# CHAPTER : 21

# DISPERSION AND SCATTERING OF LIGHT

In the previous lesson you have learnt about reflection, refraction and total internal reflection of light. You have also learnt about image formation by mirrors and lenses and their uses in daily life. When a narrow beam of ordinary light is refracted by a prism, we see colour bands. This phenomenon has to be other than reflection or refraction. *The splitting of white light into its constituent colours or wavelengths by a medium is called **dispersion**.* In this lesson, you will study about this phenomenon. A beautiful manifestation of this phenomenon in nature is in the form of rainbow. You will also learn in this lesson about the phenomenon of scattering of light, which gives sky its blue colour and the sun red colour at sunrise and sunset. Elementary idea of Raman effect will also be discussed in this lesson.

## OBJECTIVES

After studying this lesson, you should be able to :

- *explain dispersion of light;*
- *derive relation between the angle of deviation* ($\delta$), *angle of prism (A) and refractive index of the material of the prism* ($\mu$);
- *relate the refractive index with wavelength and explain dispersion through a prism;*
- *explain formation of primary and secondary rainbows;*
- *explain scattering of light and list its applications.and; and*
- *explain Raman effect.*

## 21.1 DISPERSION OF LIGHT

Natural phenomena like rings around planets (halos) and formation of rainbow etc. cannot be explained by the rectilinear propagation of light. To understand such events, light is considered as having wave nature. (You will learn about it in the next lesson.) As you know, light waves are transverse electromagnetic waves which propagate with speed $3 \times 10^8$ ms$^{-1}$ in vacuum. Of the wide range of electromagnetic spectrum, the visible light forms only a small part. Sunlight consists of seven different wavelengths corresponding to seven colours. Thus, colours may be identified with their wavelengths. You have already learnt *that the speed and wavelength of waves change when they travel from one medium to another.* The speed of light waves and their corresponding wavelengths also change with the change in the medium. The speed of a wave having a certain wavelength becomes less than its speed in free space when it enters an optically denser medium.

The refractive index $\mu$ has been defined as the ratio of the speed of light in vacuum to the speed of light in the medium. It means that the refractive index of a given medium will be different for waves having wavelengths $3.8 \times 10^{-7}$ m and $5.8 \times 10^{-7}$ m because these waves travel with different speeds in the same medium. This ***variation of 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 a non-dispersive medium.) But in an optically denser medium, the component wavelengths (colours) travel with different speeds and therefore get separated. Such a medium is called *dispersive medium*. Does this suggest that light will exhibit dispersion whenever it passes through an optically denser medium. Let us learn about it now.

### 21.1.1 Dispersion through a Prism

The separation of colours by a medium is not a sufficient condition to observe dispersion of light. These colours must be widely separated and should not mix up again after emerging from the dispersing medium. A glass slab (Fig. 21.1) is not suitable for observing dispersion as the rays of the emergent beam are very close and parallel to the incident beam

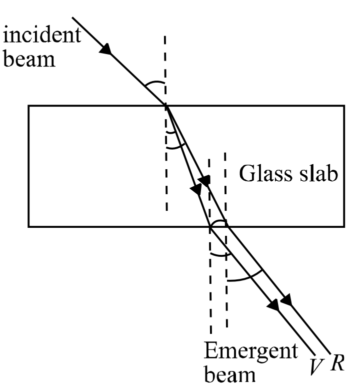


**Fig. 21.1 :** Passage of light through a glass slab

Newton used a prism to demonstrate dispersion of light. Refer to Fig. 21.2. White light from a slit falls on the face *AB* of the prism and light emerging from face *AC* is seen to split into different colours. Coloured patches can be seen on a screen. The face *AC* increases the separation between the rays refracted at the face *AB*. The incident white light *PQ* thus splits up into its component seven colours : Violet, indigo, blue, green, yellow, orange and red (VIBGYOR). The wavelengths travelling with different speeds are refracted through different angles and are thus separated. This *splitting of white light into component colours is known as dispersion*. *MR* and *MV* correspond to the red and violet light respectively. These colours on the screen produce the *spectrum.*

The bending of the original beam *PQN* along *MR* and *MV* etc. is known as ***deviation***. The angle between the emergent ray and the incident ray is known as the **angle of deviation.** Thus $\delta_v$ and $\delta_r$ represent the angles of deviation for violet light and red light, respectively.

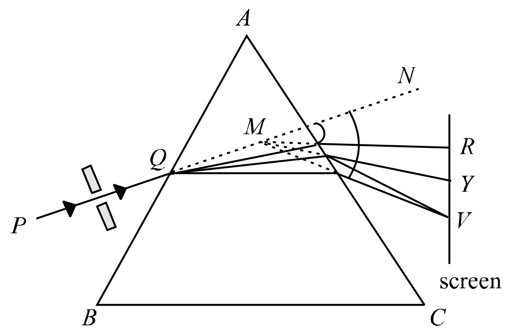


**Fig. 21.2 :** Dispersion of light by a prism

Read the following example carefully to fix the ideas on variation of the refractive index with the wavelength of light.

**Example 21.1:** A beam of light of average wavelength 600nm, on entering a glass prism, splits 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 is* speed of light in vacuum, and $\upsilon$ is speed of light in the medium (prism).

Since velocity of a wave is product of frequency and wavelength, we can write

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

where $\lambda_a$ and $\lambda_m$ are the wavelengths in air and medium respectively and $\upsilon$ is the frequency of light waves. Thus

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

For 384 nm wavelength, the refractive index is

$$\mu_1 = \frac{600\times10^{-9}\,\text{m}}{384\times10^{-9}\,\text{m}} = 1.56$$

For wave length of 589 nm :

$$\mu_2 = \frac{600\times10^{-9}\,\text{m}}{58.9\times10^{-9}\,\text{m}} = 1.02$$

and for 760nm wavelength :

$$\mu_3 = \frac{600\times10^{-9}\,\text{m}}{760\times10^{-9}\,\text{m}} = 0.8$$

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

- the nature of the material, and
- the wavelength of light.

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

### 21.1.2 The Angle of Deviation

We would now establish the relation between the angle of incidence $i$, the angle of deviation $\delta$ and the angle of prism $A$. Let us consider that a monochromatic beam of light $PQ$ is incident on the face $AB$ of the principal section of the prism $ABC$ [Fig.21.3]. 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. We draw normals $NQ$ and MR on the faces $AB$ and $AC$, respectively and produce them backward to meet at $O$. Then you can easily convince yourself that $\angle NQP = \angle i$, $\angle MRS = \angle e$, $\angle RQO = \angle r_1$, and $\angle QRO = \angle r_2$ are the angle of incidence, the angle of emergence and the angle of refraction at the faces $AB$ and AC, respectively. The angle between the emergent ray $RS$ and the incident ray $PQ$ at $D$ is known as the angle of deviation ($\delta$).

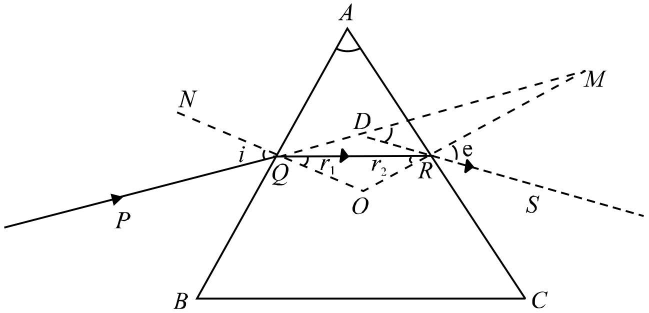


**Fig. 21.3 :** Refraction through a prism

Since $\angle MDR = \angle\delta$, As it is the external angle of the triangle $QDR$, we can write

$$\angle\delta = \angle DQR + \angle DRQ$$

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

or

$$\angle\delta = (\angle i + \angle e) - (\angle r_1 + \angle r_2) \quad (21.1)$$

You may recall that the sum of the internal angles of a quadrilateral is equal to 360º. In the quadrilateral $AQOR$, $\angle AQO = \angle ARO = 90^0$, since $NQ$ and $MR$ are normals on faces $AB$ and $AC$, respectively. Therefore

$$\angle QAR + \angle QOR = 180^0$$

or

$$\angle A + \angle QOR = 180^0 \quad (21.2)$$

But in $\Delta QOR$

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

or

$$\angle r_1 + \angle r_2 + \angle QOR = 180^0 \quad (21.3)$$

On comparing Eqns. (21.2) and (21.3), we have

$$\angle r_1 + \angle r_2 = \angle A \quad (21.4)$$

Combining this result with Eqn. (21.1), we have

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

or

$$\angle i + \angle e = \angle A + \angle\delta \quad (21.5)$$

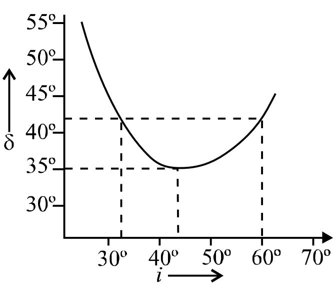


**Fig. 21.4 :** Plot between angle of incidence $i$ and angle of deviation $\delta$

### Angle of Minimum Deviation

If we vary the angle of incidence $i$, the angle of deviation $\delta$ also changes; it becomes minimum for a certain value of $i$ and again starts increasing as $i$ increases further (Fig. 21.4). The minimum value of the angle of deviation is called *angle of minimum deviation* ($\delta_m$). It depends on the material of the prism and the wavelength of light used. In fact, one angle of deviation may be obtained corresponding to two values of the angles of incidence. Using the principle of reversibility of light, we find that the second value of angle of incidence corresponds to the angle of emergence ($e$). In the minimum deviation position, there is only one value of the angle of incidence. So we have

$$\angle e = \angle i$$

Using this fact in Eqn.(21.5) and replacing $\delta$ by $\delta_m$, we have

$$\angle i = \frac{\angle A + \angle\delta_m}{2} \quad (21.6)$$

Applying the principle of reversibility of light rays and under the condition $\angle e = \angle i$, we can write $\angle r_1 = \angle r_2 = \angle r$, say

On substituting this result in Eqn. (21.4), we get

$$\angle r = \frac{\angle A}{2} \tag{21.7}$$

The light beam inside the prism, under the condition of minimum deviation, passes symmetrically through the prism and is parallel to its base. The refractive index of the material of the prism is therefore given by

$$\mu = \frac{\sin i}{\sin r} = \frac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin\frac{A}{2}} \tag{21.8}$$

The refractive index μ can be calculated using Eqn.(21.8) for a monochromatic or a polychromatic beam of light. The value of $\delta_m$ 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 prism of small angle *A*, keeping *i* and *r* small, we can write

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

Hence

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

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 this result in Eqns. (26.4) and (26.5), we get

$$\mu \angle A = \angle A + \angle \delta$$

or

$$\angle \delta = (\mu - 1)\angle A \tag{21.9}$$

We know that μ depends on the wavelength of light. So deviation will also depend on the wavelength of light. That is why $\delta_V$ is different from $\delta_R$. Since the velocity of the red light is more than that of the violet light in glass, the deviation of the red light would be less as compared to that of the violet light.

$$\delta_V > \delta_R.$$

This implies that $\mu_V > \mu_R$. This change in the refractive index of the material with the wavelength of light is responsible for dispersion phenomenon.

### 21.1.3 Angular Dispersion and Dispersive Power

The difference between the angles of deviation for any two wavelengths (colours) is known as the *angular dispersion* for those wavelengths. The angular dispersion between the red and violet wavelengths is $\delta_V - \delta_R$. In the visible part of the spectrum, the wavelength of the yellow colour is nearly the average wavelength of the spectrum. The deviation for this colour $\delta_Y$ may, therefore, be taken as the average of all deviations.

The ***ratio of the angular dispersion to the mean deviation is taken as the dispersive power*** ($\omega$) of the material of the prism :

$$\omega = \frac{\delta_V - \delta_R}{\delta_Y}$$

We can express this result in terms of the refractive indices using Eqn. (21.9) :

$$\omega = \frac{(\mu_V - 1)\angle A - (\mu_R - 1)\angle A}{(\mu_V - 1)\angle A}$$

$$= \frac{\mu_V - \mu_R}{\mu_Y - 1} = \frac{\Delta\mu}{\mu - 1} \qquad (21.10)$$

**Example 21.2 :** The refracting angle of a prism is 30′ and its refractive index is 1.6. Calculate the deviation caused by the prism.

**Solution :** We know that $\delta = (\mu - 1)\angle A$

On substituting the given data, we get

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

**Example 21.3 :** For a prism of angle $A$, the angle of minimum deviation is $A/2$. Calculate its refractive index, when a monochromatic light is used. Given $A = 60^\circ$

**Solution :** The refractive index is given by

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

Now $\delta_m = A/2$ so that

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

## INTEXT QUESTIONS 21.1

1. Most ordinary gases do not show dispersion with visible light. Why?
2. With your knowledge about the relative values of μ for the component colours of white light, state which colour is deviated more from its original direction?
3. Does dispersion depend on the size and angle of the prism?
4. Calculate the refractive index of an equilateral prism if the angle of minimum deviation is equal to the angle of the prism.

### Rainbow formation

Dispersion of sunlight through suspanded water drops in air produces a spectracular effect in nature in the form of rainbow on a rainy day. With Sun at our back, we can see a brighter and another fainter rainbow. The brighter one is called the ***primary*** rainbow and the other one is said to be ***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 our eye. Rainbow can also be seen in a fountain of water in the evening or morning when the sun rays are incident on the water drops at a definite angle.

### Primary Rainbow

The primary rainbow is formed by two refractions and a single internal reflection of sunlight in a water drop. (See Fig. 21.5(a)). Descartes explained that rainbow is seen through the rays which have suffered minimum deviation. Parallel rays from the Sun suffering deviation of 137º.29′ or making an angle of 42º.31′ at the eye with the incident ray, after emerging from the water drop, produce bright shining colours in the bow. Dispersion by water causes different colours (red to violet) to make their own arcs which lie within a cone of 43º for red and 41º for violet rays on the outer and inner sides of the bow (Fig. 21.5 (b)).

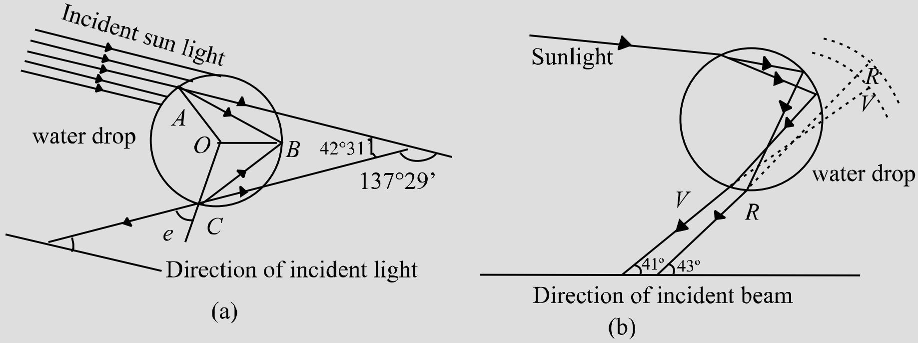


**Fig. 21.5 : (a)** A ray suffering two refractions and one internal reflection in a drop of water. Mean angle of minimum deviation is 137º29′, and (**b**) dispersion by a water drop.

### Secondary Rainbow

The secondary rainbow is formed by two refractions and two internal reflections of light on the 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 the red and 54°. for the violet colour. From Fig.21.6 it is clear that the red colour will be on the inner and the violet colour on the outer side of the bow.

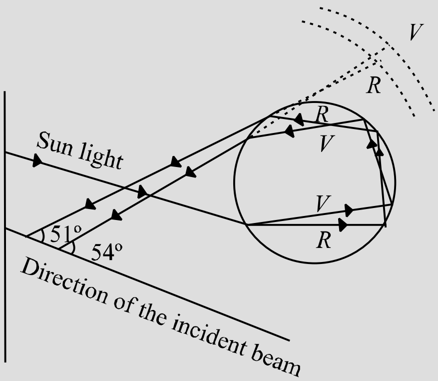

**Fig. 21.6 :** Formation of the secondary rainbow

The simultaneous appearance of the primary and secondary rainbows is shown in Fig.21.7. The space between the two bows is relatively dark. Note that the secondary rainbow lies above the primary bow.

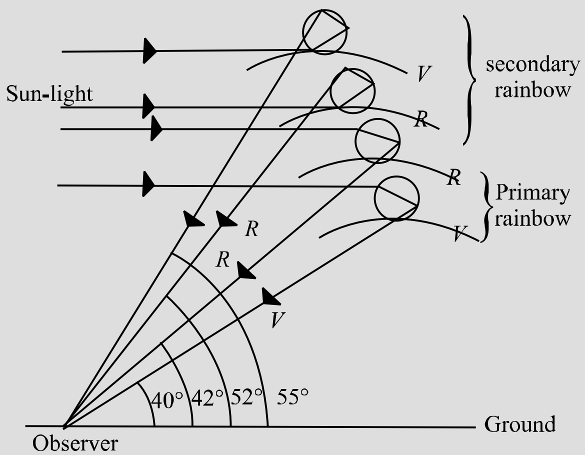

**Fig. 21.7 :** Simultaneous formation of the primary and secondary rainbow.

## 21.2 SCATTERING OF LIGHT IN ATMOSPHERE

On a clear day when we look at the sky, it appears blue. But the clouds appear white. Similarly, production of brilliant colours when sunlight passes through jewels and crystals also attracts our attention. You may like to know : How and why does it happen? These phenomena can be explained in terms of *scattering of light*. A solution of dust or particle-free benzene exposed to sunlight gives brilliant blue colour when looked sideways.

### 21.2.1 Scattering of Light

This phenomenon involves interaction of radiation with matter. Tiny dust particles are present in Earth's atmosphere. When sunlight falls on them, it gets diffused in all directions. That is why light reaches even those nooks and corners where it normally is not able to reach straight from the source.

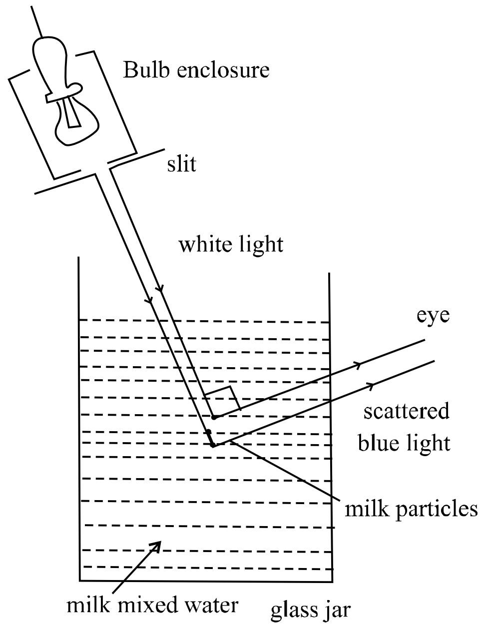


**Fig. 21.8 :** The scattering of light from milk particles

Let us perform a simple activity.

## ACTIVITY 21.1

Take a glass jar or a trough, fill it with water and add a little milk to it. Now allow a narrow beam of light from a white bulb to fall on it. Observe the light at 90°. You will see a bluish beam through water. This experiment shows that after scattering, the wavelenghts of light become a peculiarly different in a given direction (Fig. 21.14).

The phenomenon of scattering is a two step process : absorption of light by the scattering particle and then instant re-emission by it in all possible directions. 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 sized particle will scatter all the wavelengths equally. The intensity of scattered light is given by *Rayleigh's law* of scattering. According to this law, ***the intensity of scattered light is inversely proportional to the fourth power of its wavelength***:

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

Here $I$ is intensity and $\lambda$ is wavelength of the scattered light. Thus, when white light is incident on the scattering particle, the blue light is scattered the most and the red light is scattered the least.

**Example 21.4 :** 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 of these is scattered more intensely?

**Solution :** The intensity of scattered light is given by

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

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

On the basis of scattering of light, we can explain why sky appears blue, clouds appear white and the sun appears red at sunrise as well as at sunset.

**C.V. Raman**
**(1888 – 1970)**

Chandra Shekhar Venkat Raman is the only Indian national to receive Nobel prize (1930) in physics till date. His love for physics was so intense that he resigned his job of an officer in Indian finance department and accepted the post of Palit Professor of Physics at the Department of Physics, Calcutta University. His main contributions are : Raman effect on scattering of light, molecular diffraction of light, mechanical theory of bowed strings, diffraction of X-rays, theory of musical instruments and physics of crystals.

As Director of Indian Institute of Science, Bangalore and later as the founder Director of Raman Research Institute, he did yeoman's to Indian science and put it on firm footings in pre-independence period.

### (A) Blue Colour of the Sky

We know that scattering of light by air molecules, water droplets or dust particles present in the atmosphere can be explained in accordance with Rayleigh's law. The shorter wavelengths are scattered more than the longer wavelengths. Thus, the blue light is scattered almost six times more intensely than the red light as the wavelength of the blue light is roughly 0.7 times that of the red. The scattered light becomes rich in the shorter wavelengths of violet, blue and green colours. On further scattering, the violet light does not reach observe's eye as the eye is comparatively less sensitive to violet than blue and other wavelengths in its neighbourhood. So, when we look at the sky far away from the sun, it appears blue.

**Example 21.5 :** What will be the colour of the sky for an astronant in a spaceship flying at a high attitude.

**Solution :** At a high attitude, in the absence of dust particle and air molecules, the sunlight is not scattered. So, the sky will appear black.

### (B) White colour of the 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). These droplets scatter all the wavelengths with almost equal intensity. The resultant scattered light is therefore white. So, a thin layer of clouds appears white. What about dense clouds?

### (C) Red colour of the Sun at Sunrise and Sunset

We are now able to understand the red colour of the Sun at sunrise and sunset. In the morning and evening when the Sun is near the horizon, light has to travel a greater distance through the atmosphere. The violet and blue wavelengths are scattered by dust particles and air molecules at an angle of about $90^{o}$. The sunlight thus becomes devoid of shorter wavelengths and the longer wavelength of red colour reaches the observer (Fig. 21.9). So the Sun appears to us as red.

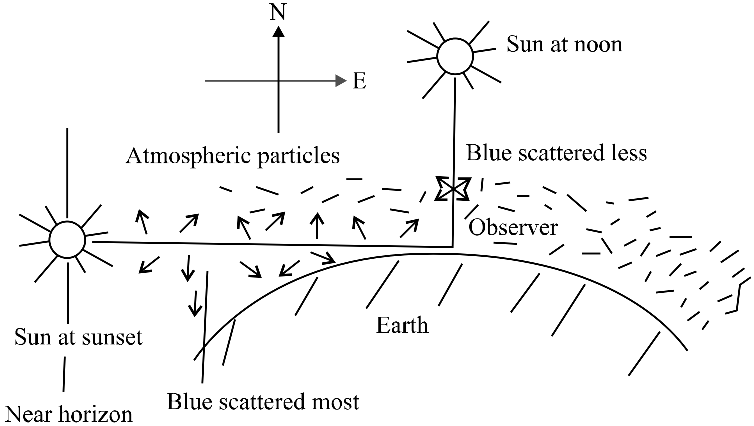


**Fig. 21.9 :** Red colour of the sun at sunset and sunrise (blue is scattered away).

At noon, the Sun is overhead and its distance from the observer is comparatively less. The blue colour is also scattered less. This results in the Sun appearing white, as a matter of fact, crimson.

## 21.2.2 Raman effect

When light radiation undergoes scattering from a transparent substance (solid, liquid or gas) then the frequency of the scattered radiation may be greater or less than the frequency of the incident radiation. This phenomenon is known as Raman effect as it was first observed by C. V. Raman in 1926. An analogue of this optical phenomenon was observed earlier by A. H. Compton in connection with the scattering of X-rays. The spectrum of the scattered radiation is known as Raman spectrum. This has lines having frequency greater than the frequency of the incident radiation (known as anti-Stokes' lines) as also lines having frequency less than the frequency of the incident radiation (called Stokes' lines).

A simple explanation of Raman effect can be given as follows. When light radiation interacts with a substance three possibilities may arise. In the first possibility, the light radiation interacting with the substance does not undergo any change of energy. Hence, its frequency remains unchanged. In the second possibility, the light radiation may impart some of its energy to the substance. As a result, the energy of the light radiation decreases. This leads to a decrease in the frequency of the scattered radiation (corresponding to Stokes' lines). In the third possibility, the incident radiation may interact with the substance which is already in the excited state. In the process, the radiation gains energy resulting into increase in its frequency (corresponding to anti-Stokes' lines).

Raman effect has lot of applications in various fields. C. V. Raman was awarded Nobel prize in physics for this discovery in 1930.

## INTEXT QUESTIONS 21.2

1. Why dense clouds appear black?
2. Why does the sky appear deep blue after rains on a clear day?
3. Can you suggest an experiment to demonstrate the red colour of the Sun at sunrise and sunset?
4. The photographs taken from a satellite show the sky dark. Why?
5. What are anti stokes' lines?

## WHAT YOU HAVE LEARNT

- Light of single wavelength or colour is said to be monochromatic but sunlight, which has several colours or wavelengths, is polychromatic.
- The splitting of light into its constituent wavelengths on entering an optically denser medium is called dispersion.
- A prism is used to produce dispersed light, which when taken on the screen, forms the spectrum.
- The angle of deviation is minimum if the angles 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 a small-angled prism are connected by the ralation $\delta = (\mu - 1)A$.
- The rainbow is formed by dispersion of sunlight by raindrops at definite angles for each colour so that the condition of minimum deviation is satisfied.
- Rainbows are of two types : primary and secondary. The outer side of the primary rainbow is red but the inner side is violet. The remaining colours lie in between to follow the order (VIBGYOR). The scheme of colours gets reversed in the secondary rainbow.
- The blue colour of the sky, the white colour of clouds and the reddish colour of the Sun at sunrise and sunset are due to scattering of light. The intensity of scattered light is inversely proportional to the fourth power of the wavelength $\left(I \, \alpha \frac{1}{\lambda^4}\right)$. This is called Rayleigh's law. So the blue colour is scattered more than the red.
- When light radiation undergoes scattering from a transparent substance, then frequency of scatered radiation may be greater or less than frequency of incident ratiation. This phenomenon is known as Raman effect.

## ANSEWERS TO INTEXT QUESTIONS

**21.1**

1. The velocity of propagation of waves of different wavelengths of visible light is almost the same in most ordinary gases. Hence, they do not disperse visible light. Their refractive index is also very close to 1.

2. Violet, because $\lambda_r > \lambda_v$ and the velocity of the red light is more than that of the violet light inside an optically denser medium.

3. No

4. $\mu = \frac{\sin 60^o}{\sin 30^o} = \sqrt{3} = 1.732$

**21.2**

1. It absorbs sunlight

2. It becomes clear of dust particles and bigger water molecules. The scattering now takes place strictly according to Rayleigh's law.

3. We can take sodium thiosulphate solution in a round bottom flask and add a small quality of sulphuric acid. On illuminating this solution with a high power bulb, we can see a scenario similar to the colour of the sun at sunrise and sunset.

4. At very high altitudes no centres (particles) of scattering of sunlight are present. So the sky appears dark.

5. The spectral lines having frequency greater than the frequency of incident radiation are known as anti stokes' lines.