SCIENCE EDUCATION SERIES

NO. 19

THE SCATTERING OF LIGHT, SUNSETS, AND AIR POLLUTION

by

GEORGE A. DISSANAIKE

NATURAL RESOURCES, ENERGY AND SCIENCE
AUTHORITY OF SRI LANKA
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FOREWORD TO THE SERIES

The dissemination of scientific information is one of the main functions of the Natural Resources, Energy & Science Authority. The Journal of the National Science Council published by this Authority provides a medium for the publication of scientific research papers, and "Vidurava", the quarterly science bulletin contains scientific articles of a general nature which is of interest to the public.

There is still a wide gap in the availability of reading material on scientific subjects of local interest. One result of this is that science students confine their reading only to their school notes and to the few available text books which are mostly published abroad. In an attempt to improve this situation, the Working Committee on Science Education Research of the Natural Resources, Energy and Science Authority decided to publish a series of booklets on scientific topics of local interest as supplementary reading material for students and the general public. The authors who have been selected by the Committee to prepare these booklets are experts in their respective fields. The manuscripts that were submitted by the authors were examined by referees before being accepted for publication. The views expressed in these publications are those of the authors and are not necessarily those of the Natural Resources, Energy & Science Authority.

I must thank the Working Committee on Science Education Research of the Natural Resources, Energy & Science Authority, and in particular Prof. V. Basnayake who is the Hony. Director of the Working Committee for the work they have done to make this project a success.

R. P. Jayewardene
Director General

INTRODUCTION

Most of us have been fascinated by the vivid spectacle of colours in the sky especially around the evening sun as it sets. Observations of such natural phenomena can serve as an important avenue of learning for the student of Physics.

In this text, the author seeks to present the Physics behind the colourful phenomena observed in the sky. Students who have not taken time off to explore the sky and enjoy its beauty are advised to read and be motivated by Chapter 5 first. An introduction to the scattering of light by particles is given in Chapters 1 and 2. Included in Chapters 3 & 4 are descriptions of demonstration experiments that could be carried out in any laboratory for a better understanding of the phenomena involved. In Chapter 6 the theoretical principles of scattering are discussed for those who may be interested.

We in Sri Lanka are especially privileged to enjoy the colourful beauty of the sunsets, most of the year around. The author has taken several colour photographs of the sequence of colours in the sky with time, in Peradeniya and also in an industrialized location in the United States, where air pollution has dulled the skies and robbed the people of enjoying nature's showpiece. It is the author's hope that students of science will develop an interest and an excitement for observing and appreciating the beauty of the skies, so as to build up a conviction for ensuring that our land and the atmosphere above it will continue to be free of pollution, in order that future generations will continue to enjoy the colourful drama of the setting sun.

CONTENTS

CHAPTER 1
THE SCATTERING OF LIGHT

1.1 An Introduction to Scattering

The various colours at sunrise and sunset, the characteristic blue of the sky, and other such effects seen in the sky, are due to the interaction of the light waves from the sun with atoms and molecules in the atmosphere and with particles of different sizes that may be floating in the air.

The theory of such interactions in respect of particles of size much smaller than the wavelength of light was first given by Lord Rayleigh (1871, 1899) using electromagnetic theory. Without using complicated theory, we need to understand in simple terms such an interaction of light waves with atoms and molecules.

Light waves are electromagnetic waves which are transverse, with the electric field intensity vector E and the magnetic flux density vector **B** mutually perpendicular (orthogonal) and lying in a plane normal to the direction of propagation of the wave. We consider the influence of the electric field intensity E of the wave and will assume that it varies with time in a simple sinusoidal form.

Atoms and molecules are agregates of positively and negatively charged particles. In particular, we consider a negative electron cloud around a positively charged atomic nucleus. When light waves impinge on an atom, the electric field at any instant would cause a relative displacement of the electric charges, negative one way and positive the opposite way, and so produce an electric dipole, *see Fig.* 1. Since the electric field E is varying sinusoidally with time. it sets the electron cloud into oscillation with respect to the positive atomic nucleus, and imparts some energy to the atom.

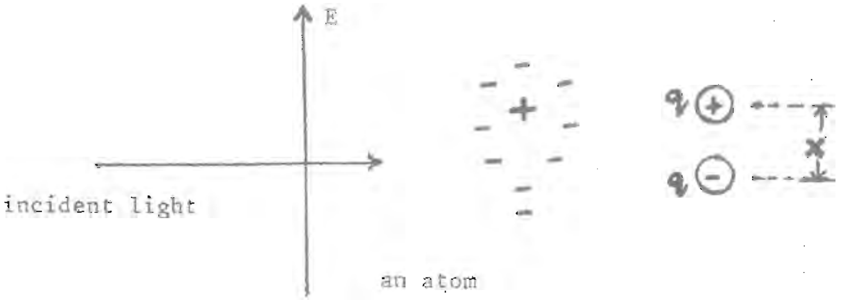

Fig. 1—Electric dipole moment induced by the electric field E of the incident light wave.

This forced oscillation of the electric dipole is appreciable only when the frequency of the light is close to the natural or resonant frequency of the atom. The oscillating electric dipole will behave as an " atomic antenna " and radiate energy in all directions at the same frequency as the incident light wave. Thus, some of the energy is removed from the incident wave and re-emitted in all directions. This phenomenon is known as *scattering*. We say that the light is scattered by the atom or molecule. In *Fig.* 2 the incident plane wave impinges on an atom or molecule at O that acts as a scattering centre. The scattered waves in the form of spherical wavelets start out from O with the same velocity as the incident wave, taking with them a portion of the energy, so the transmitted light is reduced in intensity. (This diverging scattered wave can be demonstrated clearly in a ripple tank where an obstacle of size less than the wavelength of the ripples is interposed in the path of the ripples.)

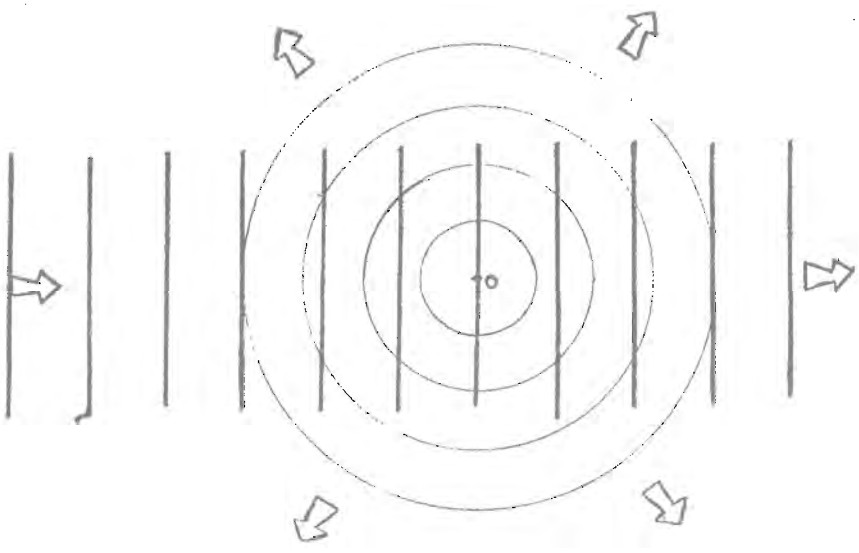

Fig. 2—Plane waves of light impinge on an atom or molecule at O. Scattered spherical waves, diverging from O, take a portion of the energy away from the incident waves.

1.2 The Scattered Light is Mainly Blue

The amplitude of the forced oscillation of the electric dipoles, and therefore the amount of energy removed from the incident wave, increases as the frequency of the wave approaches the natural frequency of the atom. For gases, where interatomic interactions are negligible, absorption of the energy will be insignificant, and the scattered wave will take more and more energy as the frequency of the light gets closer to a natural frequency of the atom. In respect of molecules of air, for example, the resonant frequencies are in the ultraviolet while the incident light is in the visible region. As the frequency of the light increases from the red towards the blue end of the spectrum, the greater will be the amount of light scattered. Thus, the sunlight passing through the atmosphere in one direction is scattered in all directions by the air molecules, the scattered light being predominantly blue. This blue light will reach the observer from many directions so the sky will appear bright and blue.

In *Fig.* 3 conditions are shown for the observation of the blue sky by scattered light and the direct sun by transmitted light. It is to be noted that the earth's atmosphere extends to a great height above the earth's surface, also that the location of the observer with respect to the sun's rays can influence the conditions of observation. An observer A sees the blue sky by scattered light, and since the light that comes directly from the overhead sun loses the blue light by scattering, the transmitted light reaching him will be of a colour 'white minus blue' or a bright yellow-orange. This is the colour of the sun in the daytime though it is too intense to be seen directly with the naked eye. An observer B however sees the sun by rays that are travelling obliquely and near the horizon, and is therefore viewing the setting sun. The sun's rays now traverse a much larger thickness of the atmosphere and would lose much more energy by scattering, also more of the light in the blue region will be scattered, so the setting sun can be viewed directly and would appear orange-red. As we shall see later, the presence of a lower layer of dust and water vapour in the air will scatter more of the colours, so the sun may be seen with a deeper red hue. Observer B would also see the blue sky by scattered light far away from the setting sun.

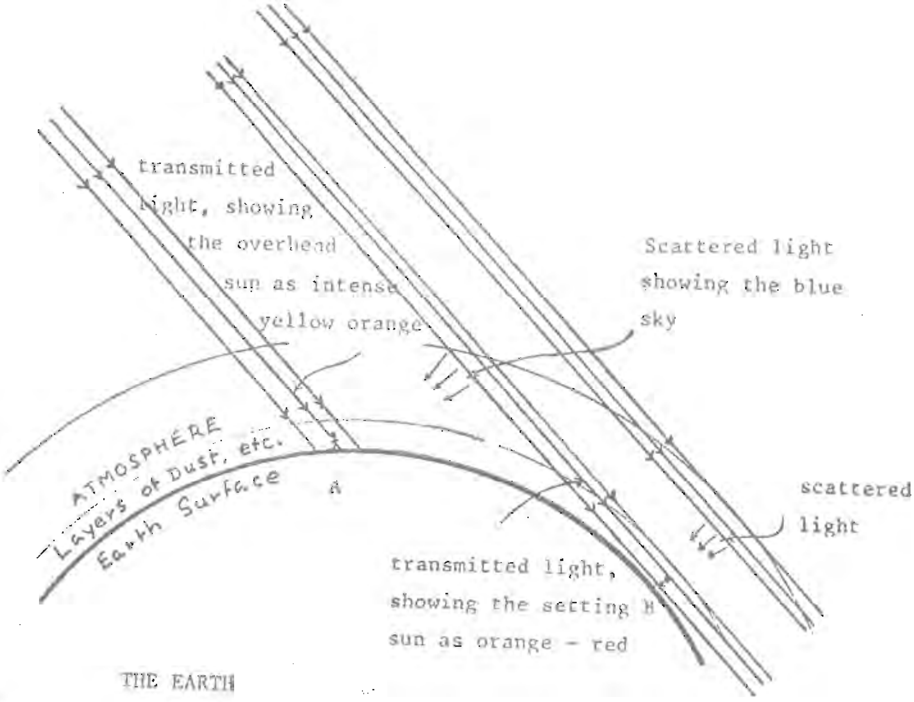

Fig. 3—Conditions for the observation of the blue sky, by scattered light, and the direct sun, by transmitted light—as viewed by two observers at A and B.

If the earth had no atmosphere, or if the observer is viewing the sky from out in space or from the moon which has no atmosphere, would the sky appear blue or could he see such beautiful sunsets? Without an atmosphere, there will be no scattering of the light, and the daytime sky would be very dark. Lunar photographs taken of the earth from the moon and the observation of astronaut's circling the earth by satellite confirm this fact.

1.3 Common Examples of Scattering

The smoke from the end of a lighted cigarette, seen against a dark background, is blue as it rises in the air, the smoke being made up of particles smaller than the wavelength of light. On the other hand, smoke that is exhaled from the mouth is covered with moisture from the warm breath and is seen grey or a dull white. Here, each droplet is larger than the average wavelength of light and so there is pronounced scattering of the longer wavelengths too. If smoke from a chimney is viewed against a bright background of bright cloud or against the sun itself, the colour that is transmitted to the observer is dull red.

When we look through a faintly misty atmosphere at a range of distant hills, they appear to be blue. The blue comes by scattering of light off the air molecules and particles of the atmosphere that lie between the hills and us. Photographs can be improved by the use of a yellow filter that cuts off this blue light.

As mentioned earlier, the bright red hue of the sun seen sometimes at sunrise or sunset is due to scattering by larger particles of dust or other matter superimposed on the effects due to the air molecules. This colour effect is more enhanced when the particles are spread out over a very wide area of the sky. When the volcanic island, Krakatoa, ejected into the atmosphere, in 1883, quantities of the finest volcanic dust, the colours of the sky seen all over the world were unusually beautiful for many months afterwards, the sun and the moon appearing sometimes green or blue, and the sunsets and sunrises being abnormally coloured.

In this industrial age, spectacular red skies, with the complete absence of the other colours, are a common feature in countries where air pollution is widespread. This topic is discussed in greater detail in Chapter 5.

1.4 Scattering of Light in the Laboratory

For the demonstration of the scattering of light in the Laboratory, an optically inhomogeneous (non-uniform) medium is required where the index of refraction is not constant but varies irregularly from point to point. Examples of such inhomogeneous media are aerosols, like smoke and fog, emulsions and colloidal solutions. These contain fine particles in suspension, the refractive index of the particles differing from that of the surrounding medium.

Tyndall (1868/1869) believed that the blue of the sky was a result of the scattering due to fine particles suspended in the atmosphere. He therefore sought to produce in the Laboratory such fine suspensions of particles inside a tube through which a pencil of sunlight was passed. In one such experiment, he evacuated a tube and admitted a mixture of air, hydrochloric acid and the vapour of butyl nitrite, which through chemical reaction formed very fine particles of uniform size suspended in air. At first, the scattered light was a faint deep blue, but as the particles gradually increased in size the blue colour became more intense but lighter in colour.

Other fine particle suspensions that have been used in the early work to study scattering of light are :

(*a*) the fog formed by the condensation of sodium vapour in hydrogen gas at low pressure,

(*b*) an emulsion formed by adding a few drops of milk into clean filtered water,

(*c*) colloidal suspension of fine sulphur particles formed by adding a few drops of dilute hydrochloric acid to a dilute solution of sodium thiosulphate (hypo). Details of a fascinating and instructive laboratory experiment using such a colloidal solution are given in Chapter 4.

Strutt (1918), using a small chamber filled with dust-free air, demonstrated the characteristic blue of light scattered solely by air molecules in the chamber. He had pointed out that moonlight, half a million times weaker than sunlight, can yet be seen in the sky at night. Thus, sunlight scattered by an amount of air about two millionth of an atmosphere should be as easily seen, and therefore a few inches of air would be sufficient to demonstrate the blue colour of scattered light. Details of a laboratory experiment that can be readily set up are given in Chapter 3.

CHAPTER 2

POLARIZATION OF SCATTERED LIGHT

2.1 Polarised & Unpolarised Light

We have noted earlier that light waves are electromagnetic waves, which are transverse, with the electric and magnetic intensity vectors E & B mutually perpendicular (orthogonal) and lying in a plane normal to the direction of propagation of the wave.

If we consider a plane harmonic wave propagated in the positive x-direction, *Fig.* 4, the wavefronts of the advancing wave are plane and the electric field intensity E will have a simple sinusoidal form of variation. The associated magnetic flux density B will also have a sinusoidal form but always normal to E.

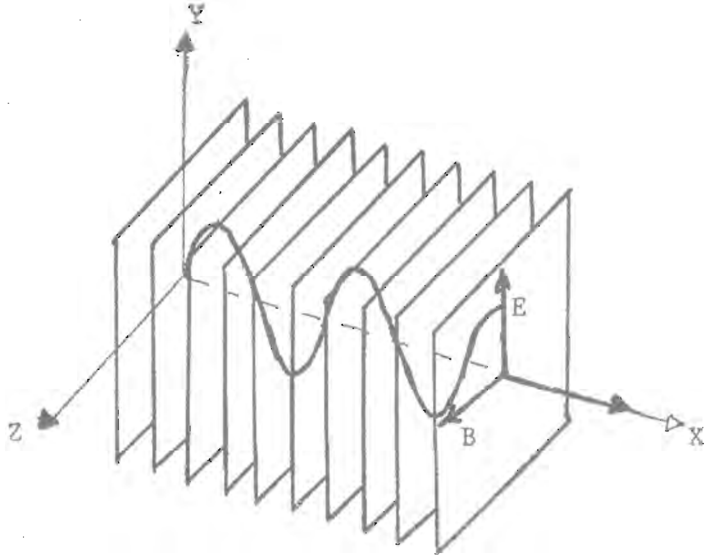

Fig. 4—A plane harmonic wave advancing along the x-direction. The electric field E at any instant has the same value at every point on a wavefront but varies sinusiodally with time and with distance along the x-direction.

If further the electric field intensity vector E is fixed in direction with vibrations confined to a plane, say parallel to the y-axis and normal to the z-axis, as in *Fig.* 5, then we have a *linearly polarised* or a *plane polarised* wave. The associated magnetic flux density B will lie on a plane parallel to the z-axis and normal to the y-axis. (We use the convention that the plane of vibration is the plane which contains the E-vector. For our discussion below, we need only to consider the influence of the E-vector).

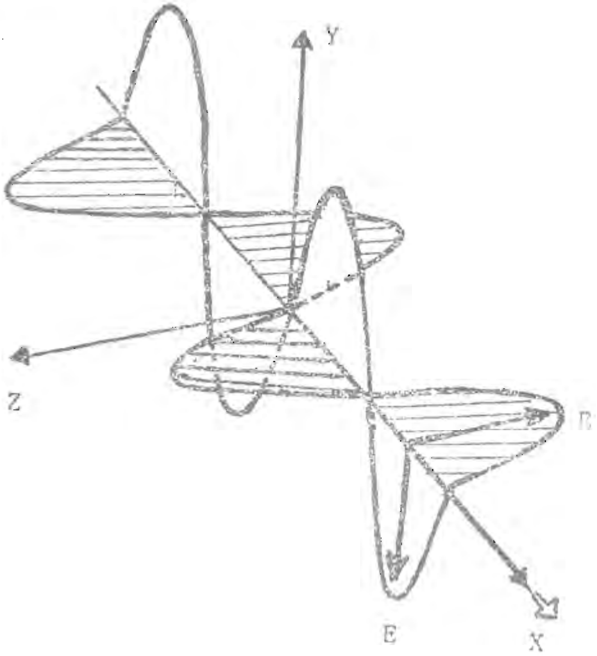

Fig. 5—A plane polarized harmonic wave advancing along the x-direction. The E-vector is confined to a plane normal to the z-axis and the B—vector to a plane normal to the y-axis. The plane of vibration of the polarized wave is the x-y plane.

If, however, the light is *unpolarised* (natural,light), all directions of vibrations are equally possible for the E-vector, and there is no specified plane of vibration. Further, the magnitude of the E-vector is the same in every direction. If there is a mixture of linearly polarised light and unpolarised light, we say the light is *partially polarised.*

We use a simple representation to distinguish between light that is linearly polarised, unpolarised and partially polarised, as shown in *Fig.* 6, Here, natural or unpolarised light is represented by equal vector arrows indicating a mixture of waves that are linearly polarised in all possible directions. For partially polarised light, the vector arrows do not have the same magnitude in all directions. Linearly polarised light is represented by a vector arrow pointing in one direction only. The vector arrows all lie in a plane normal to the direction of the travelling wave.

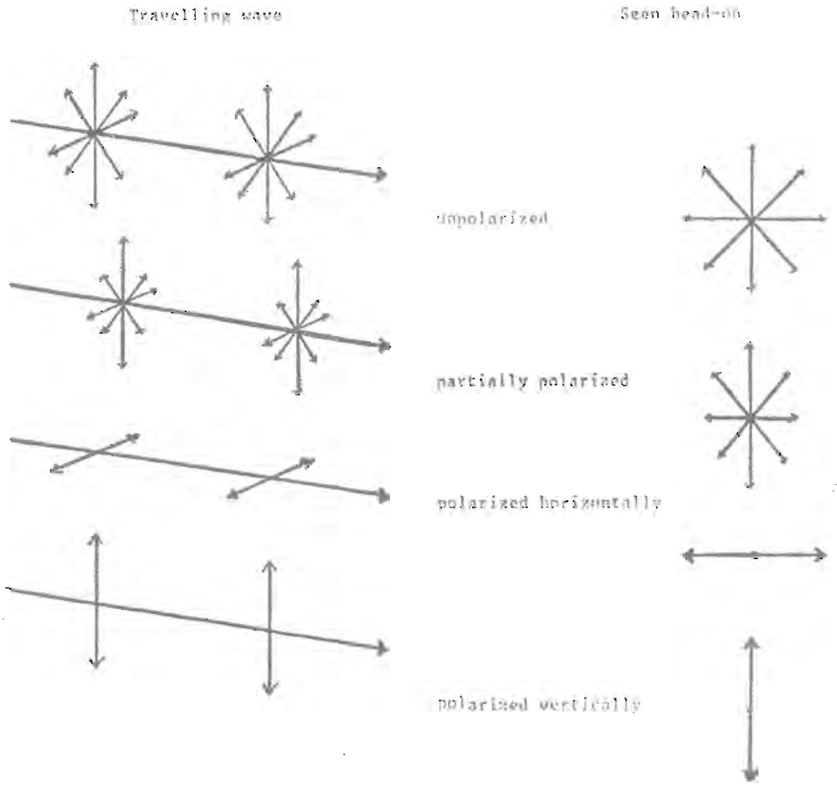

Fig. 6— Schematic representation of light that is unpolarized, partially polarized and plane polarized

2.2 Polarisation by Scattering

We consider, for simplicity, plane polarised light impinging on an air molecule, the plane of vibration being vertical, *Fig*. 7 (*a*), and horizontal in *Fig*. 7 (*b*). As discussed in Chapter 1, the harmonic electric field intensity E of the incident wave causes the positive and negative charges of the molecule to be displaced in opposite directions (but parallel to the E-vector) with the same frequency as the incident light. The oscillating electric dipole so produced behaves as a molecular "antenna", and radiates energy in all directions except in the direction of its own length. This radiated energy constitutes the scattered wave. The light scattered in the same direction as the incident light (the forward direction) is linearly polarised with the vector E parallel to the E-vector of the incident light. There will be no scattered light seen in a direction parallel to the direction of oscillation of the electric dipole.

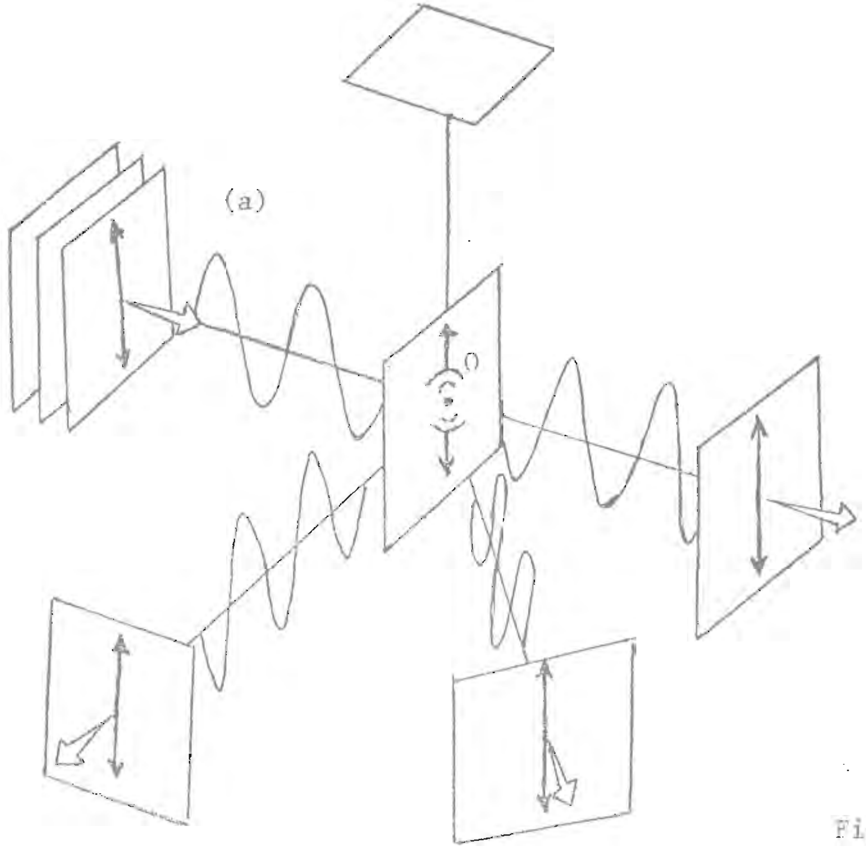

Fig.

Fig. 7 (a)—Plane polarized light incident on a molecule of gas at O, has its plane of vibration vertical. The light scattered in different directions is polarized, as shown.

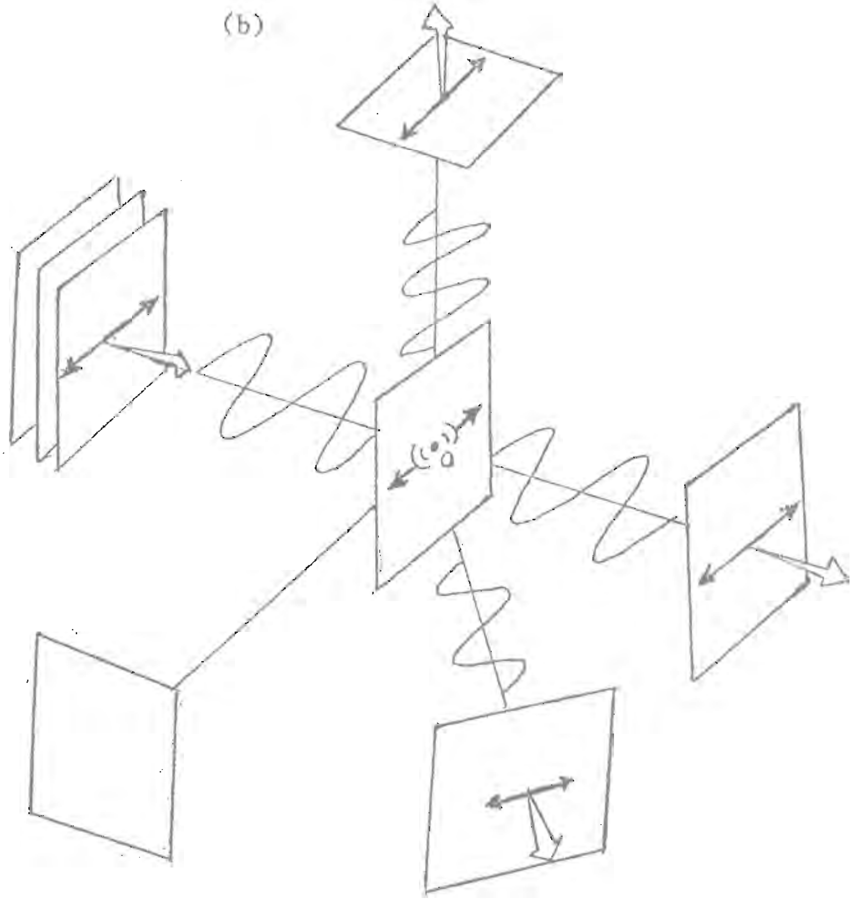

Fig. 7 (b)—Plane polarized light incident on a molecule of gas at O, has its plane of vibration horizontal. The light scattered in different directions is polarized, as shown.

If we now superpose the two cases represented in *Fig.* 7 (*a*) & (*b*), as in *Fig.* 8, we could get an idea of what happens when the incident light is natural or unpolarised. The light observed in the forward direction (in the incident direction) will be unpolarised in the same way as the incident light. At any angle (not 90°) away from the forward direction, the scattered light is partially polarised, the light becoming more and more polarised as it approaches the normal (90°) direction. *When the direction of observation is normal to the incident direction, the scattered light is completely plane polarised, the plane of vibration being normal to the plane containing the incident beam and the scattered beam, as illustrated in Fig.* 8.

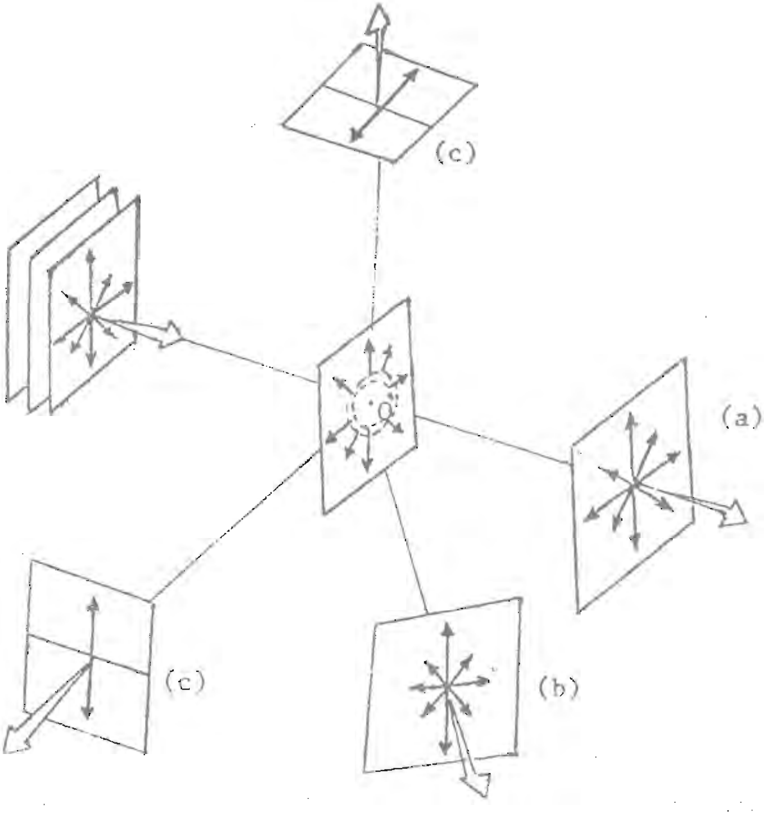

Fig. 8—Unpolarized light is incident on a molecule at O. The light that is scattered (*a*) in the forward direction will be unpolarized, (*b*) in any other direction (not 90°) will be partially polarized, and (c) in the normal direction will be plane polarized, as shown.

2.3 Polarisation of the Light from the Sky

From the simple discussion above, we expect that sunlight scattered by the air molecules will be polarised. Thus, the light from the blue sky reaching us should be polarised. If we examine the sky through a polaroid or a Nicol prism, the region of the blue sky seen approximately 90° to the direction of the Sun's rays through the atmosphere, will be polarised, as illustrated in *Fig.* 9. However the light is not fully extinguished as we rotate the axis of the polarised or Nicol. This means that the scattered light observed is not completely plane polarised as we would expect on the above reasoning. Complete plane polarisation of the observed acattered light is not possible due to the following factors : (*a*) a possible anisotropy of molecules with respect to their polarisability, (*b*) the presence of coarse particles in the atmosphere with sizes equal to or greater than the wavelength of the light, and (*c*) much of the light may reach us by multiple scattering which tends to depolarise the scattered light.

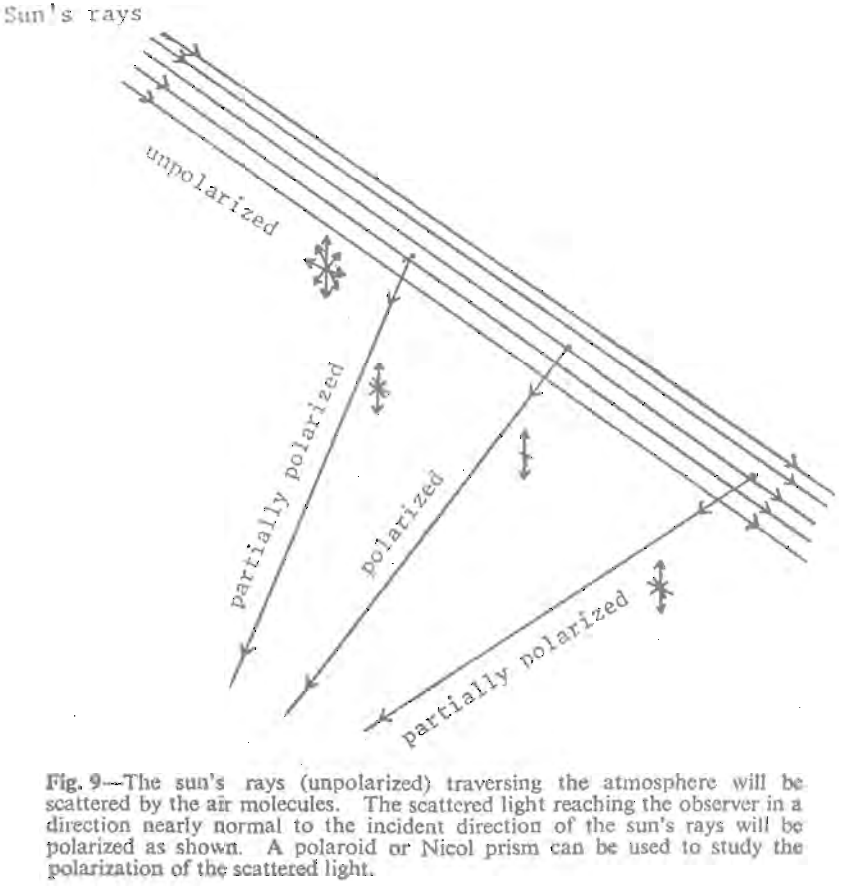

Fig. 9—The sun's rays (unpolarized) traversing the atmosphere will be scattered by the air molecules. The scattered light reaching the observer in a direction nearly normal to the incident direction of the sun's rays will be polarized as shown. A polaroid or Nicol prism can be used to study the polarization of the scattered light.

2.4 Use of a Pile of Plates

It is possible that you may not have a Nicol prism or a polaroid available. You can put together about 8 to 10 microscope slides to form a " pile of plates " (where the light passes through several layers of glass). This "pile of plates " can become a convenient polariser of light or an analyser of polarised light. (A pile of plates is used as it gives a stronger reflection than a single thickness of glass).

When natural or unpolarised light is incident on the surface of a pile of plates, part of the light is reflected and a part transmitted. For any angle i of incidence, the reflected light will be partially polarised, with a preference to those waves where the electric vector E is *perpendicular* to the plane of incidence. The transmitted light will also be partially polarised, but with the electric vector E in a preferred direction *parallel* to the plane of incidence. If now the angle of incidence is adjusted so that the reflected and transmitted rays are perpendicular to each other, the reflected light is completely plane polarised. The corresponding angle of incidence i_b will be such that

$$\tan \ i_b = \mu$$

where μ is the refractive index of glass. This angle is called the Brewster angle. *Fig.* 10 illustrates this property of polarization by reflection For glass, where $\mu = 1.53$, $i_b = 56°$.

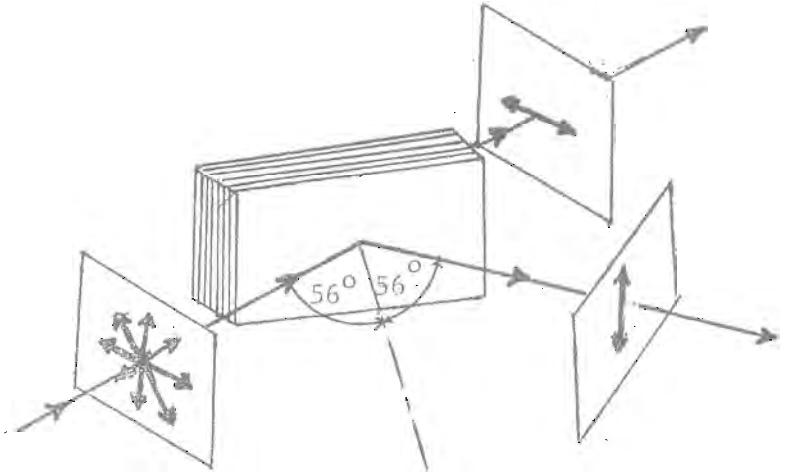

Fig. 10—Polarization of light by reflection off a Pile of Plates. When the angle of incidence is equal to the Brewster angle (equal to 56° for glass), the reflected light will be plane polarized as shown. The transmitted light too will be polarized.

If now the incident natural light is replaced by plane polarized light with the plane of vibration normal to the plane of incidence, then at the Brewster angle the light will be totally reflected as plane polarized light. If however the plane of vibration of the incident light is parallel to the plane of incidence, there will be no reflection, and all the light will be transmitted as plane polarised light.

A pile of plates can thus be used to analyse the polarized light of the sky, see *Fig.* 11 The pile of plates must be rotated about an axis parallel to PO, which is the direction of the scattered light reaching the analyser at O. When the pile of plates is positioned as in *Fig.* 11 (*a*) there will be a reflection of the blue sky seen. When the pile of plates is rorated through 90° about PO as axis, the reflected light will be greatly reduced in intensity, *Fig.* 11(*b*). The reflected light is not completely extinguished as the blue light of the sky is not completely plane polarized, as indicated in Section 2.3 of this chapter.

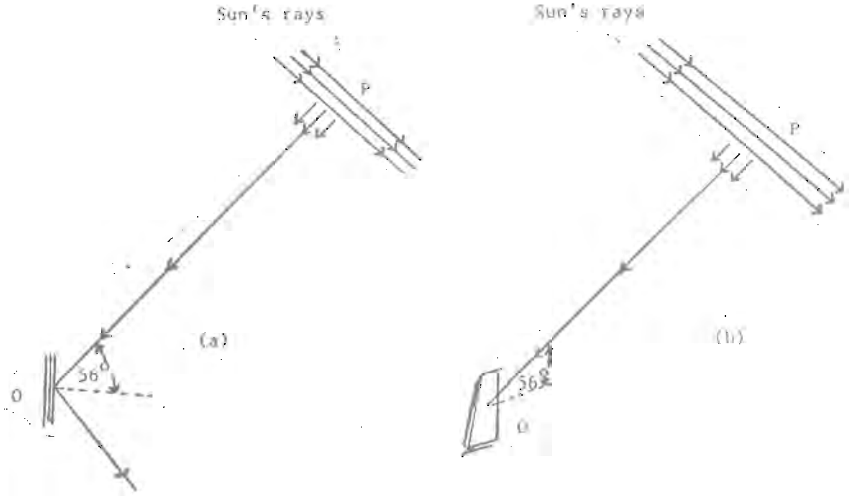

Fig. 11—The light from the sun, scattered by air molecules in a region P and coming towards an observer along PO in a direction normal to the incident light, will be polarized with vibrations normal to the plane of the diagram. The Pile of Plates, positioned as at (*a*) with the plane of reflection in the plane of the diagram, will reflect the blue sky. But when the plates are rotated through 90° about the axis PO, as in (*b*), there will hardly be a reflection.

CHAPTER 3

ARE AIR MOLECULES REALLY RESPONSIBLE FOR THE CHARACTERISTIC BLUE OF THE SKY ?

3.1 A Laboratory Experiment

A Laboratory Experiment can be set up to clearly demonstrate that the characteristic blue and the polarization of the light of the sky can arise solely due to the scattering of light by air molecules. Although the experiment described below has been carried out using a metal chamber, any teaching laboratory could assemble a composite of S-lon tubes of different sizes as a substitute chamber.

3.2 The Arrangement

The diagram of *Fig.* 12 illustrates the arrangement that may be used (Dissanaike 1971). Further details are given in the legend of the figure. The source of light S is a projector lamp (1000 watt). Lenses L_1 and L_2 are used to obtain an intense, slightly converging beam of light that is outlined by the diaphram D. The scattering chamber, of brass, is of the shape shown, with its inner surfaces blackened to a dull finish to absorb most of the light incident. The narrower limb A of the chamber is used as an eyepiece tube, and the wider limb B provides an absolute black background for viewing the light scattered in the region C. Beyond C the beam of light forms an image of the source and then diverges sharply before it is incident on a very large area of the blackened surface inside limb E. In this way, the intensity of the light reflected back from the inner surface of limb E is very much reduced, and is negligible compared to that of the primary beam in the region C.

A set of apertures a, b and c in the eyepiece tube defines the field of view in the region C and also cuts off extraneous reflected light, so that the light received at the window W consists almost wholly of light scattered by the air (or gas) in the region C of the chamber.

The air (or gas) inside the chamber must be *dust-free and dry*. This requirement is very important, as the light acattered by dust particles and water vapour is much more intense and would obscure the effects due to the much smaller air molecules. (Rayleigh's theory predicts that the intensity of scattering is directly proportional to the sixth-power of the size of the scattering particles). In the experiment, this requirement is ensured by the following arrangement. Two narrow outlet tubes, each with a stopvalve, are connected to limb E. (These outlet tubes are not shown in *Fig.* 12). The chamber is evacuated with a vacuum pump conected to one of the outlets, and an air filter and a drying chamber fitted to the other outlet admits only dust-free and dry air into the chamber. The chamber should be air tight so that the air admitted inside is maintained free of dust particles throughout the experiment.

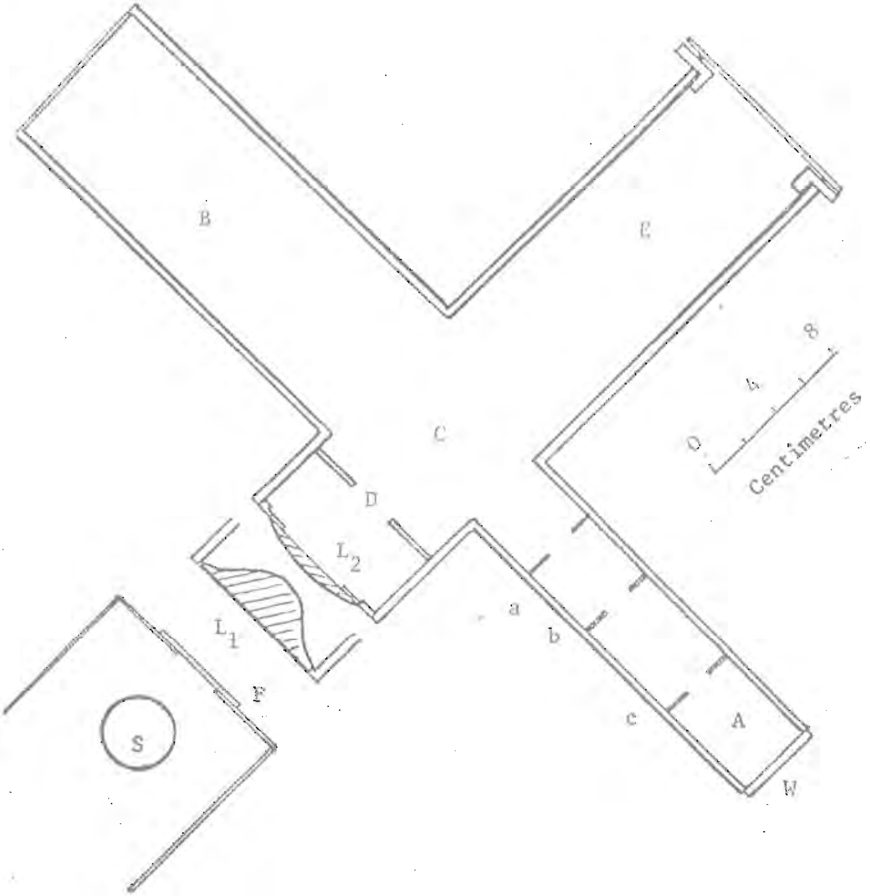

Fig. 12— Laboratory arrangement for demonstrating the scattering of light by dust-free air contained in an airtight chamber.

S—a projector lamp of 1000 W; F—a heat filter; L^1—a converging, aspheric lens (f = 7.5 cm) ; L_2 — a plano-convex lens (f = 10 cm) ; D—an aperture about 2.5 cm diameter; A—an eyepiece tube with apertures a, b and c of diameters 2.0, 1.5 and 1.25 cm. respectively ; W—a glass window. Limbs B and E are referred to in the text.

The high-watt projection lamp must be provided with adequate cooling facilities, and a water cell or a heat-absorbing glass should be interposed in front of Lens L_1 to absorb the heat of the Lamp.

3.3 Observations

The intense beam of light, viewed transversely through the eyepiece window W, appears deep blue in colour. This blue is even richer than the blue of the sky. A very satisfying record of the blue colour of the scattered light may be obtained by photography, using a colour film. With a polaroid Land Camera 180 and a colour pack film type 108, exposures of about 15 minutes at f/8 give good results. The scattered (blue) light disappears when the chamber is evacuated and reappears when it is again filled with dust-free air. There is no doubt that the air molecules in region C of the chamber must be responsible for the blue colour of the scattered light.

As mentioned earlier, the blue of the light scattered by the air in the chamber is deeper and richer than the blue of the sky. This is to be expected, since the violet and deep blue components of the light scattered in the atmosphere would be absorbed by the intervening layers of air. Such absorption is negligible in the laboratory experiment. (Absorption of light is greatest for the shorter wavelengths).

The arrangement described may be used to demonstrate the effect on the intensity of the scattered light, of using the same gas (or air) at different pressures and of different gases at the same pressure. According to the theory of scattering by Lord Rayleigh (1871), the intensity of scattering from different gases at the same pressure should vary as $(\mu-1)^2$, where μ is the index of refraction of the gas. Again, the intensity of scattering should be directly proportional to the number of scattering particles and therefore to the pressure. Such verification of theory by detailed measurements was carried out by Strutt (1918). This is further discussed in Chapter 6.

For such a quantitive study, using the laboratory arrangement described above, it would be convenient to use a photomultiplier tube (*eg.* a RCA 931 A) and a sensitive microammeter as a detector.

3.4 Polarisation of the Scattered Light

A discussion of the polarisation of light scattered by air molecules has already been given in Chapter 2.

A polaroid sheet held in front of the eye at the window W (*Fig.* 12) extinguishes the scattered light when the axis of the polaroid is parallel to the direction of the incident beam. This is to be expected as the plane of vibration of scattered light is normal to the plane containing the incident beam and the scattered beam, and is therefore normal to the axis of the polaroid. When the polaroid axis is turned through 90°, the scattered light is clearly seen.

3.5 Effect of Dust Particles on the Scattering

As we have discussed earlier, the presence of dust particles and water vapour in the air can change the character of the scattering because (*a*) the intensity of scattering varies as the sixth-power of the size of the particles and (*b*) particles larger than the wavelength of light would tend to scatter most colours besides the violet blue. Thus, the scattered light is expected to become much brighter and be bluish-white in colour, with only the deeper red light being transmitted.

We could demonstrate the effect of dust particles in suspension by introducing the air into the scattering chamber without filtering same. A more intense, bluish-white beam is seen due to scattering. This beam is not much affected when viewed through a polaroid with its axis normal to the plane containing the incident beam and the scattered beam, but when the polaroid is rotated through 90°, the beam is *not* fully extinguished but is much less bright and of a deeper blue colour. Polarisation of the light scattered at 90° is not complete when the scattering particles are as large as the dust particles.

CHAPTER 4

SCATTERING BY COLLOIDAL PARTICLES

4.1 An Instructive and Fascinating Experiment

A simple Laboratory arrangement for the study of the scattering of light by colloidal particles in suspension is described below. This arrangement has been found very suitable for demonstrating the following :

(*a*) Rayleigh scattering, for particles must smaller than the wavelength of light,

(*b*) The change in the nature of scattering as the particles increase in size,

(*c*) the " residual blue " effect first reported by Tyndall,

(*d*) the sequence of colour changes in the transmitted light as the size of the particles increase,

(*e*) the basis for the striking contrast in the colour of the Setting Sun, when seen through a clean, dust-free and dry atmosphere and when seen through a polluted atmosphere, where coarse particler in suspension obscure the characteristic effects of moleculas scattering.

4.2 The Arrangement :

The experimental arrangement (Dissanaike 1971) is shown in *Fig.* 13.

A narrow, nearly parallel beam of white light traverses vertically the colloidal solution under study. This solution is contained in a cylindrical tube that should have a flat, distortion-free bottom. Details of the optics used are given in the legend of the figure. A mirror M reflects the transmitted beam to a ground glass screen G. By an adjustment of the Lens L and the position of the screen G, a disc-shaped image of the aperture A, formed by rays traversing the solution, could be focussed on the screen, to simulate the image of the sun as it sets.

A box blackened on the inside encloses the cylindrical tube. One side of the box could be hinged, so that the box could be opened when required. A vertical slot cut on this side acts as a window W for observing the light scattered sideways. The experiment is best carried out in a darkened room.

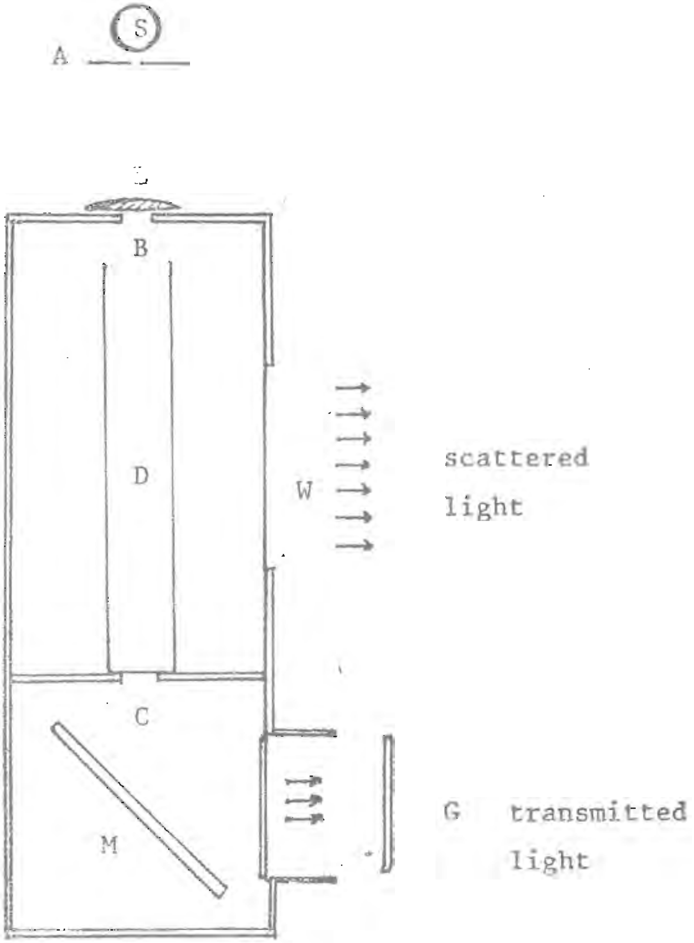

Fig. 13—Laboratory arrangement for studying the scattering of light by colloidal particles in suspension and for simulating the setting sun and the blue sky.

S—50 W single filament lamp; A—an aperture about 0.4 cm. diameter; L—a converging lens (f = 7.5 cm) ; B—an aperture 1.5 cm. diameter ; D— the colloidal solution in a flat-bottomed cylinrical tube approximately 20 cm high and 2.0 cm diameter ; M—plane glass mirror ; C—an aperture about 2.0 cm diameter ; W—a window; G—a ground screen on which the image of aperture A is formed.

4.3 Rayleigh-type Scattering

A colloidal suspension of particles, at an early stage of growth would have sizes much smaller than the wavelength of light. Such a colloidal suspension would scatter light in a way very similar to the molecules of a gas, producing the Rayleigh scattering discussed earlier.

A colloidal suspension of fine sulphur particles may be produced by adding a few drops of dilute hydrochloric acid (about 0.4 ml of 0.02 N HCl) to about 100 ml of a weak solution (about 2%) of Sodium thiosulphate ("hypo") contained in the cylindrical tube. The solution is stirred gently, the tube placed in position and the box closed.

It is important that the solution should be well filtered and that the solution of sodium thiosulphate be completely free of tiny air bubbles before the drops of hydrochloric acid are added. This precaution is necessary as we are seeking to observe the scattering by very fine particles much less than the wavelength of light, and the presence of extraneous particles or air bubbles in the solution would completely obscure the characteristic effects of Rayleigh scattering.

Within a couple of minutes of adding the drops of dilute hydrochloric acid, scattered light of a deep blue colour may be observed through the window W. The laboratory room should be fully darkened in order to see the scattered light. As observed for the scattering of light by air molecules in the laboratory, (discussed in Chapter 3), the blue light seen in this experiment too is of a deeper blue than the blue of the sky. The scattering intensity is inversely proportional to λ^4 and thus the colours in the violet end of the spectrum will be preferentially scattered. The blue colour seen here is the effect due to a mixture of these shorter wavelengths that are scattered. For scattering by the air molecules in the atmosphere, the same colours near the violet end of the spectrum are preferentially scattered, but there is absorption, in the intervening layers of the atmosphere, of the colours in the violet region, the absorption being greater the shorter the wavelength. The characteristic 'sky blue' colour then is the result of both scattering and absorption of light in the atmosphere. In the laboratory experiments, the absorption is almost totally absent, so that the violet and indigo come through with the blue, to give the deeper blue hue in the scattered light.

A polaroid, interposed in front of the eye and rotated, will extinguish the scattered light when its axis is vertical (parallel to the plane containing the incident beam and the scattered beam). When the polaroid is now rotated through 90°, the blue colour comes through with maximum brightness. This confirms that the scattered light is plane polarised, as expected.

In order to give the observer much time to study the scattered light, its colour and its polarisation, the growth of the colloidal particles may be halted after a few minutes by adding a few drops of dilute ammonium hydroxide (about 0.5 ml of 0.02 N solution).

The light transmitted through the solution, focussed on the ground glass screen as a circular patch resembling the sun, would be bright orange-yellow in colour (white minus blue), much like the colour of the sun at daytime. A colour photograph could be taken at this stage to record the colour of the scattered light (simulating the sky) and of the transmitted light (simulating the setting sun).

4.4 Effects due to the Growth of Particle Size

The addition of a few drops of 0.02 N hydrochloric acid once again makes the colloidal particles to begin growing in size. As the size of the scattering particles gradually increase, the simple theory of scattering (Rayleigh 1871) is no longer valid. Rayleigh (1881) has given a more general theory to include such cases, and has shown that in respect of larger scattering particles, if the incident light is plane polarised with its vibrations parallel, say, to the z-axis, the intensity of the light scattered along the z-axis would vary as the inverse 8th power of the wavelength, that is proportional to $1/\lambda^8$. Thus, in the above arrangement, if a polaroid is held with its axis vertical, in the position in which it (earlier) extinguished the scattered light for Rayleigh-type scattering, the colour coming through now would be an even deeper and richer blue, called the "residual blue" first observed by Tyndall.

The rate of growth of the particles size can be increased by adding more drops of dilute (0.02 N) hydrochloric acid and if it is desired to arrest the growth at any particular stage, the corresponding amount of 0.02 N ammonium hydroxide may be added. In this way, the study of the scattering effect, as the particle size increases, can be conveniently made, taking time at each stage of growth to fully investigate the colours of the scattered and transmitted light, and the polarization of the scattered light.

The author has taken several colour photographs with the above arrangement, recording the sequence of colour changes as the size of the colloidal particles increases.

The addition of an adequate amount of 0.02 N hydrochloric acid can speed the process of particle growth so the particle size becomes, comparable with the wavelength of light. Most wavelengths are now scattered. The transmitted light takes on a deeper and deeper shade of red, which gradually fades in intensity as more light is lost by scattering. The scattered light seen in this arrangement becomes almost white with only a tinge of blue.

A colour photograph has been taken at this stage, superposed on a previous photograph taken when the scattering was of the Rayleigh type (that gave blue scattered light and bright orange-yellow for the transmitted light). This photograph is reproduced in Plate I. There is seen a striking contrast in the colour and intensity of the transmitted light (shown as spots of light adjacent to each other) at the two stages of the particle growth, one at the very begining when the size was much smaller than the wavelength of light and the other when scattering by larger particles predominates.

In the next Chapter, there is a discussion included of the effect of a polluted atmosphere on the colours seen in the sky, especially near sunset. Colour photographs of sunsets have been taken at two places: (*a*) in Sri Lanka (from Peradeniya Campus) where the air is clean and relatively free of dust and coarse particles, and (*b*) near the city of Boston, Massachussetts, U. S. A., where the atmosphere is clearly polluted with waste gases and other air pollutants. The setting sun observed in Sri Lanka and in Boston appear to show the same contrast in colour and intensity as the two spots of transmitted light seen superposed in Plate I. This is further discussed in Chapter 5.

4.5 Mie Scattering

As mentioned earlier, when the size of the scattering particles increases, the conditions for Rayleigh scattering no longer hold, and Mie scattering (1908) then takes over. Mie worked out a general theory of scattering for both absorbing and non-absorbing spherical particles of size comparable to or greater than the wavelength of light. La Mer and co-workers have carried out extensive studies on colloidal particles of sulphur using dilute solutions of sodium thiosulphate and hydrochloric acid. By starting with very dilute solutions and observing over a period of several hours so that the particles grow uniformly and gradually in size, they have confirmed the following features (La Mer and Johnson, 1947) :

Plate I

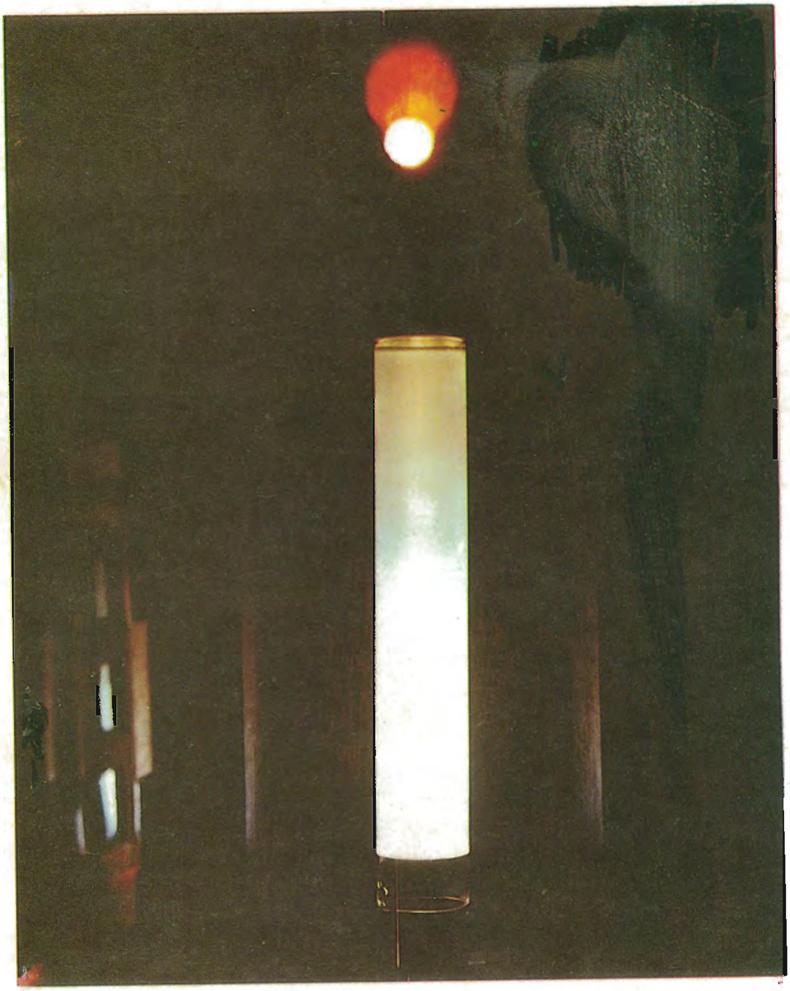

Plate I A colour photograph taken of the scattered light and the transmitted light seen in the arrangement of Fig. 13 as described in Chapter 4. The two spots of light, seen at the lower end, of widely different colour and intensity arise from the transmitted light passing through the colloidal suspension of sulphur at two stages of particle growth: (a) the bright yellow-orange spot, when the particle size is much smaller than the wavelength of the light and (b) the dull red spot, at a much later stage when the size of particle is greater than the wavelength. Two exposures have been made.

(*i*) there is more light scattered in the forward direction than in the backward,

(*ii*) in a direction normal to the incident light, the scattered light seen through a polaroid, with its axis parallel to the plane of scattering, is of a deeper blue, as noted in section 4.4.

(*iii*) the particle size increases gradually from about 0.2 μm to 1.0μm in several hours,

(*iv*) the angular distribution of the scattered intensity shows maxima and minima, corresponding to what is termed high order Tyndall spectra, the angular positions of the order depending on the particle size (see Chapter 6, section 6.6),

(*v*) red and green coloured bands are observed at various scattering angles.

Such studies show clearly the possible applications of light scattering methods for determing particle sizes of aerosols and colloidal particles (hydrosols). Recently, Dissanayake and Premaratne (1984) have used such a method to determine the number concentration and average size of particulate matter in water samples collected at Peradeniya.

CHAPTER 5

EXPLORING THE SKY

5.1 Learning by Observing

The observation of nature and of the world outside offers an important avenue of learning for the student of Physics. One of the most fascinating pursuits is the study of light and colour in the sky. As we have seen in earlier chapters, such investigations, supported by experiments conducted in the laboratory, can lead to an understanding and appreciation of nature and its secrets.

5.2 The Drama of the Setting Sun

We in Sri Lanka have the distinct privilege of enjoying, most of the year, the colourful spectacle of the evening skies and the setting sun, a spectacle that no skilled artist can surpass on canvas or a gifted poet adequately portray in verse. Yet, very few of us take time off to gaze at the skies in wonder and delight, and to study the sequence of colours in and around the sun as it sets over the horizon.

The air over Peradeniya is often clear and clean, setting the stage for viewing a beautiful sunset from the hills overlooking the Campus. The author has captured this colourful drama of the sunset, at intervals of about ten minutes, in colour photographs on 35 mm Kodachrome slides, that record the sequence of colour changes with distance across the sky and with time. A pattern of clouds reflect the light of the sky and add to the beauty of the scene. Three of these photographs are reproduced in Plates II to IV. Such sunsets are possible when the air is clean and generally free of foreign particles in suspension, so that the scattering of light is mainly due to the air molecules themselves.

In sharp contrast are the photographs of sunsets (*see* Plates V and VI) taken in the same way in a highly industrialized country, near the city of Boston, Massachussetts, U. S. A. In such an industrialized location, the atmosphere is clearly polluted with industrial gaseous effluents. At times, the pollution is so thick that the sun fades into a dull red disc that is barely seen in the sky, long before it sets over the horizon. Often, the red glow of the setting sun fills the region of the sky and, after the sun sets, the sky appears as two broad bands of colour, red below and

Plate II

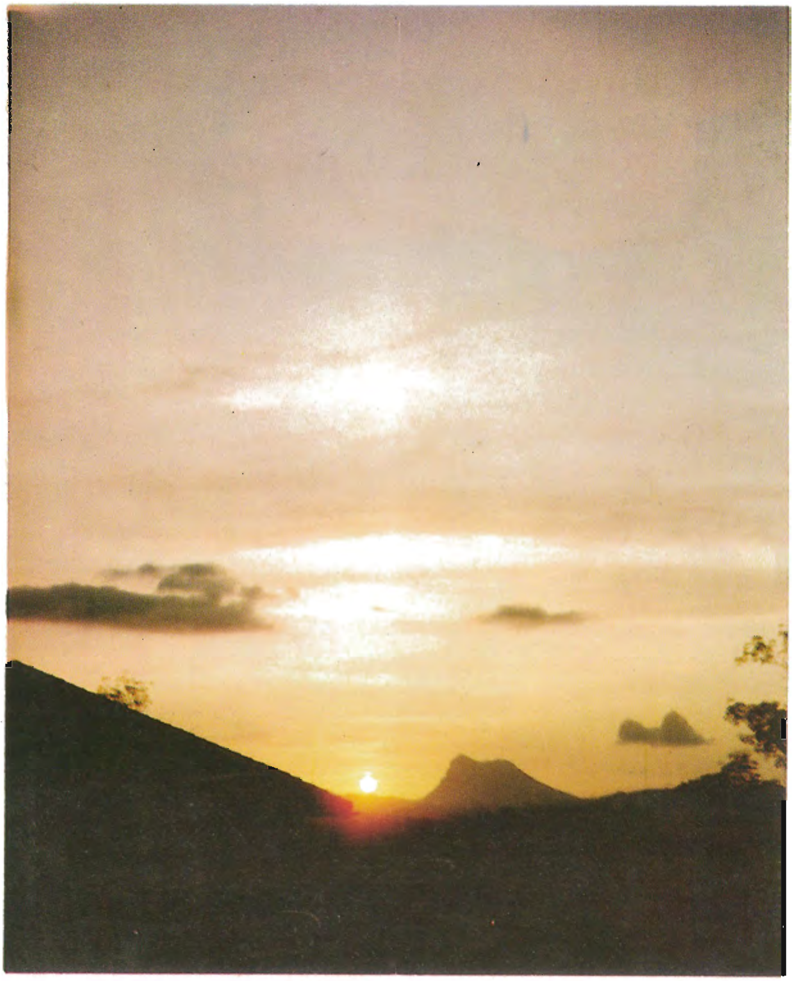

Plate II to IV Colour photographs of a sunset taken from the Peradeniya Campus on a clear day (in 1968). The sequence of colours across the sky, near and away from the sun, may be observed, varying for different times during the sunset.

Plate II shows the sun just setting over the horizon to the side of Alagala Rock. Plate III shows the western sky after the sun has set, with more of the blue appearing in the sky. The clouds at the lower region reflect the orange-red of the direct sunlight, while the thinner cloud higher up show a tinge of violet, as the blue of the sky mingles with the orange-red of the sunlight reflected off the cloud. Plate IV shows the sky much later in the evening, where shades of blue now dominate the sky. (The exposure times of the photographs of Plate III and IV are longer than for Plate II).

Plate III

Plate IV

Plate V

Plate V and VI Colour photographs of sunsets taken from near Boston, Massachussetts, on two separate occasions (in 1969). Plate V shows a typical sunset observed when the pollutant aerosols in the atmosphere are not too dense. Graded regions of colour indicate layers of pollution. Most of the sky has about the same shade of colour as the sun's disc, which is a crimson red. Plate VI shows a photograph taken on a day when the air pollution is thick. The sun's disc is faint and a dull red long before it sets over the horizon, and the shades of colour seen indicate the layers of pollution.

Plate VI

blue above, completely different in sequence of colour to the sunsets in an unpolluted sky. From the discussion in Chapter 4, it should be clear that these effects, seen in a polluted sky, arise from the scattering of light by particles in suspension (air pollutants) of size comparable to or greater than the wavelength of light, (Dissanaike 1983).

5.3 The Red Light on Pollution

It is the author's belief that such sharp contrasts in the colour and form of sunsets, in polluted and unpolluted skies, will serve as a warning to the people of this country. The industrialization of a country might be regarded as a necessary evil, but the authorities must take strict and adequate measures to safeguard the atmosphere, the land and the water from the dangers of pollution. Indeed, the crimson sun of a polluted sky (as observed in other countries) can serve as a "red light" and a forewarning to us in Sri Lanka !

Again, the author expresses the hope that there will arise a generation of young scientists, who will seek to observe, understand and appreciate the world around them, and thereby develop a conviction and create strong public opinion to preserve the environment against pollution, so that the future generations may continue to enjoy the colourful drama of the setting sun.

5.4 Halo round the Moon

On a clear moonlit night, when there is present thin, feathery cirrus clouds high up in the sky, a spectacular and large halo of light, with a sharp inner edge, may be seen around the moon. This halo is caused by the tiny ice crystals found in the cloud at higher altitudes. The crystals are hexagonal in shape and act as prisms of 60° angle. The moonlight, refracted through these crystals, would reach the eye after being deviated. The minimum deviation in respect of refraction by a 60° prism is given by the well-known formula.

$$\mu = \frac{\mathrm{Sin}\,(A + D)/2}{\mathrm{Sin}\,(A/2)}$$

and substituting for $\mu = 1.31$ for ice, and $A = 60°$, we get the angle D of minimum deviation equal to 22°. Since the intensity of light refracted by a prism has a maximum at the position of minimum deviation, the halo is brightest close to the inner edge at 22°, and this inner edge is well-defined because of the minimum deviation.

Using a simple instrument for measuring angles, a student could verify that the inner edge of this halo is in fact at an angle of about 22° with respect to the centre of the moon. The moon itself has an angular diameter of only half a degree (30^1).

During the day, conditions are possible for the halo to be formed around the sun in the same manner. However, because of the intense brightness of the sun itself, the halo may not be so distinct, and it is certainly not advisable for anyone even to attempt to look for it, unless there is an adequate means of masking or covering the bright disc of the sun first.

5.5 Diffraction Rings round the Moon

When thin cloud at lower altitudes (containing tiny water droplets) drifts over the disc of the moon, diffused coloured rings may be observed close to the moon. The light waves from the moon bend round the edges of the droplets, or are said to be " diffracted ", to produce these rings. The smaller the droplets, the larger the rings seen. The rings seen are not more than about ten times the diameter of the moon. Since the water droplets are not uniform in size, and also not distributed uniformly, the coloured rings seen may not be circular throughout and may be quite diffuse or blurred.

Such diffraction rings can be easily observed by blowing warm breath on to a clean glass slide or a spectacle lens and viewing a distant street lamp or the moon itself. The diffraction pattern will be seen while the tiny particles of moisture remain on the glass surface before evaporation. Fine particles of lycopodeum power sprinkled thinly on a glass surface can also be used, and if a candle is viewed at a distance of about half a metre, diffraction rings may be seen. In fact, such diffraction patterns observed using, say, a sodium flame, could give an estimate of the size of the diffracting particle. If the angular radius of the first dark ring (after the central bright patch) is $\varnothing$, d the average diameter of the particle, and λ the wavelength of the light, then the diameter can be estimated using the relation.

$$\text{Sin}\ \varnothing = 1.22\ \lambda/d.$$

5.6 The Rainbow

Another familiar but colourful phenomenon seen in the sky is the Rainbow, which is usually observed after a shower of rain, or in mist, or in the fine spray produced from a water fall. The small spherical droplets of water are responsible for dispersing and reflecting internally the sunlight passing through them.

A pencil of rays incident on a spherical droplet *Fig.* 14(*a*) will be refracted into the droplet, suffer one internal reflection, and emerge out of the droplet. Different colours (different wavelengths) of the incident light are refracted differently and will emerge at different deviations from the original direction. As mentioned earlier, it is in the position of minimum deviation that there is the greatest intensity of refracted light and thus, for a given colour, the light received by an observer is seen brightest at the position of minimum deviation for that colour. The acute angle corresponding to the minimum deviation is 42°20′ for red light and 40°23′ for violet light, as shown in *Fig.* 14(*a*). These give the conditions under which an eye at O receives the red and violet light, *Fig.* 14(*c*), after the light has been deviated by water droplets at a particular region of the sky. Since all droplets contributing to any one colour (same angle of minimum deviation) must lie on the surface of a cone, whose axis passes through O and is paralled to the sun's rays, the colour is seen as part of a circular bow, different colours being arranged according to the wavelengths, the violet on the inside and the red on the outside. This is the *Primary Rainbow*, due to conditions illustrated in *Fig.* 14(*a*).

A weaker *Secondary Rainbow* may also be seen outside the primary bow, due to conditions shown in *Fig.* 14(*b*). Here, the light passing into the droplet suffers *two* internal reflections before emerging. The corresponding acute angle for minimum deviation is 50° 34' for red and 54° for violet. Thus, the secondary bow has red on the inside and violet on the outside

A student observing the rainbow should take note of the following :

(*i*) The rainbow is not an object that is visible at a definite location, but is seen due to light coming *from a particular direction*. Thus the rainbow " moves " with the observer. There is a legend that one can find a pot of gold at the foot of a rainbow. You can be certain that that pot of gold can never be found !

(*ii*) The rainbow can only be seen when the sun is behind the observer, and the centre of the bow is in the direction of the shadow of the head of the observer.

(*iii*) The bow is only an arc of a circle because the water droplets are all located well above the observer. If the observer is viewing the rainbow from a aeroplane at high altitude, the bow can be seen almost as closed circles with the shadow of the plane lying in the direction of their common centre.

(*iv*) The secondary bow is much weaker as it is formed after two internal reflections. At each internal reflection, part of the light emerges out and is lost to view.

(*v*) The sky between the two bows is *darker* than the rest of the sky. This is because the droplets between the two bows cannot send any colours to the eye (as the deviation would then have to be *less* than the minimum.)

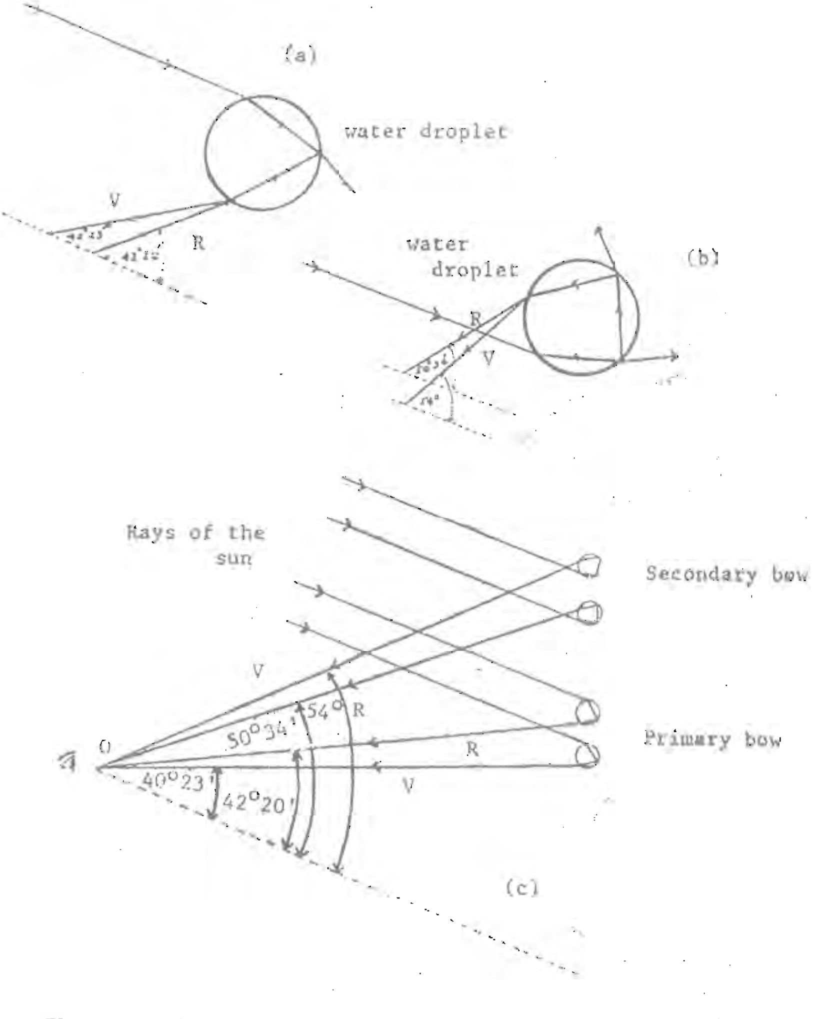

Fig. 14—Conditions for observing the primary and secondary rainbow

CHAPTER 6

ELEMENTARY THEORY OF SCATTERING

6.1 Observed Features

We have been discussing in earlier chapters some interesting effects due to the scattering of light by small particles. These particles may be molecules of air or a gas, they may be aerosols (that is, particles suspended in a gaseous medium) like smoke, fog, and dust, or colloidal particles in suspension in a liquid.

If the scattering particles *are small compared to the wavelength of light* and exhibit no absorption of their own, then the following features may be observed in the scattered light :

(*a*) The intensity of the scattered light varies as a function of the scattering angle Θ, being greatest for scattering in the forward and backward direction ($\Theta = 0°$ and $180°$) and weakest for the direction normal to the direction of the incident light ($\Theta = 90°$).

(*b*) In the direction normal to the incident light, the light is completely plane polarised, with the electric vector (and the plane of vibration) perpendicular to the plane containing the incident beam and the scattered beam.

(*c*) The degree of polarisation decreases gradually to zero as the angle Θ of scattering changes from 90° to 0° or 90° to 180°. At $\Theta = 0°$ and $\Theta = 180°$, the scattered light is unpolarised, like the incident light.

(*d*) The intensity of the scattered light increases rapidly as the wavelength of the light decreases. If white light is used, the shorter wavelengths are predominantly scattered, thus resulting in the blue colour of the scattered light. The transmitted light is therefore ' white minus blue ' or of a bright yellow-orange colour.

6.2 Interaction of Light with Matter

We consider a medium that is non-homogeneous, like aerosols, colloidal particles or molecules of a gas. It was Lord Rayleigh (1871, 1899) who first gave an explanation of the blue colour of the sky, deriving a theory which is applicable for gases, and also applicable for non-absorbing particles in suspension in a medium *provided the particles are small compared to the wavelength of light.* He used electromagnetic theory to obtain an expression for the intensity I_{sc} of the scattered light. According to his theory, I_{sc} should be dependent as follows :

(*a*) vary inversely as the fourth-power of the wavelength λ,

(*b*) vary directly as the square of the volume of each particle, or as the sixth-power of the particle diameter d,

(*c*) vary inversely as the square of the distance of the observer from the scattering centre,

(*d*) vary with the angle Θ of scattering by the factor $(1 + \operatorname{Cos}^2 \Theta)$,

(*e*) be proportional to the number of scattering particles per unit volume,

(*f*) be proportional to $(n_1^2 - n_o^2)^2 / (n_1^2 + 2n_o^2)^2$,

where n_1 and n_o are the refractive indices of the material of the particles and of the surrounding medium respectively.

In respect of air or gas molecules, the scattered intensity is proportional to $(\mu - 1)^2$, where μ is the refractive index of the air or gas.

The predictions of this theory have been verified by laboratory experiments, and the theory gives an explanation of the chief features of scattering by small particles of size much less than the wavelength, as listed in section 6.1 above.

6.3 Dependence on the Wavelength

Rayleigh's theory is beyond the scope of this article. A simple theory may be given, based on the well-known laws of electromagnetism that an induced e.m.f. is proportional to the rate of change of a current and is in a direction such as to oppose the change of current.

We consider a particle much smaller than the wavelength λ of the light. The alternating electric field of the light wave (an electromagnetic wave) will cause the electrons and the positive atomic nuclei to be displaced in opposite directions so that an electric dipole moment is induced. This induced electric dipole moment for a single atom has been illustrated in *Fig.* 1 and is denoted by P.

For an isotropic material, this induced electric moment P is parallel to the incident electric field E and, when E is small, is given by

$$P = S E$$

where S is called the polarizability.

The induced electric dipole moment P will alternate or oscillate with the frequency of oscillation of the electric vector E of the incident light. According to classical electromagnetism, an oscillating electric dipole will radiate electromagnetic waves, and thus behave as an ' atomic antenna '.

The radiated or scattered wave will have an electric vector E_{sc} that

(*a*) is of the same frequency of oscillation as the incident wave,

(*b*) is in the same direction as E (for isotropic material),

(*c*) bears a simple relation to E.

We may consider the electric dipole induced (*see Fig.* 1) as equivalent to opposite charges + q and - q separated by a distance x.

Thus $$P = qx \tag{1}$$

and the induced current

$$i = q \frac{dx}{dt} \tag{2}$$

Since the induced e.m.f. is proportional to the rate of change of current and acts in the opposite direction, the induced or scattered electric field

E_{sc} will be proportional to $-\left(\frac{di}{dt}\right)$.

Thus $$E_{sc} \propto -\frac{d}{dt}\left(q\frac{dx}{dt}\right)$$

and from Eq (1), $$E_{sc} \propto -\frac{d}{dt}\left(\frac{dP}{dt}\right) = -\frac{d^2P}{dt^2} \tag{3}$$

If the incident light has a frequency p the electric dipole moment P will also alternate with the same frequency p, and may be expressed by

$$P = P_0 \sin 2\pi pt$$

and so $$\frac{d^2P}{dt^2} = -(2\pi p)^2 P.$$

From relation (3) above, we have

$$E_{sc} \propto (2\pi p)^2 P$$

and therefore since the intensity of scattered light is proportional to the square of the amplitude of the E_{sc} vector,

$$I_{sc} = (E_{sc})^2 \propto 16\pi^4 p^4 P^2.$$

If c is the velocity of the light waves, then $p = \frac{c}{\lambda}$ and

$$I_{sc} \propto \frac{16\pi^4 c^4}{\lambda^4} P^2.$$

Thus, our simple theory shows that

$$I_{sc} \propto {}^1/\lambda^4,$$

which relation expresses the inverse fourth-power law of Rayleigh scattering.

We note that :

(*i*) the theory applies to particles that are small compared with the wavelength λ of the light, and

(*ii*) the scattered light is in phase with the induced polarization, but it does *not* follow that the scattered light is in phase with the incident light. In general, there is a phase difference between the incident light wave and the induced polarization, and therefore the scattered wave may interfere with the incident wave.

6.4 Dependence on the Pressure or Density of a Gas

Rayleigh's theory predicts that I_{sc} is proportional to the number of particles per unit volume, and therefore on the pressure or density of the gas. An absolute value for I_{sc} can be calculated on this theory in respect of the scattering of sunlight by air molecules in the atmosphere on a clear day. Rayleigh (1899) showed that the brightness of the blue sky could be accounted for almost entirely by the scattering of air molecules alone, and was thus able to estimate a value for the number of air molecules per unit volume. Using this value, he obtained an approximate value for Avogadro's constant $N_A = 7 \times 10^{23}$ per gramme molecule.

Strutt (1918) has carried out extensive studies of the intensity of light scattered by gases in the laboratory and has verified Rayleigh's theory in respect of the dependence on the pressure or density of the gas, and on the factor $(\mu - 1)^2$, where μ is the refractive index of gas.

6.5 Scattering by Larger Particles

The discussion above has been confined to the scattering by small particles of diameter $d << \lambda$.

If the size of particle is not so small, so $(d \sim \lambda)$, the induced polarization at any instant will vary across the particle. This makes the problem more complicated, and the fourth-power law no longer holds. Mie (1908) worked out a general theory of scattering of light both for absorbing and non-absorbing spherical particles. The scattered intensity varies in a complicated manner with particle diameter d, refractive indices n_1 and n_o and angle of scatter Θ. For the case where $d/\lambda >> 1$, the determination of numerical values can only be done with a computer.

Mie scattering is important in considering the behaviour of clouds and smoke (aerosols), and of colloidal particles in suspension (hydrosols). An experiment has been described in Chapter 4 for studying the scattering by colloidal particles of sulphur. It was noted that as the particle size increases, Rayleigh-type scattering is no longer observed, and the findings can only be interpreted in terms of Mie scattering theory.

6.6 Angular Dependence of Scattering Intensity and Polarization

According to Rayleigh theory, for scattering by particles of diameter $d << \lambda$, the intensity of scattering when the incident light is unpolarized is proportional to the factor $(1 + \text{Cos}^2\Theta)$, where Θ is the angle of scattering.

In this factor $(1 + \text{Cos}^2 \Theta)$, the first term 1 gives the magnitude of the scattered component whose plane of vibration is *perpendicular* to the plane containing the incident and the scattered beams, and the $\text{Cos}^2 \Theta$ term gives the magnitude of the component whose plane of vibration is *parallel to* the plane of scattering.

The radiation figure or scattering diagram corresponding to Rayleigh scattering of unpolarized light by small particles is illustrated in *Fig.* 15. The total intensity of scattering for an angle Θ is given by the magnitude

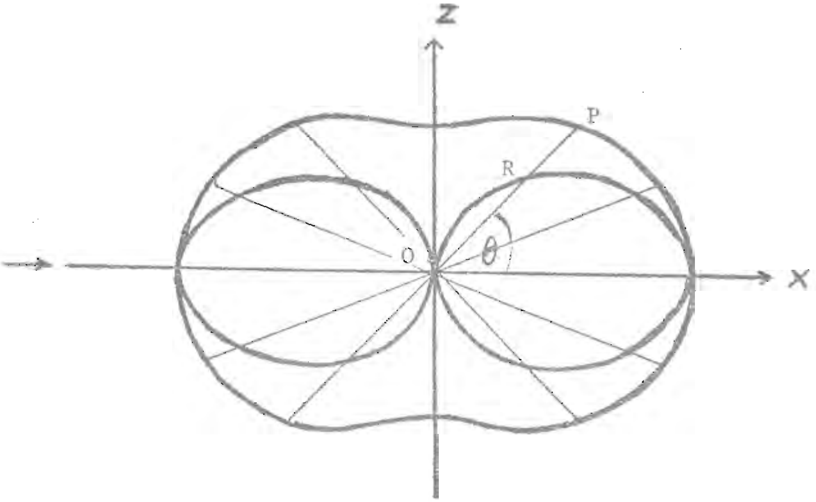

Fig. 15—The radiation figure (or scattering diagram) when unpolarized light is incident on a particle of size $d < < \lambda$. (Rayleigh scattering). The intensity of scattering is given, for an angle θ, by the magnitude of the vector OP of which the polarized component is given by RP. For θ= 90°, the scattered light is completely polarized.

of the vector OP of which the polarized component is given by the magnitude of the vector RP. Thus, for $\Theta = 90°$, the scattered light is completely polarized, and for $\Theta = 0°$, there is no polarized component in the scattered light. The above considerations are not valid when the size of the particles increases and becomes comparable to the wavelength of the light. Mie scattering theory (1908) must then be used to obtain the intensity of scattering for different scattering angles in respect of particles of different diameter d. The ratio n_1/n_o of the refractive indices of the particles and of the surrounding medium is also a parameter. For example, the radiation figure for the polarised component perpendicular to the plane of scattering, determined from Mie scattering theory when unpolarised light is incident on a particle of diameter $d=2\lambda$, with $n_1/n_o = 1.44$, is as shown in *Fig.* 16. Sharp maxima and minima are therefore expected at various angles, different for different values of λ (different colours). The extensive studies carried out by La Mer and co-workers are referred to in Chapter 4, section 4.5. Further details may be obtained from the paper of La Mer and Johnson (1947).

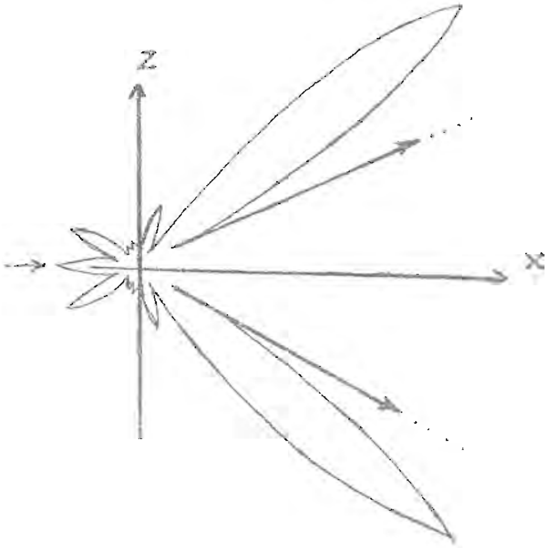

Fig. 16—The radiation figure when unpolarized light is incident on a particle of diameter $d = 2\lambda$, (Mie scattering). Sharp maxima and minimamay be seen in the scattered light which is mainly in the forward direction. Here $n_1/n_0 = 1.44$.

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