitter (Fig. 26.8 (c)). These spectra are immensely useful in identification of elements in mixture and in the atmosphere of stars.

26.6.2 Absorption Spectra

Let us conduct an experiement with sodium vapours. With hot vapour, the spectrometer shows a bright line spectrum at wavelength positions 5890Å and 5896 Å. But, when light from a hot carbon arc passes through relatively cooler sodium vapours interposed between the arc and the spectrometer we get two dark lines exactly at the same postion (Fig. 26.9) where two yellow lines were seen in the emission spectrum. The two lines thus obtained are the absorption line spectrum of sodium produced by selective absorption. The phenomenon in this case is called reversal of sodium lines.

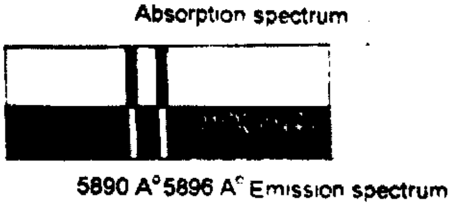


Fig. 26.9: Absorption and emission spectra of Na

Absorption spectrum, as pointed out earlier, is produced either by selective or whole absorption of white light from a source at a higher temperature by the substance at lower temperature. In addition to line absorption spectrum as discussed above and shown in Fig. 26.8 (d) [compare it with Fig. 26.8(c)] we also have absorption band spectra (Fig. 26.8(e)] and continuous or whole absorption spectra (Fig. 26.8 (f)). Light passing through lamp black is wholly absorbed and gives rise to the last type of spectra. Line and band absorption spectra are characteristic of absorber. Cobalt glass, potassium salt, aniline dye etc. give absorption band spectra whereas lamp black, blue glass etc. produce continuous absorption spectrum. The absorption spectra is widely used in chemical analysis.

26.6.3 Fraunhofer Lines

The Absorption spectra are explained by **Kirchoff's law** which states *"A substance, which gives out waves of definite frequencies when heated to incandescence, will selectively absorb waves of the same frequencies (colours) when cold and light from a source at the lighter temperature is made to pass through it."* Sun being the hottest source of light, it is but natural that one expects absorption spectra when the sunlight passes through its atmosphere which is relatively cooler (see Fig. 26.10). Fraunhofer, while studying the spectrum of the chromosphere of the Sun during total solar eclipse in 1814, found many dark lines in it. He measured the positions of 324 lines out of 600 counted by him. By comparing the positions of these lines with the emission spectra of elements on the Earth, he was able to identiy 60 of these lines. The more prominent out of them were named by him in alphabets (Table 26.1). A new element called helium (after helius i.e. Sun) was discovered in solar atmosphere corresponding to a prominent absorption line. Major absorption of visible light takes place in the chromosphere which contains large number of elements in atomic state.

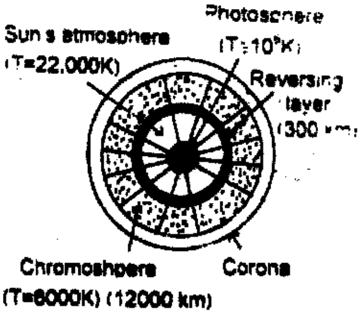


Fig. 26.10: *Various temperature layers of the sun*

Table 26.1

Wave length (Å)	*Line*	*Element*
7594	A	Atmospheric O_2
6867	B	At. Oxygen
6563	C	Hydrogen
5859	D_1	Sodium
5890	D_2	Sodium
4861	F	Hydrogen
4341	G_1	Hydrogen
3969	H	Calcium

INTEXT QUESTIONS 26.3

1. *Identify the type of spectra produced by following sources*
   (i) Hydrogen , (ii) candle flame , (iii) electric bulb and (iv) mercury lamp.

   ....

2. *Which law explains the absorption spectra?*

   ....

3. *After passing through a blue filter what will be the colour of yellow light?*

   ....

4. *What type of spectrum is produced by a window glass when Sun light passes through it.*

   ....

5. *What are Fraunhofer lines? Give their importance.*

   ....

6. *Can you get different types of spectra with the same substance?*

   ....

26.7 SCATTERING OF LIGHT IN THE ATMOSPHERE

After the day break in the morning light reaches in our rooms even if no direct sunlight is coming inside the room; every thing becomes visible. During the clean day when we look towards the sky it appears blue, but clouds appear white why? Many other natural phenomenon (such as production of brilliant colours when sunlight passes through jewels and crystals) always attract our attention We want to know how it happens. The events cited above are explained with the help of phenomenon of *scattering of light*. A solution of dust or particle free benzene exposed to sunlight gives brilliant blue colour when looked sideway.

26.7.1 Scattering of Light

This phenomenon involves interaction of radiation with matter. Tiny particles are present in the Earth's atmosphere like dust particles or carbon particles. When sunlight is incident on them it is diffused in all directions. by these particles. This is why the light reaches even those positions and corners where normally it does not come directly from the source.

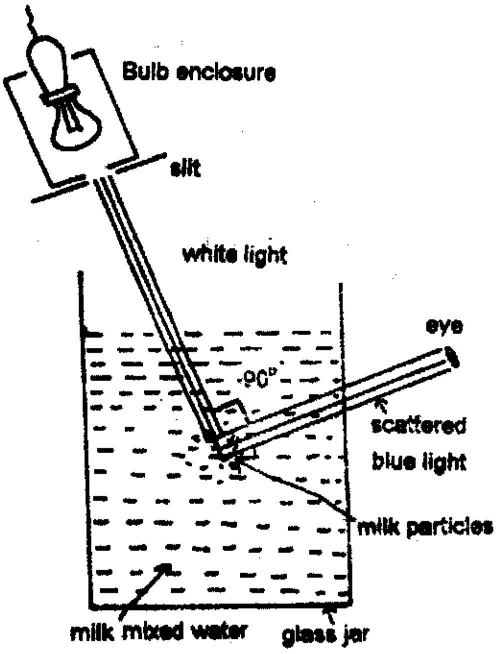


Fig. 26.11: *Scattering of light from milk particles.*

We do a small experiment in our home. Take glass jar or a trough, fill it with water and add very quantity of milk in it. Now allow a narrow beam of light from a milky bulk to fall on it. Observe the light at 90°, you see bluish beam through the water. This experiment shows that after scattering the wavelength of light is peculiar in a given direction (Fig. 26.11)

The phenomenon of scattering involves first obsorption of light by the particle and instantly re-emission in all possible direction. Thus, this phenomenon is different from reflection. The scattered light does not obey the laws of reflection. It is important to note that the size of the particle must be less than the wavelength of light incident on it. A bigger size of the particle will scatter all wavelengths equally. The intensity of scattered light is given by *Rayleigh law* of scattering. According to this law ***the intensity of scattered light is inversely proportional to the fourth power of the wavelength.*** Thus, out of white light incident on the scattering partile blue is scattered most and red the least.

$$I \alpha \frac{1}{\lambda^4}$$

Here, I is the intensity and λ the wavelength of the light scattered

Example 26.5 : *Waves of wavelength 3934Å, 5890Å and 6867Å are found in the scattered beam when sunlight is incident on a thin layer of chimeny smoke. Which one of these is scattered most intensely.*

Solution : The intensity of scattered light is given by

$$I \alpha \frac{1}{\lambda^4}$$

Since 3934Å is the smallest wavelength, hence it is scattered most intensely.

26.7.2 Blue Colour of Sky

With the knowledge of scattering as described in the previous section we can now understand why the sky appears blue. The air molecules, water droplets and dust particles scatter the sunlight in according with the Rayleighs law. The shorter wavelengths are scattered more than the longer wavelengths. Thus, blue light is scattered 16 times more intensely than the red as the wavelength of blue is half that of the red. The scattered light becomes rich in the shortest wavelength of violet, blue and green colours. On further scattering the violet does not reach observes eye as the eye is much less sensitive to violet than for blue and wavelengths in the neighbourhood or blue get scattered most intensely. So when we look in the sky far away from the sun it appears blue. Practically most of yellow light is scattered away.

Example 26.6 : *What will be the colour of sky for a passenger in a space craft flying at high attitude.*

Solution: At high attitude, in the absence of particles like dust and air molecules, the sunlight is not scattered so, sky appears black.

26.7.3 White colour of Clouds

The clouds are formed by the assembly of small water drops whose size becomes more than the average wavelength of the visible light (5000Å). As pointed out in section 26.7.1 such objects will scatter all wavelengths with nearly equal intensity. The resultant scattered light will be white, so thin layer of clouds appears white. What about dense clouds?

26.7.4 Reddish colour of Sun at Sunrise and Sunset

We are now able to understand the reddish colour of Sun at sunrise and sunset. In the morning and evening when the Sun is near the horizon, light has to travel a greater length of atmosphere containing scattering particle such as dust and air molecules. The violet and blue are scattered away at an angle of about 90°. The sunlight thus becomes devoid of shorter wavelengths and the longer wavelength of red colour reaches the observer (Fig. 26.12) so, we see Sun of red color.

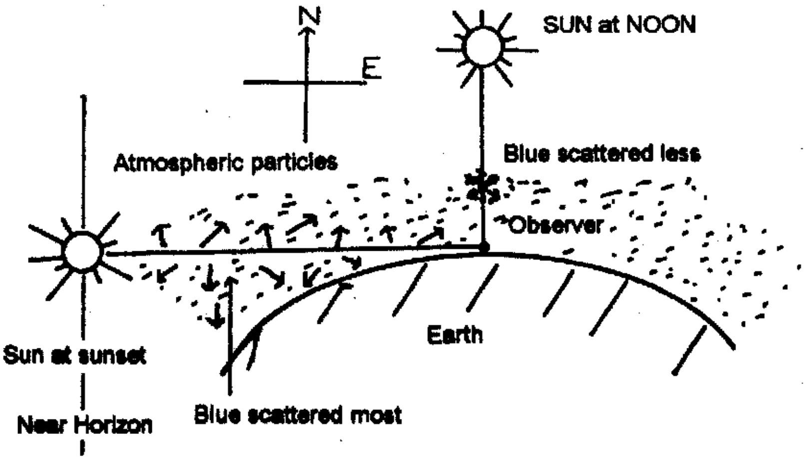


Fig. 26.12: *Reddish colour of sun at sunset and sunrise (blue is scattered away.)*

At noon the Sun is overhead, its distance from observer is less. The blue is also scattered less. This results in the Sun appearing white in fact crimson.

INTEXT QUESTIONS 26.4

1. *Why dense cloud appear black ?*

   ....

2. *Why sky appears deep blue after rains on a clear day?*

   ....

3. *Can you suggest an experiement to demonstrate the reddish colour of Sun at sunrise and sunset?*

   ....

4. *The photographs taken from a satellite show the sky dark why?*

   ....

26.8 RAINBOW

The phenomenon of dispersion and deviation of sunlight produce spectracular event in nature in the form of rainbow. Water drops hanging in the atmosphere disperse and deviate sunlight at certain definite angle and produce rainbow. With Sun at our back we can see a primary and a secondary, though weak, rainbows. The inner one is called the ***primary*** rainbow and the outer the ***secondary rainbow.*** Sometimes we see only one ***rainbow.*** The bows are in the form of coloured arcs whose common centre lies at the line joining the Sun and the observer's eye. Rainbow can be seen in a fountain of water in the evening or morning when the sun rays are incident on water drops at a definite angle.

26.8.1 Primary Rainbow

The primary rainbow is formed by two refraction and an internal reflection of sunlight in a water drop. (See Fig, 26.13(a). Descartes (1637) found that rainbow is seen through the rays which have suffered minimum deviation. All rays of the same colour in the vicinity of the ray which has suffered minimum deviation will be reflected in the same direction close to the later and thus enhance the intensity of the beam of that colour. Parallel rays from the Sun suffering deviation of 137°29' or making angle of 42°31' at the eye with the incident ray after emerging from the water drop produce bright shinning colour in the bow. The rays below and above CL do not satisfy this condition hence will not be visible. All drops which lie on a circle having angular radius 42°31' and centre lying opposite to the Sun appear strongly illuminated. Dispersion by water causes red to violet colours to make their own arcs which lie within cone of 43° for red and 41° for violet rays on the outer and inner sides of the bow. (Fig. 26.13 (b)

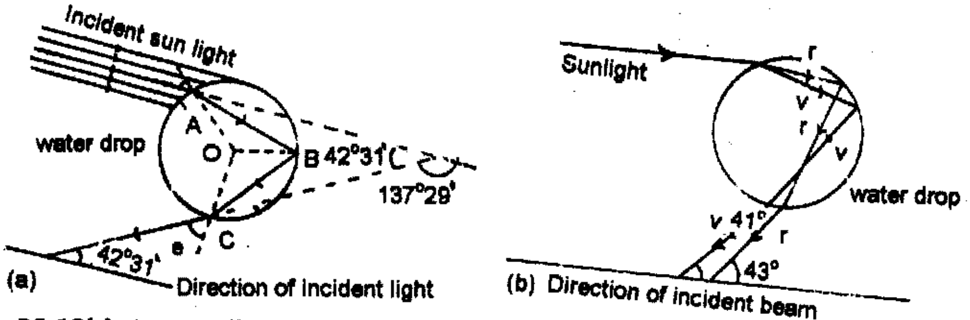


Fig. 26.13(a): *A ray suffering two refractions and one internal reflection in a drop of water Mean angle of minimum deviation is 137°29'. (b)Dispersion by water drop and angles subtended by red and violet lights at the eye.*

26.8.2 Secondary Rainbow

The seoncdary rainbow is formed by two refraction and two internal reflections of the light from water drop. The angles of minimum deviations for red and violet colours are 231° and 234° respectively, so they subtend a cone of 51° for red and 54° for violet colour. From Fig. 26.14 it is clear that red will be on the inner and violet on the outerside of the bow. The simultaneous appearance of the primary and secondary rainbows is shown in Fig. 26.15. The space between the two bows is relatively dark. It is also clear that secondary rainbow lies above the primary bow.

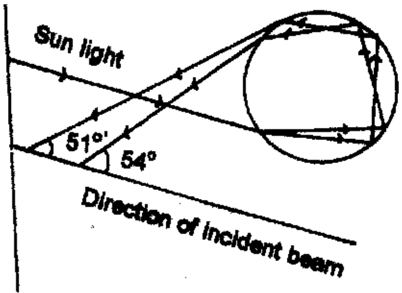


Fig. 26.14: *Formation of secondary rainbow*

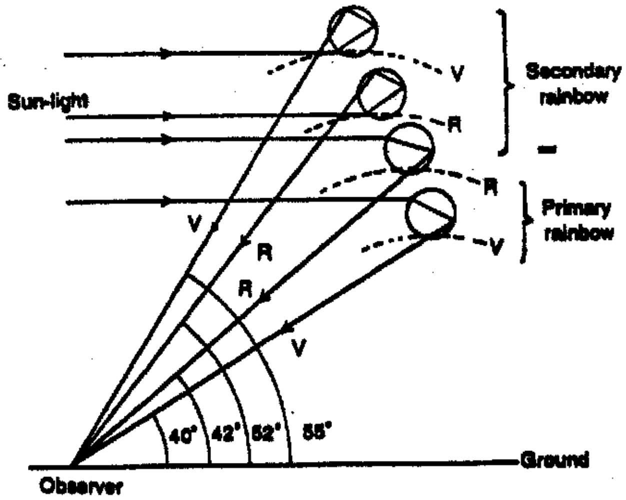


Fig. 26.15: *Simultaneous formation of primary and secondary rainbows.*

INTEXT QUESTIONS 26.5

1. *Why the space between primary and secondary rainbows is relatively dark?*

   ....

2. *Colours in rainbow make a pure or an impure spectrum?*

   ....

3. *Can you see a rainbow if your back is not towards the Sun?*

   ....

4. *Write the order of colours in primary and secondary rainbows.*

   ....

5. *Can a phenomenon like rainbow be seen with light other than the sun light?*

   ....

6. *Does the same set of raindrops form the rainbow at all places?*

   ....

7. *What is the effect on rainbow if the elevation of (a) sun is raised (b) observer is raised.*

....

26.9 DEFECTS IN IMAGE FORMATION

As you have seen in the previous lesson lenses and mirros are widely used in our daily life. It has been observed that these ordinary optical components do not give point image of a point object. This can be seen by holding a lens against the Sun and observing its image. We find it is not exactly circular on a paper. Mirrors too do not produce a perfect image. The defects in image formation are known as ***aberrations***. The aberrations depend on (i) the quality of lens or mirror and (ii) the type of light used.

Two major aberrations are observed in lenses and mirrors namely (a) ***spherical aberration*** and (b) ***chromatic aberration*** (see Fig. 26.16 (a) to (d). The former is a monochromatic-error and later is an error due to polychromatic beam of light. These errors produce serious defects in the images formed by camera. telescopes and miscroscopes.

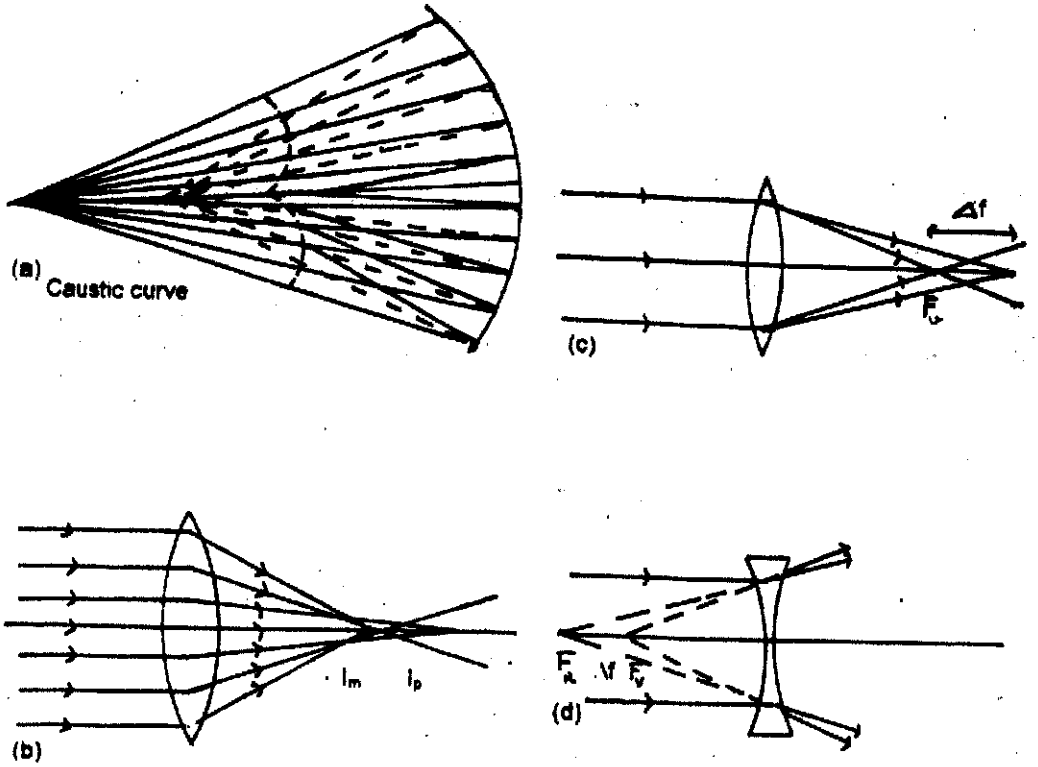


Fig.26.16: *(a), (b) spherical aberration in mirror and lens; (c), (d) Chromatic aberration in lenses*

26.9.1 Spherical Aberration

This monochromatic defect in image formation arises due to the sphericity and aperture of the refracting or reflecting surfaces. The paraxial (i.e. rays near the axis) rays and the marginal rays form images at different points even by a moderate aperture of the surface. (Fig. 26.16 and 26.17). These are represented by I_p and I_m respectively.

When laws of reflection and refraction are used to form the image of a point object we find that the rays fail to arrive at a single point after reflection or refraction. A *Caustic Curve* can be clearly seen with a large aperture concave mirror (Fig.26.16(A). You can see yourself such a curve in a cup of tea or a bowl of milk when light is incident on them from above. In case of lenses we get a circle of minimum diameter, called the ***circle of least confusion*** between circular images formed at I_p and I_m.

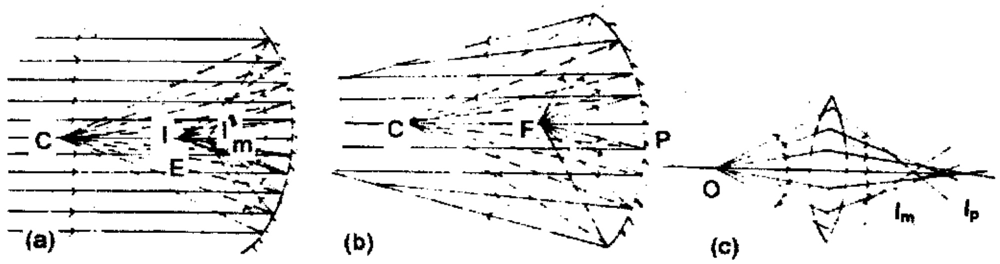


Fig. 26.17: *Spherical aberration in mirrors (A) & (B) and lens (C). I_p image by paraxial rays and I_m by marginal rays*

To ***eliminate*** or ***reduce spherical aberration***, the cause of aberration has to be kept in mind. Both in mirrors and lenses the spherical aberration can be reduced by allowing only the paraxial rays to be incident on the surface. It is done by using stops or narrow apertures (See Fig. 26.18 (a) & (b).

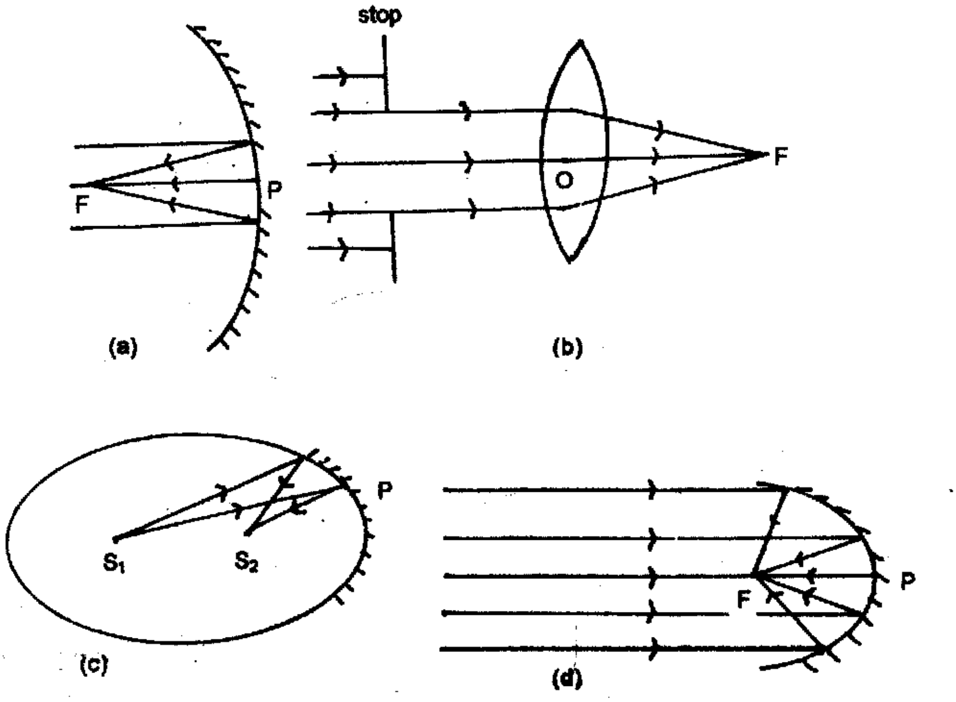


Fig. 26.18: *Removal of Spherical aberration by use of stops (a) & (b) and using elliptical (c) and parabolic mirror (d).*

Elliptical and parabolic mirrors are very widely used due to their special properties. The image of a point object at one focus of an ellipse will be formed at the other focus (Fig. 26.18(c). Similarly parallel rays incident on a parabolic mirror are always focussed at a single point which is its focus. Such reflectors are widely used in torches, head lights of motor vehicles and the flood lights in a sports stadium (Fig. 26.18(d).

Spherical aberration in lenses is reduced by many methods, in addition to the use of stops. One principle is that more convex surface faces more parallel rays (Fig. 26.19 (b). Another way is to use planeconvex lenses (Fig. 26.19) (a). The third method involves dividing total deviation on a number of surfaces (Fig. 26.19 (c). Since convergent lens converges rays and concave lens diverges them so a combination of the two will be free from spherical aberration (Fig. 26.19(d)

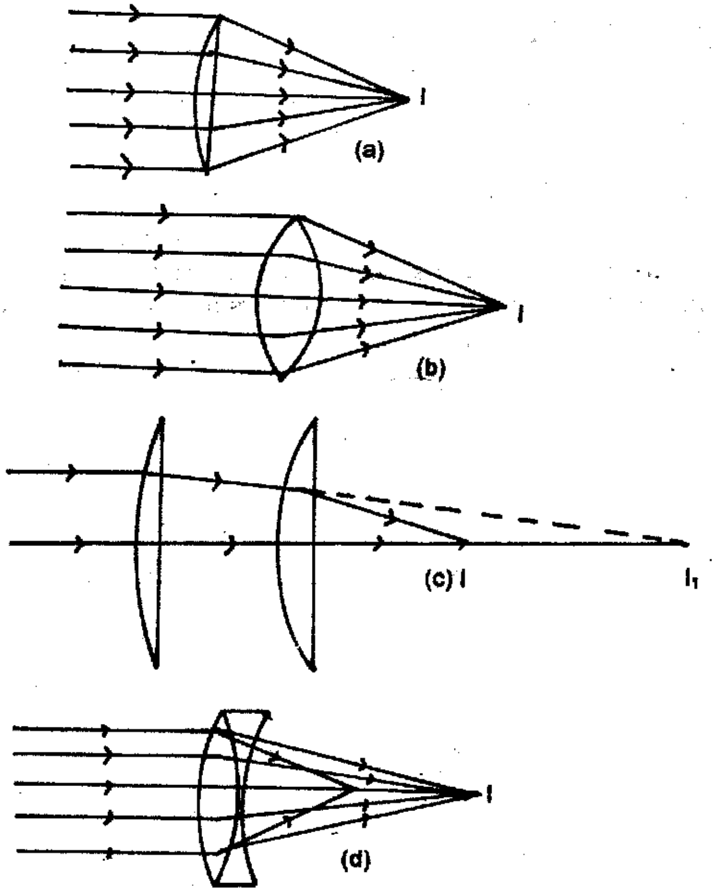


Fig. 26.19: *Removal of spherical aberration in lenses.*

26.9.2 Chromatic Aberration

A convex lens may be taken equivalent to two small angled prisms placed base to base and the concave lens equal to such prisms placed vertex to vertex. Thus, a polychromatic beam incident on a lens will get dispersed. The parallel beam will be focussed at different coloured focii. This defect in image formation by lenses is called ***chromatic aberration***. It occurs due to dispersion of a coloured incident beam (Fig. 26.20 (a), (b). Obviously in convex lens red is focussed away from the lens but in concave it is focussed near the lens, (Recall the case of prism) on the other side.

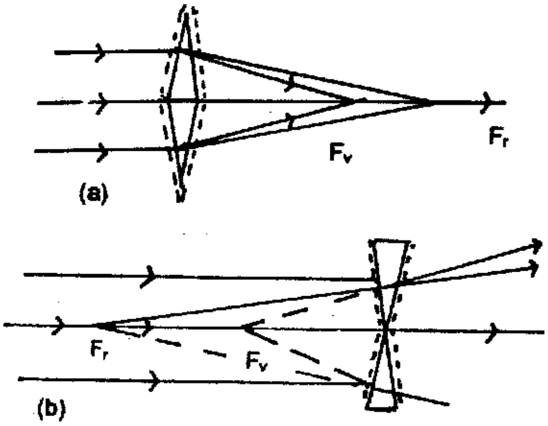


Fig. 26.20: *Chromatic aberration (extreem rays)*

This is because of the fact that red deviates lesser than violet colour. The difference in focal lengths i.e. the coloured images of extreem colours f_r-f_v is the measure of ***linear chromatic aberration*** extended objects give ***transverse chromatic aberration.***

Formation of colourless point image of a point object is called ***achromatism***. The dispersion produced by a convex lens can be annuled by a concave lens as shown in Fig. 26.21. Thus, a convergent lens of suitable material and focal length when combined with a divergent lens of suitable focal length and material may produce image free from chromatic aberration. Such a lens combination is called an ***achromatic doublet*** (Fig. 26.21 (b). The focal length of the concave lens can be found from the necessary condition for achromatism given by

$$\frac{\omega_1}{f_1}+\frac{\omega_2}{f_2}=0$$

or

$$\boxed{f_2=-f_1\frac{\omega_2}{\omega_1}} \qquad \text{......(26.11)}$$

where ω_1 is the dispersive power of convex lens (crown glass) and ω_2 the dispersive power of concave lens (flint glass) f_1 and f_2 are their focal lengths. $|f_2| > |f_1|$ i.e. the focal length of concave lens must be more than the focal length of convex lens so that the doublet behaves like a convergent lens.

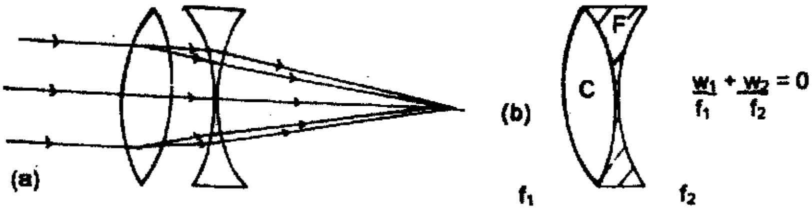


Fig. 26.21(a),(b) : *An achromatic doublet*

There are several other defects found in image formation by lenses but these are beyond the scope of present course.

INTEXT QUESTIONS 26.6

1. *Why a convex lens does not make a point image of a monochromatic point source?*

   ....

2. *Explain how a caustic curve is formed in a cup of tea?*

   ....

3. *Explain chromatic aberration, what is achromatism?*

   ....

4. *Do mirrors also produce chromatic aberration?*

   ....

5. *Discuss how spherical aberration can be minimised.*

   ....

26.10 WHAT YOU HAVE LEARNT

- Light has wave nature and each colour has a specific wavelength.
- Light of one wavelength or colour is called monochromatic but lights like sunlight, which have several colours or wavelength are called polychromatic
- Splitting of light into its constituent wavelengths on entering an optically denser medium is called dispersion
- Prism is used to produce dispersed light which when taken on the screen forms spectrum.
- The angle of deviation is minimum if the angle of incidence and emergence become equal. In this situation the beam is most intense for that colour
- The angle of deviation and refractive index for small angled prism is given by $\delta=(\mu-1)A$.
- Colours overlap in an impure sepctrum but they are distinctly visible as separate in a pure spectrum. Spectrometer is used to produce pure spectrum.
- Spectra can be either emission or absorption spectra which are further classified into (a) continuous (b) band and (c) line spectra.
- The emission spectrum is produced by hot substance and absorption spectra by a relatively cooler substance placed in the path of light from a hot source according to Kirchoff's law.
- The absorption lines or emission lines are highly characteristic of the absorber or emitter. They give us information about the internal constitution of the substance.

- Absorption spectra of Sun. gives us characteristic, Fraunhofer lines
- Rainbow is formed by dispersion of sunlight by raindrops at certain definite angle for each colour so that condition of minimum deviation is satisfied.
- Rainbows are of two types – primary and secondary rainbow. The outer side of primary rainbow is red but inner side is violet. The remaining colours lie in between in order. The scheme of colour is reverse in the secondary rainbow.
- The blue colour of sky, white colour of clouds and reddish colour of the Sun at sunrise and sunset can be explained by the scattering of light. The intensity of scattered light is inversely proportional to the fourth power of the wavelength of light $I \alpha \frac{1}{\lambda^4}$. This is called Rayleigh law. So blue is scattered most intensely.
- The failure of a lens or a mirror to produce point image of a point object is called aberration.
- Spherical aberration arises due to aperture or sphericity of the reflecting or refracting surface.
- Lenses also disperse light and thus coloured images having some dimension are formed by a lens when the incident light is polychromatic. This defect is called chromatic aberration. An achromatic doublet reduces this defect.

26.11 TERMINAL QUESTIONS

1. Show in a prism $i + e = A + \delta$.
2. Would you prefer a small angle or a large angle prism to produce dispersion and why?
3. Differentiate between emission and absorption spectrum.
4. Under what condition the deviation caused by a prism is directly proportional to its refractive index?
5. Define angular dispersion and dispersive power of a prism.
6. Explain the function of collimator and telescope in a spectrometer.
7. How can you determine the refractive index of glass for yellow light using a prism spectrometer?
8. What information do you get from Fraunhofer lines?
9. Do materials show same colour of light in reflected and transmitted beams ?
10. Explain why sea water appears blue at high seas.
11. To an astonaut the sky appears black whereas to us it is blue, explain why is it so?
12. Does the same water drop produce all colour arches of the rainbow?
13. Why do we use parabolic reflectors in the car headlights?

14. Explain chromatic aberration, how will you remove it?
15. Distinguish between refraction and deviation.
16. Why moon appears yellow at night and white during the day?
17. The angle of minimum deviation for a glass prism of 60° is 39°. Find the refractive index of the glass.
18. The deviation produced for red, yellow and violet colours by crown glass are 2.84°, 3.28° and 3.72° respectively. Find the dispersive power of the glass.
19. Claculate the dispersive power for flint glass from the following data $\mu_C = 1.6444$, $\mu_D = 1.6520$ and $\mu_F = 1.6637$, where C, D & F are Fraunhofer nomenclatures.
20. A crown and a flint glass lenses placed in contact make an achromatic doublet of focal length 20 cm. Their dispersive powers are 0.016 and 0.032 respectively find their focal lengths.

CHECK YOUR ANSWERS

Intext Questions 26.1

1. Graphite and carbon are opaque to visible light but allow very short wavelength radiations like x-rays to pass through. So, the dispersion can be shown by them with the use of x-rays.
2. The velocity of propagation of waves of different wavelengths of the visible light is almost same in most ordinary gases, hence these donot disperse visible light. The refractive index is also nearly 1.
3. Violet because $\lambda_r \approx 2\lambda_\upsilon$ and the velocity of red ray is more than that of violet inside the optically denser medium.
4. No
5. 0.48°, 0.193
6. (a) Vacuum (b) Air (c) any optically denser transparent medium
7. A suitable combination of two prisms, one of crown and another of flint glass when placed in contact with the refracting edge of the second prism towards the base of the first can give dispersion without deviation or deviation without dispersion as shown in adjacent diagram. The angle of the second prism should satisfy the following conditions.

$$A^1 = \left(\frac{\mu - 1}{\mu' - 1}\right)A$$ for dispersion without deviation

$$A^1 = \left(\frac{\mu_v - \mu_r}{\mu'_v - \mu'_r}\right)A$$ for deviation without dispersion

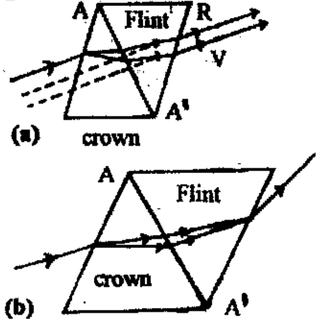


Fig. 26.22:(a) Dispersion without deviation. (b) Deviation without dispersion

Intext Questions 26.2

1. $\mu=\sqrt{3}$
2. $i = (\mu A - 90)^\circ$
3. To confine the incident beam in a narrow region and slit acts as a narrow source for collimator lens.
4. Yes
5. It causes greater dispersion
6. See section 26.5.1
7. 40

Intext Questions 26.3

1. (i) Line (ii) band (iii) continuous (iv) line
2. Kirchoff's law.
3. Black
4. No spectrum
5. See section 26.6.3
6. Yes

Intext Questions 26.4

1. It absorbs the Sunlight
2. It becomes clear of dust particles and bigger water molecules. The scattering now takes place strictly according to Rayleigh law.
3. We can take sodium thiosulphide solution in a round bottom flask and mix small amount of sulphuric acid in it. On illuminating this solution with a high power bulb one can see situation similar to the colour of sun at sunrise and Sunset.
4. At very high altitudes no centres (Particles) of scattering of sunlight are present so the sky appears dark.

Intext Questions 26.5

1. Light dispersion from water drops in this region does not fulfill the condition of minimum deviation between incident and emergent rays. So, the water drop, here do not shine and compared to the rainbows this region appears dark.
2. Impure spectrum due to finite size of the Sun, the rays are not exactly parallel. Thus, there is an overlapping due to which colours do not produce pure spectrum.
3. No
4. Primary: violent, indigo, blue, green, yellow, orange and red from inner to outer side.

Secondary:red, orange, yellow, green, blue, indigo and violet from inner to outer side.

5. Any polychromatic beam under certain conditions can show it.
6. No, different sets of drops give different colours.
7. (i) As the elevation of Sun is increased the part of visible primary rainbow decreases. When the elevation is more then 42°, the primary rainbow disappears but part of secondary rainbow is visible which also disappears when the elevation of the Sun exceeds 54°.

   (ii) With increase in the elevation of observer, the common centre of the bows is also raised and greater part of the rainbow becomes visible. With Sun overhead and clouds down complete circular rainbow can be seen by observer at certain elevation.

Intext Questions 26.6

1. Due to spherical aberration
2. Walls of the cup reflect light. The curvature is large so spherical aberration gives rise to caustic curve.
3. See section 26.9.2
4. No, as they do not disperse light.
5. See section 26.9.1

TERMINAL QUESTIONS

17. $\mu = 1.52$

18. $\omega = 0.268$

19. $\omega = 0.02961$

20. $f_1 = 10$ cm, $f_2 = -20$ cm.