LECTURES ON PHYSICAL OPTICS

PART I

(Sayaji Rao Gaekwar Foundation Lectures)

BY

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Prefatory note

In the month of February 1941, the author visited Baroda and delivered a course of two lectures on 'Light as Wave-motion' and 'Light as Corpuscles' respectively. It was the desire of the Foundation which invited the author to Baroda that the subject matter of these lectures should be developed and written out in the form of a series of six lectures for publication. It was planned that the lectures would deal with the following topics: (I) Interference of Light, (II) Diffraction of Light, (III) Coronae, Haloes and Glories, (IV) Optics of Heterogeneous Media,* (V) Light in Ultrasonic Fields* and (VI) Molecular Scattering of Light.* These topics had been the field of investigation by the author and his collaborators for many years and it was intended that the principal results of those investigations should find a place in the published lectures.

The preoccupations of the author slowed down the writing up of the volume for publication and finally brought it to a stop in the year 1943 after 160 pages had been printed off. Much labour and thought had been devoted to the work and it is believed that it contains material of enduring value and interest. Accordingly, it appeared desirable to release the part already printed as part I of the lectures and thus make it available for perusal by those interested in optical theory and experiment.

*Not published.

Lecture I

Interference of light

LIGHT is a phenomenon which we perceive and which plays a fundamental role in human life and activity. Constant experience makes us familiar with various aspects of the behaviour of light. These may broadly be classified under three headings. The first group of experiences relates to the geometric aspects of the propagation of light. Under this heading come the rectilinear path pursued by light from the source to the observer in free space, the casting of shadows by obstacles and the geometric laws of reflection and refraction at the boundary between different substances. The second group of experiences relates to the character of the sensations produced by light, which are three-fold, namely, the brightness of light, the colour and the degree of its saturation. The third group of experiences connects light with the properties of material bodies, namely their capacity to emit, absorb, reflect, refract and scatter light, thereby making themselves visible. The study of the phenomena of light under these headings respectively constitute the three great divisions of optical science, namely, geometrical, physiological and physical optics.

The three categories of optical experience defined above can be brought into intimate relationship with each other only through an understanding of the ultimate nature of the emanation which we perceive as light. Experimental studies enable us to distinguish between those phenomena which are of a subjective or physiological nature and the properties of light that have a definite physical basis. The spectroscope, for example, enables us to separate out the rays of light of different colour and warns us that light which is perceived as yellow visually is not necessarily the same as the light which appears as yellow after spectral analysis. The spectroscope, in fact, enables us to make the first real step in understanding the physical nature of light. It indicates that there are different kinds of light which are physically different, yet analogous to each other, and that if optics is to be an exact science, we must consider the behaviour and properties of light which is truly monochromatic, in other words appears as a sharp single line in the spectrum. Fortunately, various sources of light are available in which the luminous centres are gaseous atoms, the radiations from which on examination through a spectroscope appear as discrete lines of sufficient intensity to be practically useful. Amongst these, the mercury vapour lamp is by far the most generally useful; it is indeed a veritable Alladin's lamp for the student of optics. Other sources of light are occasionally needed for special purposes. Amongst these may be mentioned specially the zinc amalgam lamp, which gives three lines in the blue region of the spectrum which are highly monochromatic, two of them being fairly intense. The lines of the mercury arc appear sharp and single when examined through an ordinary prismatic spectroscope. But examined through a high resolving-power instrument such as a Fabry–Perot etalon, a Lummer–Gehrcke plate or a reflection echelon grating, the mercury lines exhibit numerous components or satellites, while the lines due to the zinc atoms appear as truly single or monochromatic. In figure 1(a) is illustrated the spectrum of the zinc amalgam lamp as recorded by an ordinary spectroscope. Figure 1(b), 1(c) and 1(d) record respectively the same spectrum as further analysed by a Fabry–Perot etalon, a Lummer–Gehrcke plate and a reflection echelon grating. Each of the lines is marked with its approximate wavelength in Angstrom units ($\text{Å} = 10^{-8}$ centimetre), the symbols Hg and Zn denoting that the radiations are due to the mercury and zinc atoms respectively.

The interference of light: The geometric theory of light rays forms the basis of applied optics and is extensively and successfully employed in the computation and design of the lens systems used in optical instruments of various kinds. The practical use made of these instruments in the field and in the laboratory also assumes the validity of the laws of geometrical optics, including especially the rectilinear propagation of light in uniform media. The wave-theory starts with a different view of the nature of light, namely that it is wave-motion propagated through space and that monochromatic light has associated with it a definite frequency of oscillation and a definite wavelength, the product of the two being equal to the wave-velocity in the medium. In certain simple cases, namely in the cases of plane and spherical waves in an isotropic medium, the relation between the ray and wave concepts of light is readily stated; the direction of the geometric rays in these cases is identical with the direction of movement of the wave-fronts. The essentially new possibility which the wave-concept involves is that of interference, viz., that when two beams of light originally derived from the same light source are superposed on each other, the light intensity at any point in the field may be either greater or less than the arithmetic sum of the intensities due to

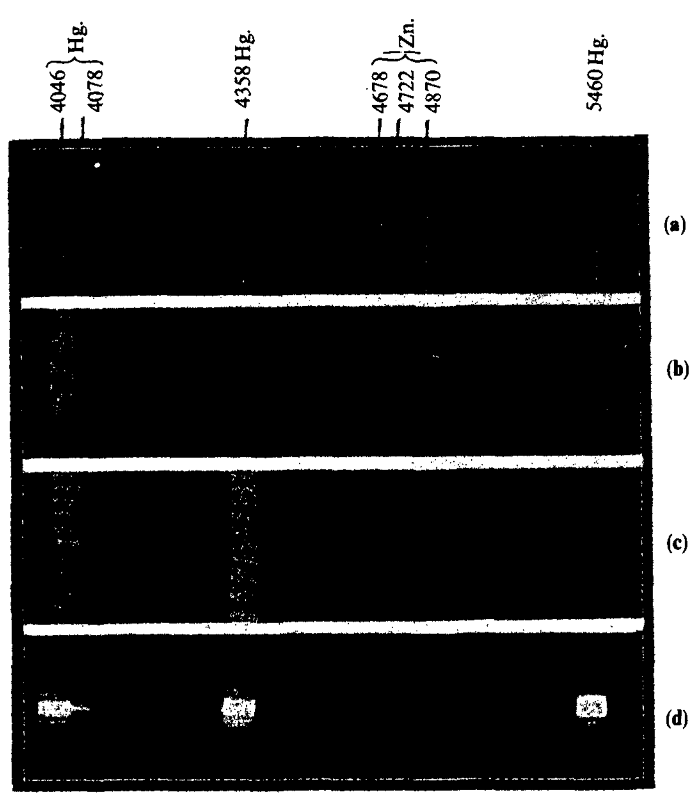

Figure 1. Spectrum of zinc amalgam lamp. (**a**) Prism spectrograph. (**b**) Fabry–Perot etalon. (**c**) Lummer–Gehrcke plate. (**d**) Reflection echelon grating.

either separately. That such an effect is actually observed forms the strongest support for the wave-theory of light.

We may illustrate the principle of interference by considering the case of two beams of light which are divided from the same original beam by suitable optical arrangements and which traverse together a limited region of space before again separating. It will be assumed that the light beams consist of polarised light of wavelength λ and that the directions of their travel lie in the plane of the paper and cross each other at an angle 2Ψ (figure 2). The amplitudes and directions of the light vector in the two wave-trains may be assumed to be identical and to be normal to the plane of the paper. The thin oblique lines in the figure represent the wave-fronts in which the light vector at a particular epoch is a maximum

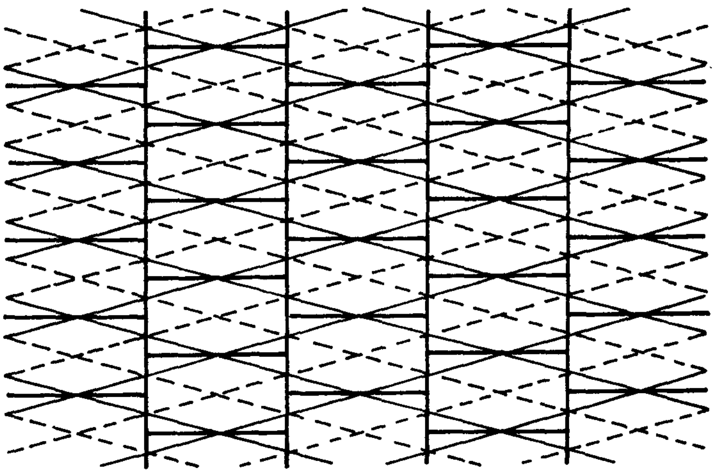

Figure 2. Interference of plane wave-trains.

upwards, while the broken lines represent the intermediate planes at which it is a maximum downwards. The thick lines which have been drawn bisecting the obtuse angles between the wave-fronts represent planes in which the light-vectors are in opposite phases and the resultant intensity is, therefore, zero. At the intermediate planes, the intensity would be a maximum. The thick lines bisecting the acute angles between the wave-fronts are the planes along which the resultant light vector at the given epoch is a maximum upwards. The spacings of these two sets of planes are given by the relations $\lambda = 2D \sin \Psi$ and $\lambda = 2d \cos \Psi$ respectively. When Ψ is zero, D is infinite and d is $\lambda/2$, while when $\Psi = \pi/2$, D is $\lambda/2$, and d is infinite. It is evident that the amplitude of the resultant disturbance oscillates as we pass along the horizontal lines in the figure, while its phase is reversed whenever we cross any of the vertical lines of zero intensity. Hence, the horizontal lines cannot be considered as representing true wave-fronts and they do not therefore possess any significance from the standpoint of geometrical optics. This will be further evident when we recollect that when the two wave-trains separate, they pursue their courses independently along their original directions of propagation. The alteration of the energy distribution in the field indicated by the principle of interference is thus not in any way a contradiction of the basic ideas of geometrical optics.

It is evident from figure 2 that the effect of interference between the two sets of plane waves is to produce a stratification of intensity in the medium, the spacing of which is very wide when the inclination between the wave-fronts is small and diminishes as the inclination increases, reaching the limiting value $\lambda/2$ when the waves travel in opposite directions. When the stratifications of intensity are widely separated, they are readily seen as interference bands in the field. The observation becomes less easy and needs special technique when the spacing of the stratifications narrows down and approaches the limiting value of half the wavelength of light. The optical conditions represented in the figure can be experimentally realised in a variety of ways. The simplest method is to obtain one of the two beams by reflection at the surface of a mirror at the desired angle of incidence, while the other beam is furnished by the incident light itself. It is readily seen from the figures that the character of the resultant disturbance would, in general, be very different when the incident light is polarised with the vibrations respectively parallel and perpendicular to the plane of incidence of the light on the mirror. In the latter case, which is the one discussed above, the light vectors in the interfering wave-trains would be parallel to each other and would differ only in phase, and the alternations in intensity resulting from interference would therefore be most noticeable. On the other hand, when the light vectors lie in the plane of incidence, they would be parallel to the wave-fronts and would therefore be inclined to each other in the two wave-trains. The resulting disturbance would therefore, in general, be elliptically polarised. It is evident that except in the cases of nearly normal or nearly grazing incidence of the light on the mirror, the interferences in this case would result in less conspicuous variations of intensity than when the light vectors are perpendicular to the plane of incidence.

Interferences of parallel plates: As remarked above, the spacing of the stratifications of light intensity in an interference field depends on the angle at which the wave-fronts cross; the larger the angle, the less easily noticeable would they be. The optical conditions for observing the results of interference would obviously thus be most favourable when the superposed beams of light are completely coincident in direction, as the intensity of illumination over the entire field would then be enhanced or diminished, and it would be possible also to use an extended source of light. Such a situation arises when a pencil of light is reflected by or transmitted through a plate of transparent material bounded by plane parallel surfaces. In the light reflected by such a plate, a series of successive reflections at its surfaces appear superposed, the first external and internal reflections being the two strongest and nearly equal in intensity. Similarly, the light beam transmitted by the plate has superposed on it the light beams which have suffered an even number of internal reflections within the plate, these being much weaker. It is readily shown that the optical difference of path between the successive superposed beams in either case is $2\mu t \sin\theta$ where μ is the refractive index and t the thickness of the plate, and θ is the glancing angle of internal reflection. The reversal of phase which occurs at an external reflection has also to be taken into account. Accordingly, in the light reflected by the plate, we have the minimum intensity if $2\mu t \sin\theta = n\lambda$ where n is an integer and λ the wavelength of the light in vacuum. The same condition gives the maximum intensity for the transmitted light.

The considerations stated above indicate that the intensities of the light reflected and transmitted by a plate should exhibit fluctuations if either the thickness of the plate or the angle at which it is viewed be varied. Interferences of this kind are very readily observed and were indeed historically the first to be noticed and explained on the principles of the wave-theory. If the plate be sufficiently thin, white light may be used for the observations, the alternations of intensity then manifesting themselves as variations in the colour of the reflected or transmitted light. The colours of soap films, for instance, arise in this way. If a flat soap-film be set vertically, the horizontal bands of colour which develop on its surface are the result of the thickness of the film increasing as we go downwards. Colour bands on a soap-film may, however, also arise from a variation of the angle at which its surface is viewed by the eye. This effect is well shown by a spherical soap bubble; if the bubble is blown of a uniform thickness, the colour bands on its surface are due solely to the varying obliquity of observation and appear as concentric circles around the line of sight, irrespective of the direction from which the sphere is viewed. On the other hand, if a bubble be of non-uniform thickness, the distribution of colour depends on the direction from which the bubble is viewed. The colour bands are horizontal circles when the bubble is viewed from above or below. But when the bubble is viewed horizontally, the circles appear deformed or displaced downwards, as the result of the effects of varying thickness and of varying obliquity of observation appearing in combination. A spherical bubble at rest tends to drain downwards. This may however be counteracted and the bubble maintained in a state of uniform thickness by gentle currents of air impinging on its surface.*

The phenomena referred to above are illustrated in figure 3, the two upper pictures being respectively those of a uniform and non-uniform bubble viewed horizontally by transmitted light, while the two lower pictures represent similar bubbles by reflected light. The figures also illustrate other features of interest. It will be noticed that the interferences as seen in transmission and by reflection are complementary in appearance. This is to be expected, as the energy that disappears in reflection appears as transmitted light, and *vice versa*. The dark and bright rings in the transmitted light, therefore, correspond respectively to the bright and dark rings seen by reflection. The contrast between the dark and bright rings by transmitted light is evidently much less than in reflection. This is also to be expected, as the interfering beams are not of comparable intensity in the former case, whereas they are of practically equal intensity in the latter. It will be noticed, also, that the contrast between the dark and bright rings by transmitted light rapidly increases towards the margin of the bubble. This is due to the increased

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*C V Raman and V S Rajagopalan, *Proc. Indian Acad. Sci.*, 1939, **A10**, 317.

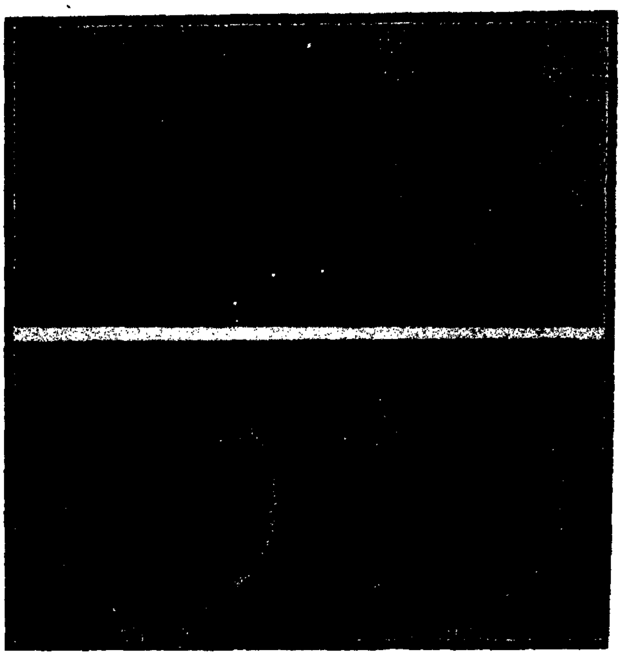

Figure 3. Soap bubbles in monochromatic light.

reflecting power at oblique incidences which makes the intensity of the interfering beams much more nearly equal. Very near the margin of the sphere, the dark rings as seen by reflected light are much sharper than the bright rings, while by transmitted light we have the opposite effect. This is due to the influence of multiple reflections within the film which tend to sharpen the interference bands, a principle which is utilised in the Fabry–Perot etalon and the Lummer–Gehrcke plate.

Haidinger's rings: The interference colours exhibited by parallel plates in white light naturally cease to be visible when the plate is not very thin. The interferences may, however, be observed with thick plates if we use monochromatic light. The case in which the plate is of uniform thickness is of particular interest, as the fluctuations of intensity would then be solely due to variations of the angle of incidence at which the plate is viewed. If an extended source of monochromatic light is seen by reflection at the surfaces of such a plate, the eye being adjusted for distant vision, a set of dark circles would be seen at infinity in the directions corresponding to the values of θ for which the formula $2\mu t \sin\theta = n\lambda$ is satisfied, while bright circles would be seen in intermediate directions. It is evident from the formula that the rings would be centred around the direction of the normal to the plate. As also shown by the formula, they would appear widely separated in the vicinity of the normal, would crowd up in more oblique directions, and open out again in directions nearly parallel to the surface of the plate which correspond to nearly critical incidence of the light within the plate.

The theory of these rings was implicit in the explanation of the colours of thin plates given by Thomas Young in 1809. They were, however, first observed by Haidinger in 1849. It is obvious that to enable them to be seen perfectly in all circumstances, the thickness of the plate should be rigorously constant. In the earliest observation of the rings by Haidinger, this condition was realised by the use of a natural cleavage sheet of mica, the yellow flame of a lamp with salted wick being viewed by reflection at its faces.* The Haidinger rings are of great interest in optics, as they are utilised for the spectroscopic examination of light in the Fabry–Perot etalon and the Lummer–Gehrcke plate, and also furnish the theoretical background for the interferences observed in other instruments, e.g., the Michelson and the Jamin interferometers. In these applications, it is necessary that the plates used should be thick and uniform, and their preparation, therefore, requires a high degree of technical skill. So much emphasis is usually laid on this point that the impression naturally prevails that optically worked plane-parallel plates of glass are essential for the observation of the rings. This impression is, however, not justified. Actually, the rings can be seen in any ordinary plate of glass and it is not necessary that it should be uniform or even plane.† The possibility of observing the rings under these conditions depends upon limiting the area of the plate used to such extent as may be necessary. This may be accomplished using a diffusing screen of smooth board, white in front and blackened behind, with a small circular aperture at its centre. The screen is held very close to and behind the plate of glass with which the rings are to be observed, the white side facing the plate and illuminated by the light of a mercury lamp. The rings are then seen against a dark background by the observer's eye placed behind the aperture in the screen (figure 4). If the plate is both thick and non-uniform, the circular aperture in the screen may be replaced by a fine slit which can be turned round and set parallel to the contour lines of uniform thickness of the plate. A section of the ring-system is then seen in perfect definition along the length of the slit. Figure 5 shows such a system of interferences photographed with a plate of glass 3·5 millimetres thick and so non-uniform that distant objects exhibited by reflection in it two distinct images of varying separation.

If with the arrangements described above, the plate is moved away from the viewing screen, the rings gradually transform to the interferences of the Newtonian type due to the varying thickness of the glass plate. These are located at or near the surface of the plate, while the Haidinger pattern for a flat plate is located at infinity. It is also possible to observe the Haidinger's rings in a curved

*See also T K Chinmayanandam, *Proc. R. Soc. London*, 1918, **A95**, 176.
†C V Raman and V S Rajagopalan, *Philos. Mag.*, 1940, **29**, 508.

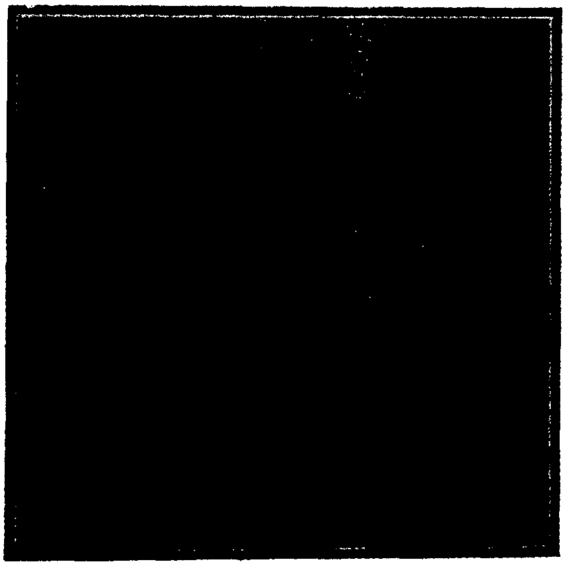

Figure 4. Haidinger's rings in a glass plate.

Figure 5. Haidinger's rings in a non-uniform plate.

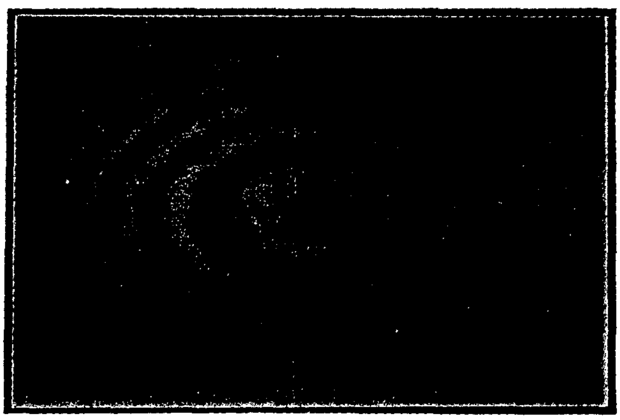

Figure 6. Haidinger's rings in a cylindrical plate.

plate of mica* with the viewing arrangement described above. The configuration of the rings then depends on the distance of the eye from the plate. If the plate be uniform in thickness, the pattern seen is determined solely by the variation of the obliquity with which the surface of the plate is viewed by the observer, and it is readily verified that it is equivalent to the normal Haidinger system modified in the same way as the image of a set of concentric circles would be, if seen by reflection at the curved surface of the plate (see figure 6).

The Fabry–Perot etalon: The Haidinger rings in a plate half-silvered on both sides and seen by transmitted light form the essential principle of the Fabry–Perot etalon which, as already mentioned, is a most useful and powerful appliance for the analysis of light. A very great improvement in the appearance of the fringes seen in transmission is effected by the half-silvering which makes the intensities of the interfering beams much more comparable, and as the result of multiple reflections, also largely increases their number. In practice, it is found more convenient to use a plate of air enclosed between two optically worked plane surfaces of glass; these surfaces are half-silvered and kept strictly parallel at a suitable distance apart by a separating ring of invar metal. The Fabry–Perot rings, as they are called, are observed when an extended source of monochromatic light is viewed in transmission through the plate. If the light used be highly monochromatic, they are seen as sharp bright circles on a dark background. As the result of the silvering and of the multiple reflections resulting therefrom, the transmitted light is much enfeebled and its intensity is negligible except in the precise directions for which all the emerging beams differ in path by the same integral number of wavelengths and can, therefore, totally reinforce each other. For a thick plate, these directions vary very rapidly with the wavelength, and the rings corresponding to closely spaced spectral components in the radiation are, therefore, clearly separated.

It is naturally desirable to use etalon plates of a fairly large area, as more illumination is thereby secured, which is a matter of great importance when working with very faint sources of light. The utility of the etalon is greatly enhanced when the separation of the plates can be varied to suit the problem under investigation. This is conveniently effected by having a selection of metal rings of different thicknesses, the aggregate of which, together with the plates themselves, makes up the total space within which the etalon is mounted. An invar ring of the thickness desired is placed between the plates, while other metal rings fill the gap outside. The etalon plates are adjusted to perfect parallelism by a delicate mechanism which exerts the minimum pressure necessary to tilt and hold them in position. It is convenient to place the etalon between the source of light and the slit of the spectrograph. An image of the interference pattern is focussed

*C V Raman and V S Rajagopalan, *J. Opt. Soc. Am.*, 1939, **29**, 413.

carefully on the slit, and the adjustment of the etalon is made by trial till the best definition of the rings is obtained. The slit of the spectrograph is kept wide open so that a section of the ring pattern is recorded on the photographic plate, the different spectral lines, however, being separated by the dispersion of the spectrograph. Different etalon separations may be used to check the order of interference corresponding to any particular ring seen in the pattern. The absolute wavelength of the radiations can also be determined exactly from the positions of the rings, if the etalon separations are known.

The Jamin interferometer: This very useful instrument which has been extensively employed in refractometry is an application of the phenomenon known as Brewster's bands. Sir David Brewster observed coloured interference bands crossing the image of a source of white light seen by reflection successively at the surface of two plates of glass of equal thickness. The width of the fringes decreases with increasing inclination of the plates to each other.

The course of the interfering beams in the Jamin instrument is shown in figure 7. Part of the light incident on the first plate is reflected at its front surface, and then at the rear surface of the second plate; another part is reflected at the rear surface of the first plate and then at the front surface of the second. The paths of these two beams are equal, irrespective of the angle of incidence, provided the plates are of the same thickness and parallel to each other. If, however, the plates are inclined to each other, the paths are equal only when the incident beams make equal angles with the two plates; for other directions, the path difference would progressively increase. The appearance of fringes with an achromatic centre, and with a width diminishing with increasing inclination of the plates is, therefore, readily understood.

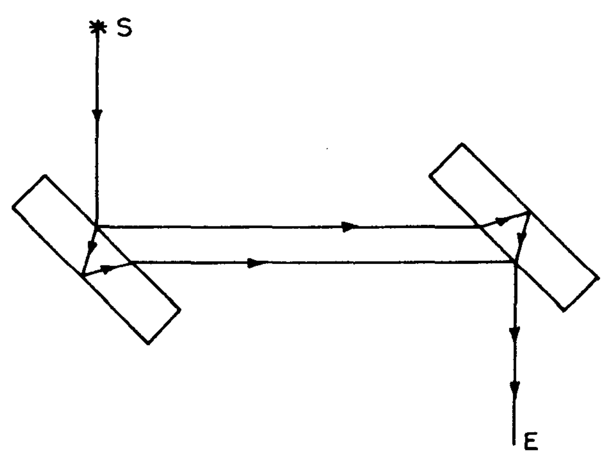

Figure 7. Principle of Brewster's bands.

Brewster's bands can, of course, be seen also with monochromatic light, and indeed the observations can be pushed much further with it. Ketteler, Lummer and others have studied the form of the interference figures over a wide range of incidences and of inclinations of the two plates relative to each other and also for plates of unequal thickness. The figures observed fall into two classes. These correspond to the cases in which the interference occurs under a path difference equal to the sum and the difference respectively of $2\mu_1 t_1 \sin\theta_1$ and $2\mu_2 t_2 \sin\theta_2$, these quantities being the relative retardation of the light beams reflected at the front and rear surfaces of each of the plates separately. It will be noticed that these quantities determine the Haidinger patterns of the two plates, and this suggests an alternative and very instructive way of regarding the theory of Brewster's bands.

It is evident from the diagram (figure 7) that the pattern seen by the eye placed at E and viewing an extended source at S is really the Haidinger system of reflected rings formed by the first plate and then again by the second, in other words, a multiplication of the intensities of the two systems.* The angular position of the dark rings in the two systems are given by the usual expressions

$$2\mu_1 t_1 \sin\theta_1 = n_1\lambda \quad \text{and} \quad 2\mu_2 t_2 \sin\theta_2 = n_2\lambda.$$

The effect of the multiplications of intensities is to give a series of superposition figures,† which may be classified as differentials and summationals of the first, second and higher orders, and the form of which may be derived graphically or analytically. As the Haidinger rings are widely separated at normal incidence, and after first closing up, open out again at more oblique incidence, the complete first order differential pattern consists of two sets of closed curves, the configurations of which relative to the Haidinger's rings are indicated in figure 8 for a particular inclination of two plates of equal thickness. It will be noticed that in the centre of the field, which corresponds to the symmetric direction, the fringes are straight. These are the Brewster bands observed in white light.

Optical study of percussion figures: We shall now consider as an example of interferences of the Newtonian type, a case arising in the study of the permanent deformation of plane surfaces by impact or static pressure. Hertz's well known theory of impact was found to be a correct description of the facts in the case of spheres impinging on each other, only if their surfaces are smooth‡ and highly polished and the velocity of impact is sufficiently small. Accordingly, for an experimental test of this theory as extended to the impact of spheres upon flat plates,§ it was decided to study the collision of polished hard steel balls on smooth

*A Schuster, *Philos. Mag.*, 1924, **48**, 609.
†C V Raman and S K Datta, *Trans. Opt. Soc.*, 1925, **27**, 52 and 1927, **28**, 214.
‡C V Raman, *Phys. Rev.*, 1918, **12**, 442.
§*ibid.*, 1920, **15**, 277.

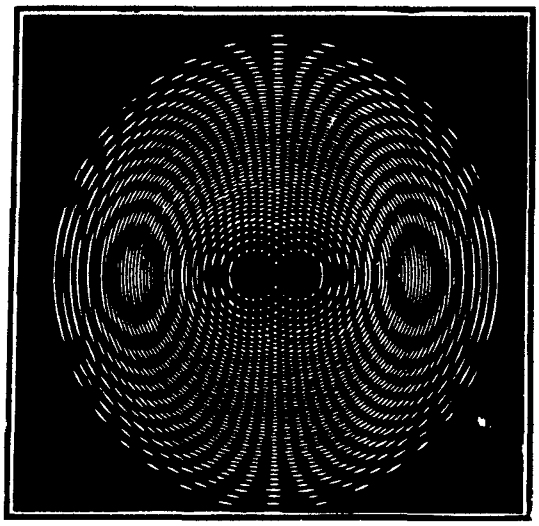

Figure 8. Superposition of Haidinger patterns.

glass plates. It was then discovered that if the size of the balls or their velocity exceeded certain limits, the impact resulted in the production of percussion figures of beautiful geometric form in the glass plates.* A circular crack starts from the surface of the plate and spreads obliquely inwards in the form of a surface of revolution, revealing itself by the light which it reflects. The deformation of the external surface of the glass plate resulting from the collision is very conveniently exhibited by laying another flat glass plate on it, thus forming a wedge-shaped film of air between the two surfaces. The light of a mercury lamp passed by a green ray filter and incident nearly normally upon this film and reflected by it results in interferences which can be readily photographed, the camera being focussed on the percussion figure itself.†

It is evident that the method for the study of percussion figures illustrated in figure 9 can be extended to all solids which are capable of being polished to have a smooth reflecting surface. An inspection of the photograph reproduced shows three distinct regions in the figure. Firstly, there is a central area which is circular and is apparently unaffected by the impact, as is shown by the fringes passing through it being straight and parallel. Secondly, there is a narrow annular region of fracture full of a network of irregular fringes, showing severe injury to the surface. Thirdly and just beyond this, there is a sudden elevation of the surface which slopes down, first quickly and then more slowly, to the original level of the

*C V Raman, *Nature (London)*, 1919, **104**, 113.
†C V Raman, *J. Opt. Soc. Am.*, 1926, **12**, 387.

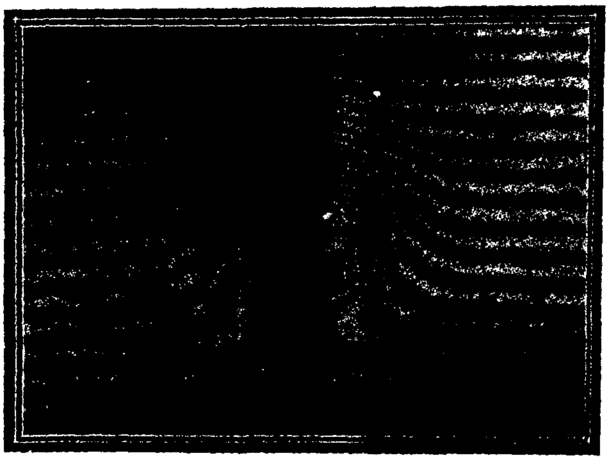

Figure 9. Percussion figure in a glass plate.

surface at the edge of an area which sets the limit to the percussion figure. Closer examination reveals another remarkable feature, namely, that the central area of the percussion figure, though it remains plane and apparently undisturbed, has, in reality, been *depressed below* the original level of the surface by an appreciable fraction of a wavelength, as shown by the fact that the course of the fringes outside the percussion area and within the central circle are distinctly out of register. This feature is observed in the percussion figures even with very thick plates of glass. Additonal details are given in a paper by K Banerji,* where further work is reported on with glass and metal plates. A brief note has also appeared on the percussion figures of crystalline rock-salt photographed by the same method.†

Visibility of interferences in white light: The colours exhibited by thin films illustrate the general principle that when the path-differences are sufficiently small, the effects of interference are perceptible to the eye even with white light. In all interference experiments, if the path-difference is zero and the maxima or minima of illumination for all wavelengths are therefore coincident at some point in the field, an achromatic fringe is there seen, appearing white or black as the case may be. Further out, the fringes are appreciated by the eye principally as alternations of colour, some six or seven of these being seen of gradually diminishing clearness. The explanation of these effects becomes clear when the interferences are examined with a spectroscope with the slit set parallel to the fringes, so that the interferences appear as dark and bright bands crossing the

*K Banerji, *Indian J. Phys.*, 1926, **1**, 59.
†S Smith, *Nature (London)*, 1931, **127**, 856.

spectrum. The number of such bands is small when the slit is near the achromatic fringe, but increases rapidly as the slit is moved away from it, till ultimately the bands are distributed over the spectrum with some approach to uniformity. The failure of the eye to appreciate any differences of colour or intensity in such circumstances is not surprising.

The number of orders of interference visible in white light may be greatly increased by causing the interfering beams to traverse approximately equal optical paths in two media of different dispersive powers. We may, for instance, using white light, interpose a glass plate in one of the arms of a Michelson interferometer and adjust the air path in the other arm to approximate equality. Several hundreds or even some thousands of interferences may then be seen and enumerated, the number depending on the thickness of the glass plate and its dispersive power, but the fringes are visible only as very small alternations of colour in the field.* The explanation of this effect is as follows: The addition of an optical path D in glass of refractive index μ (relative to air) in one arm of the interferometer and of an air path t in the other arm, changes the order of the interference at any point in the field by the number $(\mu D - t)/\lambda$, λ being the wavelength in air of a particular region in the spectrum. The position of the interferences in the field is therefore stationary for small changes of λ, if the variation of this number is zero, that is if

$$D(\mu - \lambda \mathrm{d}\mu/\mathrm{d}\lambda) = t. \tag{1}$$

Equation (1) is equivalent to the statement that the retardation of a *wave group* produced by the extra path D in glass is exactly balanced by the additional air-path t. The corresponding change in the order of interference, in other words, the shift of the "achromatic" band measured by the number of fringes is

$$D \cdot \mathrm{d}\mu/\mathrm{d}\lambda. \tag{2}$$

If the glass plate be thick or if its dispersive power be great, this shift may be quite large. But since $\mathrm{d}\mu/\mathrm{d}\lambda$ alters with the wavelength, neither the thickness t of the compensating air-path, nor the order of interference $D \cdot \mathrm{d}\mu/\mathrm{d}\lambda$ for which equation (1) is satisfied, is even approximately independent of λ. The interferences are therefore "achromatic" only for a limited region of the spectrum, and the position of the "achromatic" band in the field shifts with the part of the spectrum under consideration. In other words, the achromatic band is "dispersed" by the introduction of the glass plate and the number of interferences visible in white light is thereby increased enormously, but only at the expense of diminishing the visibility of the individual fringes almost to the limit. The extraordinary sensitivity of the eye to small differences in colour in adjacent areas, however, enables such fringes to be observed and enumerated.

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*N K Sethi, *Phys. Rev.*, 1924, **23**, 69.

Sethi* to whom the foregoing explanation of the facts observed by himself is due, has shown that it covers also the increase in the number of interferences visible with white light in a plate of non-uniform thickness produced by viewing them through a dispersing prism—an observation originally made by Newton. Its correctness is proved by spectroscopic examination of the interference fringes at various parts of the field. It is then noticed that the interference bands are widely separated in a particular part of the spectrum and crowd together on either side of it. The region of the spectrum at which this effect is observed is found to vary with the part of the interference field under observation. Why the interferences are perceptible to the eye in spite of the great number of bands crossing the spectrum is thereby made intelligible.

Interferences in polarised light: The light reflected at both the surfaces of a transparent plate bounded by the same medium is completely polarised at a particular angle of incidence on the external surface, and if viewed through a polariser set so as to transmit only vibrations in the plane of incidence, is completely quenched. It follows that the plate would, at this incidence, exhibit no interferences by transmitted light for the vibration parallel to the plane of incidence. When the light falls more obliquely, the interferences reappear in the parallel component, but would continue to be weaker than those in the perpendicular component until grazing incidence is reached. Holding up a plate of glass obliquely against a mercury lamp and viewing the interferences through a polariser, it is readily verified that in the fringes seen by *reflection, the maxima* are broader and more intense, while the minima are narrower and more sharply defined for the perpendicular than for the parallel component of vibration. In the fringes seen by *transmission* we have the complementary effect, the minima being broader and darker and the maxima narrower and more sharply defined in the same circumstances.

The cases where the plate is bounded by two different media present some special features of interest. Such a situation arises when a film has one free surface and a solid or liquid backing. The phenomena are then influenced by the optical properties of both the film and the backing material, as also by the nature of the transition between them. The reflections at the front and back surfaces may be of very unequal strength, and this would naturally affect the liveliness of the interferences. The incidence (if any) at which the light is polarised by reflection and beyond which a phase-reversal occurs for the parallel component of vibration would also, in general, not be the same for the two surfaces. Hence the circumstances in which interference occurs would, in general, differ widely for the two components of vibration. If such a plate be viewed through a polariser held in front of the eye and the latter is rotated, striking changes in the colour and

*N K Sethi, *Proc. Indian Assoc. Cultiv. Sci.*, 1921, 7, 37.

intensity of the reflected light may be noticed depending on the obliquity of incidence. As a noteworthy example of this kind, we may mention the oxidation colours exhibited by a polished plate of copper which has been heated up in contact with air. The colours as seen in the parallel component are, in general, more vivid than in the perpendicular component; the two are also observed to be of a complementary character at sufficiently oblique incidences.

Soap bubbles between crossed nicols: Some beautiful and interesting phenomena are noticed* when a soap-bubble is placed between two crossed nicols or polaroids and viewed by transmission against a bright source of light. When only one of the nicols is present, the usual colours by transmitted light are noticed, except that they are slightly more vivid towards the end of the one diameter of the sphere and slightly less vivid at the ends of the perpendicular diameter. With both nicols present, a black cross appears on the surface of the bubble with its arms parallel to the vibration planes of the two nicols. Elsewhere, the surface of the bubble exhibits striking colours which recall those seen by reflected light in their vividness and are, indeed, complementary to the usual transmission tints. With a monochromatic light source, the interferences are as striking as those ordinarily seen by reflected light. Near the margins of the bubble, the minima are sharp and much finer than the maxima, thus reversing the effects usually observed in transmitted light. As the bubble thins down, the interferences successively disappear so that in the penultimate stage its entire surface is bright except for the dark cross. When, finally, the soap bubble goes "black", it retains a faint luminosity, while its spherical margin shines brightly as a crescent of light interrupted by the intersections with the black cross. These effects are illustrated in the series of six photographs reproduced in figure 10. These are arranged in order of increasing thickness of the soap film, the first being that of a bubble which has gone black near the top.†

When the nicols are set with their vibration planes not exactly at right angles, the black cross breaks up into two curved arcs or isogyres. These shorten and approach the margins of the sphere rapidly as one of the nicols is further turned round. With a thick film, the isogyres are themselves the most vividly coloured parts of the bubble. With thinner films it is noticed that when the nicol is turned so that the isogyre moves across an area of the bubble, the colour of the same alters to the complementary tint. With monochromatic light, the isogyres show notable alternations of intensity and appear distorted where they cut the interference curves, while the latter exhibit dislocations at these points which may amount to as much as half a fringe. A "black spot" on the bubble usually appears as a dark

*Unpublished observations by the author.

†The so-called "liquid soap" which is commercially available can very conveniently be used for such experiments. Stable and uniform bubbles are obtained with a highly diluted solution of the same. This should be freshly prepared.

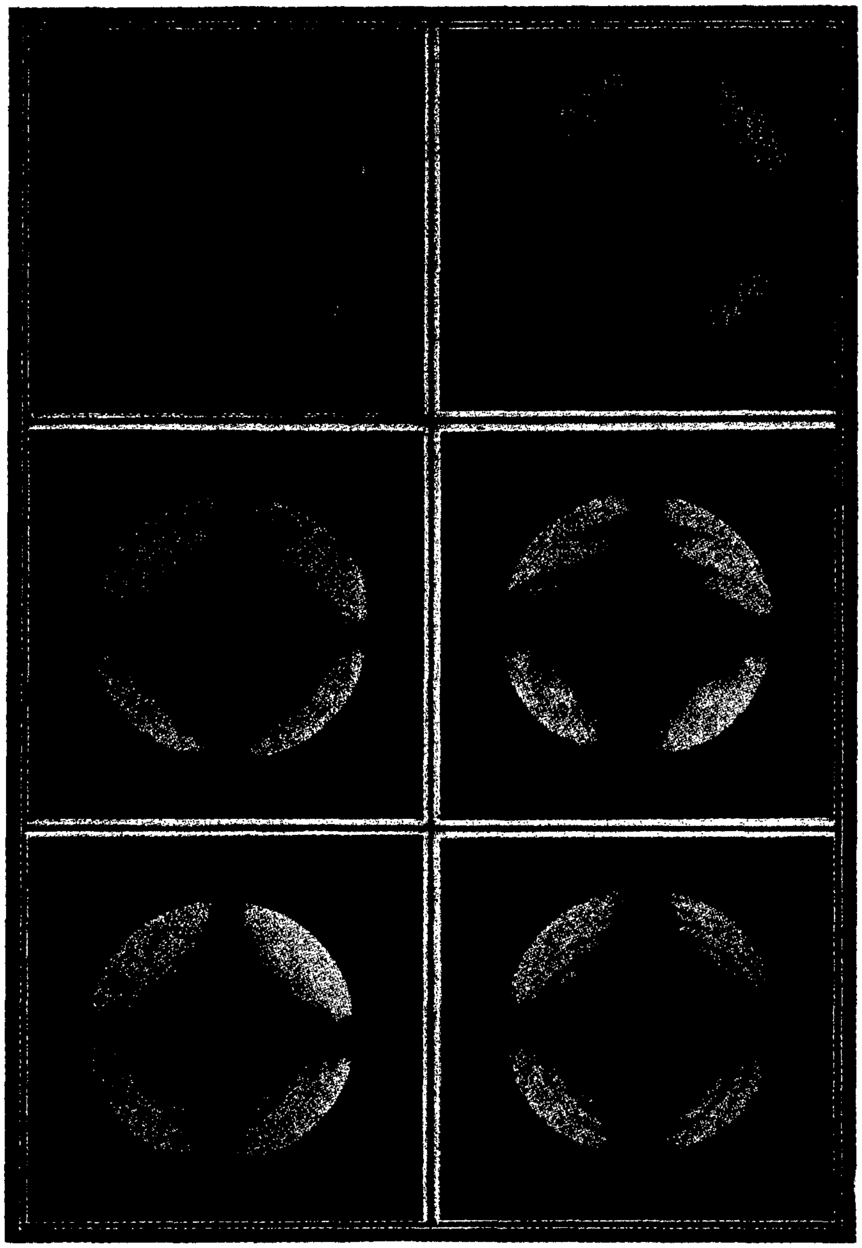


Figure 10. Soap bubbles between crossed nicols.

area on a bright background. But when it passes over one of the isogyres, its optical character reverses and it is then seen as a *bright spot on a dark background.*

The explanation of these effects has been discussed in a paper by K S Krishnan* on the assumption that the films are optically isotropic.† When plane-polarised light is incident on the bubble, the coefficients of transmission and internal reflection are different for the components of the vibration parallel and perpendicular to the plane of incidence. Hence, except when one or other of these components vanishes, the plane of polarisation is rotated by transmission or internal reflection at the surfaces; the light vector turns away from the plane of incidence in transmission and turns towards that plane further at each successive reflection. These rotations are, of course, superposed when a beam undergoes transmissions and reflections successively. In general, therefore, the second polariser fails to extinguish the transmitted and reflected beams. Their components emerging from it accordingly interfere and give the observed luminosity. The smallness of the rotation of the light vector in the transmitted beam taken together with its much greater magnitude and its opposite sense for the light vector in the reflected beam makes the relative amplitudes of these beams after passage through the second polariser comparable, and also involves a reversal of their relative phases. The vividness of the interferences and their similarity to those ordinarily exhibited by the bubble in reflected light are thus readily understood. At nearly grazing incidences, the transmission coefficients become small and the reflection coefficients increase considerably, and the resultant rotations of the light vectors for the transmitted and multiple reflected beams are also no longer in opposite directions. Hence, the considerations stated above require some modification at nearly grazing incidences. Taking these circumstances into account, Krishnan has given an explanation of the luminous crescent exhibited by the "black" bubbles.

Haidinger's rings in crystals: The natural cleavages of various crystals, e.g., mica or gypsum, enable us readily to obtain transparent plates with good optical surfaces which are suitable for the study of the Haidinger interferences. The technique of observation described in an earlier page—namely, that of holding a smooth white illuminated screen containing a viewing aperture very close to the specimen—is particularly well suited for use with crystals. For, with the close approach of the observer's eye to the plate made possible in this way, an extended area of surface coupled with perfect uniformity of thickness becomes unnecessary, and it is possible to see and photograph a large number of rings satisfactorily even with small and not quite perfect specimens *by reflected light.* A photograph of Haidinger's rings obtained in this way with a sheet of mica and the 4358 A.U. radiations of the mercury arc is reproduced as figure 11. The rings as seen by

*K S Krishnan, *Indian J. Phys.*, 1929, 4, 385.

†It may be remarked that stratified films should, theoretically, be birefringent.

normal transmission are, of course, weak. But they may be greatly improved in this respect by half-silvering the surfaces of the plate, in which case the bright rings also become much sharper. For viewing the rings as formed by *reflection*, however, such silvering is unnecessary. An alternative way of observing the interferences of crystalline plates is to hold the specimen obliquely against a monochromatic source and to view the light reflected by or transmitted through it. In this case, of course, only a small part of the interference field is seen at a given time. But we have the advantage that the fringes are then widely separated and the minima (or maxima as the case may be) are also much sharper than in the rings formed by reflection or transmission at normal incidence.

On an examination of figure 11, it will be noticed that the rings do not appear with the same clearness everywhere, their visibility being a minimum along four arcs of roughly hyperbolic form. The interferences exhibit dislocations where they cut these arcs, the dark rings on one side running into the bright rings on the other and *vice versa*, while a distinct doubling of the interferences can be noticed where they run nearly parallel to the arcs of minimum visibility. The form of these arcs of minimum bears an obvious resemblance to the isochromatic curves in the birefringence colours exhibited by a sheet of mica in the polariscope. Indeed, the resemblance is seen to be perfect if the isochromatic curves are viewed with a plate *twice as thick* as that used for the observation of the Haidinger's rings and the observations include a sufficiently wide range of angles. The curves of minimum visibility have then exactly the same shape as the interference figures in polarised light.*

From the facts stated, it is evident that we have, in fact, two sets of Haidinger's rings which overlap and which are seen most clearly where they are in coincidence, and least clearly where the bright rings of one system falls on the dark rings of the other and *vice versa*. That these two sets correspond to light polarised with its vibrations respectively along two perpendicular directions can be directly verified by looking at the ring system through a nicol; as this is rotated, the lines of minimum visibility disappear absolutely in four positions of the nicol at right angles to each other. The two systems therefore also correspond to the two different velocities of propagation of light through the crystal, and the directions in space in which they appear are hence given by the two formulae

$$\delta_1 = 2dv_0/v_1 \cdot \cos r_1, \quad \delta_2 = 2dv_0/v_2 \cdot \cos r_2$$

where v_0 is the wave-velocity in air, and v_1, v_2 are the wave-velocities in the crystal, while r_1 and r_2 are the corresponding angles of refraction of the light into the plate. The lines of minimum visibility of the interferences accordingly correspond to

$$\delta_1 - \delta_2 = 2d \cdot v_0(\cos r_1/v_1 - \cos r_2/v_2) = (2p+1)\lambda/2.$$

*T K Chinmayanandam, *Proc. R. Soc. London*, 1918, **A95**, 176.

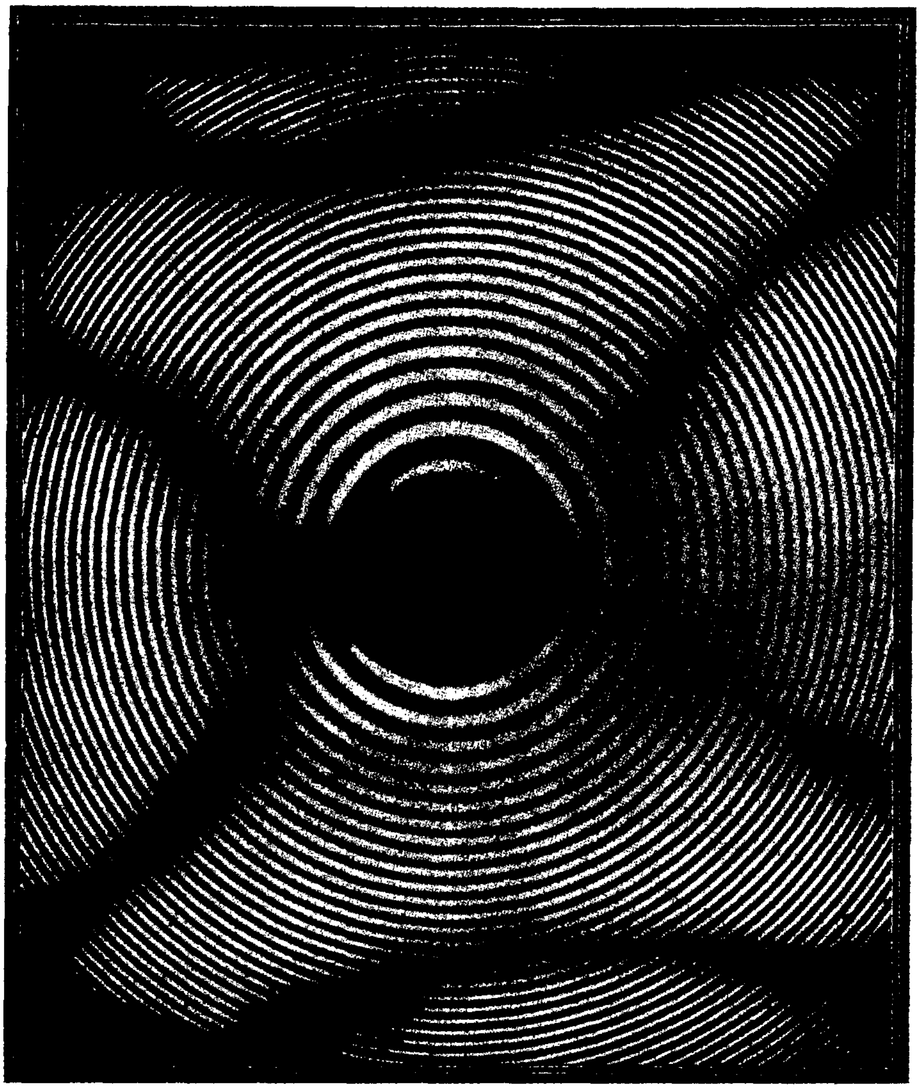


Figure 11. Haidinger's rings in mica.

This is also the well known formula giving the form of the isochromatic lines in convergent polarised light for a plate of thickness $2d$.

Since the wave-velocities v_1 and v_2 in a biaxial crystal depend on the direction of propagation, it is apparent that the rings cannot have a circular form as in the case of an isotropic plate. Their configurations can however be deduced from the expressions given above and the known form of the wave-velocity surface in the crystal. They are, in general, curves of the fourth degree whose form depends on the crystal and on the direction in which the plate is cut. In the particular case when the plate is normal to the plane containing the binormals, and provided the angular separation of the latter is sufficiently great (as in the case of muscovite mica), the form of the curves in the vicinity of the normal to the plate can be shown to be approximately ellipses, their equations being

$$a^2y^2 + b^2x^2 = \text{constant}, \quad \text{and} \quad b^2x^2 + c^2y^2 = \text{constant},$$

where a, b, c are the three principal wave-velocities in the crystal. It is readily shown that the overlapping of two sets of rings of this form would give a set of hyperbolae as the lines of minimum visibility.

The case of uniaxial crystals is also of interest. We may consider three typical examples, viz., a plate normal to the optic axis, a plate parallel to it and a plate cut at an angle of 45°. The configuration of the "isochromatic" curves in these cases is well known. They are in the first case, a set of widely spaced circles, in the second case a family of rectangular hyperbolae which are wide apart near the centre of the field and crowd together towards the margin, and in the third case a series of curved arcs running parallel and close to each other throughout the field. It follows that when unpolarised light is used, the Haidinger rings would be best seen with the first plate, less clearly with the second and should be scarcely visible in the third. Observations were made* with three plates of quartz five millimetres thick (figured by the firm of Hilger) and having the orientation stated, the rings being observed both by reflection and by transmission, in the latter case after half-silvering the plates. Polarisation of the incident light made a great improvement in the visibility of the rings as seen by reflection with the second plate; when it was rotated in its own plane, the rings were clearly seen in four positions and were very confused in four intermediate positions. The positions of the rings were also different for settings of the crystal at right angles to each other. The bifurcation of the rings could be clearly observed in the interference pattern as seen by transmitted light with the half-silvered plates, towards the margin of the field with the first plate and even at the centre with the second. It was evident from these observations that while both sets of Haidinger rings in the first plate were circular, in the second plate one set was circular and the other was elliptic.

Colours of stratified media: Several examples are known of substances exhibiting interesting optical effects ascribable to their possession of a periodic laminated structure. The optical behaviour of such substances includes a variety of phenomena, some of which lie outside the scope of the present lecture. We shall here consider only such of them as come under the category of the interferences of thin plates. Their essential features may be understood by considering the case of

*P N Ghosh, *Proc. Indian Assoc. Cultiv. Sci.*, 1921, 7, 57.

a medium made up of a succession of alternate strata of two different substances having a thickness d_1 and d_2 and refractive index μ_1 and μ_2 respectively. A beam of parallel light enters and tranverses such a medium, its angles of refraction into the alternate strata being r_1 and r_2 respectively. The reflections to which it gives rise at the boundaries of each layer would extinguish each other by interference

$$\text{if}\quad 2\mu_1 d_1 \cos r_1 = n_1\lambda$$

$$\text{or if}\quad 2\mu_2 d_2 \cos r_2 = n_2\lambda$$

as the case may be. On the other hand, if the condition

$$2\mu_1 d_1 \cos r_1 + 2\mu_2 d_2 \cos r_2 = n\lambda$$

is satisfied, the reflections at all the boundaries form two sequences in each of which there is complete agreement of phase. Accordingly, if this condition be satisfied, the advance of the incident wave through the medium results in the successive reflections reinforcing each other. We have then a strong wave reflected *backwards* which ultimately becomes as strong as the primary wave itself. *Per contra*, when the wave thus reflected travels backwards, it meets the successive boundaries in the reverse order, and gives rise to a second series of reflections which join up and build a strong wave travelling *forward*. This being in the same direction as the incident radiation, they interfere with the result that the amplitude of the primary wave progressively diminishes until it is finally extinguished. The net result is thus a *total reflection* in the backward direction of the incident light when it has traversed a sufficient depth of the medium.

We may ask at this stage, how many laminae are required to give a sensibly perfect reflection? The answer depends on the strength of the resultant reflection from a single pair of strata in the medium. The greater the strength of the individual reflections, the more quickly would they add up so as to approach totality. It follows that the number of pairs of strata necessary to secure this result would be of the same order of magnitude as the reciprocal of the amplitude of the reflection from a single pair of strata. The incident wave would then penetrate into the medium to a depth not much greater than this number of strata. Accordingly, the rest of the medium is superfluous and may be removed without the totality of the reflection of this particular wavelength being sensibly affected.

The nature of the result to be expected if the relation

$$2\mu_1 d_1 \cos r_1 + 2\mu_2 d_2 \cos r_2 = n\lambda$$

is not exactly satisfied, clearly depends on the extent to which λ diverges from the value given by the relation. It is *prima facie* evident that the reflection would be sensibly total also for values of λ which differ from it, provided that the resulting disagreement of phase between the reflections from the first and last layers which sensibly contribute to its intensity is a sufficiently small fraction of the wavelength, say one-fourth or less. Accordingly, we infer that *the reflection would* *be sensibly total over a finite range of wavelengths which is proportional to the reflecting power of a single pair of strata and is independent of the total number of strata present*, if this is sufficiently great. Outside the selected range of wavelengths, the intensity of reflection must fall off with extreme rapidity. For, any failure of totality of reflection would involve a greater depth of penetration and thus introduce more reflections which would conspire to extinguish the effects of the earlier layers by interfering with them.

It is evident from the foregoing discussion that when white light is incident on a regularly stratified medium, we obtain a reflection which is more or less perfectly monochromatic, the range of wavelengths included diminishing with the reflecting power of the individual laminations, a sufficiently large number of these being assumed to be present. The reflecting power of an individual pair of strata would be small and the reflection would therefore be highly monochromatic if the alternate strata are nearly equal refractive index or if one of them is of vanishingly small thickness. The number of laminations present influences the intensity and spectral character of the principal band of reflection only when the individual layers reflect so feebly that the radiation of the selected wavelengths penetrates the entire depth of the medium.

It is evident also that weaker subsidiary maxima of reflection would accompany the principal band of reflection in the spectrum. For, the wavelengths outside the range of total reflection would penetrate freely into the medium and the successive reflections would be all of comparable amplitude and of progressively altering phase. Hence, their resultant would not generally vanish but would remain finite, exhibiting oscillations of intensity which progressively diminish as we may move away from the principal band of reflection. The intensity and spread in the spectrum of these subsidiary maxima of reflection would be determined by the number of laminations present. They would be most noticeable when this number is small.

It should be remarked also that the *distribution of intensity of the subsidiary maxima of reflection may be unsymmetric with respect to the principal band of reflection.* For, this distribution would depend on the strength of the reflection by a single pair of strata, and the principal band may well fall in a region where the strength of such reflection alters rapidly with the wavelength. If, for instance, one of the layers is of very small thickness in comparison with the other, the principal *maximum* of reflection would fall in a region of the spectrum in the near vicinity of the *minimum* of intensity in the reflection by a single pair of strata. In such a case, it is evident that the subsidiary maxima would be weak on one side and strong on the other side of the principal maximum.

It is evident also that, in general, several orders of monochromatic reflection would be possible in the spectrum, depending upon the thickness of the stratifications and their refractive index. The relative intensities with which these orders appear would depend on the ratio of the thickness of the alternate strata and for particular values of this ratio, some of the orders of reflection would be missing. Why this should happen becomes clear if we express the periodic variation of refractive index along the normal to the stratifications as a Fourier series of harmonic components. Provided that the variations of refractive index are sufficiently small, each Fourier component thus derived can give rise only to one order of reflection which is observable when the wavelength of the incident light and the angle of its incidence satisfy the relation $2\mu\Delta\cos r = \lambda$, Δ being the spacing of the Fourier component. The absence of a particular Fourier component would thus involve the non-appearance of the corresponding order of reflection. This way of approaching the subject is of value as it enables us more generally to appreciate how the character of the stratifications determines the spectral distribution of intensity amongst the various orders of reflection. It is evident, in particular, why stratifications with a discontinuous distribution of refractive index favour the appearance of a large number of orders of reflection. It should be remarked, however, that the non-appearance of particular orders of reflection with certain types of discontinuous variation of refractive index can also be explained without the aid of the Fourier analysis, by a direct calculation of intensities.

The mathematical theory of the phenomena described above in general terms has been developed in a simple and elegant manner by G N Ramachandran,* and we proceed to give a sketch of it. As already indicated, we have, within the medium, two streams of energy, one travelling forwards and the other backwards. Each layer contributes to the backward stream of energy by reflecting part of the forward stream, and *vice versa*, while it reduces the strengths of these streams directly by transmission through it. Accordingly, if we denote the reflection and transmission coefficients of each layer by the complex numbers r and t respectively, then we have

$$R_s = rT_s + tR_{s+1}$$

$$T_s = rR_s + tT_{s-1}$$

where R_s and T_s represent the amplitudes of the backward and forward streams of energy at a point midway between the $(s-1)$th and the sth layers. Combining successive equations of the above type, we obtain

$$T_{s-1} = yT_s - T_{s+1} \quad \text{and} \quad R_{s-1} = yR_s - R_{s+1},$$

where y stands for $(1 - r^2 + t^2)/t$. Assuming that there are only n laminations we note that $R_{n+1} = 0$, from which it is readily deduced that

$$R_1 = f_n(y)R_n$$

$$T_1 = \left[\frac{1}{t}f_n(y) - f_{n-1}(y)\right]T_{n+1}$$

*G N Ramachandran, *Proc. Indian Acad. Sci.*, 1942, 16, 336.

and

$$R_1 = \frac{r}{t} f_n(y) T_{n+1}$$

where $f_n(y)$ is the finite series $y^{n-1} - [(n-2)/\lfloor 1]y^{n-3} + [(n-4)(n-3)/\lfloor 2]y^{n-5} - \ldots$ to $(n-1)/2$ terms if n is odd, and to $(n-2)/2$ terms if n is even. Putting $y = 2\cosh\beta$, and $r/\sinh\beta = \sinh\alpha$, the series $f_n(y)$ sums up to the expression $\sinh n\beta/\sinh\beta$, and we get

$$\frac{R_1}{\sinh n\beta} = \frac{T_{n+1}}{\sinh\alpha} = \frac{T_1}{\sinh(\alpha + n\beta)}$$

where

$$\sinh^2\alpha = \frac{\{(r+t)^2 - 1\}\{(r-t)^2 - 1\}}{4r^2}$$

and

$$\sinh^2\beta = \frac{\{(r+t)^2 - 1\}\{(r-t)^2 - 1\}}{4t^2}.$$

These expressions are quite general, and involve no assumptions as to the nature of the reflecting layers. If now, we take the stratifications to be of the type considered in the preceding discussion, then by a simple application of the electromagnetic theory of light, it can be shown that r and t have the values

$$r = \frac{-\eta(\exp(ik\delta_1) - 1)}{(\exp(ik\delta_1 - \eta^2)\exp(\frac{1}{2}ik\delta_2)}; \quad t = \frac{(1-\eta^2)\exp(\frac{1}{2}ik\delta_1)}{(\exp(ik\delta_1) - \eta^2)\exp(\frac{1}{2}ik\delta_2)}$$

where η is the reflecting power of the boundaries of separation between the two media, $\delta_1 = 2\mu_1 d_1 \cos r_1, \delta_2 = 2\mu_2 d_2 \cos r_2$, and $k = 2\pi/\lambda$. From these, putting $\frac{1}{4}k(\delta_1 + \delta_2) = \phi$, and $(\delta_1 - \delta_2)/(\delta_1 + \delta_2) = c$, we get

$$\sinh^2\alpha = (\cos^2\phi - \eta^2\cos^2 c\phi)(\sin^2\phi - \eta^2\sin^2 c\phi)/\eta^2\sin^2(1+c)\phi.$$

$$\sinh^2\beta = -4(\cos^2\phi - \eta^2\cos^2 c\phi)(\sin^2\phi - \eta^2\sin^2 c\phi)/(1-\eta^2)^2.$$

The expressions for the reflection and transmission intensities can be discussed using the foregoing values of $\sinh\alpha$ and $\sinh\beta$, and the results so obtained confirm those indicated by the general discussion. It is found that the spectrum of the light reflected at any angle can be divided into two regions, viz., those of the primary and the secondary maxima. These correspond to the regions where $\sinh\alpha$ is imaginary and $\sinh\beta$ is real, and *vice-versa*, respectively. The width of the former region, which determines the sharpness of the reflection, decreases as the number of laminations n is increased, but soon reaches a limiting value. The secondary maxima, however, steadily increase in number as n is increased.

To illustrate these points, the spectral distribution of intensity in the neighbourhood of the first order principal maximum has been drawn in figure 12 for 2, 10, 20, 50 and 100 plates. The reflecting power η is supposed to be 0·1, and the value of

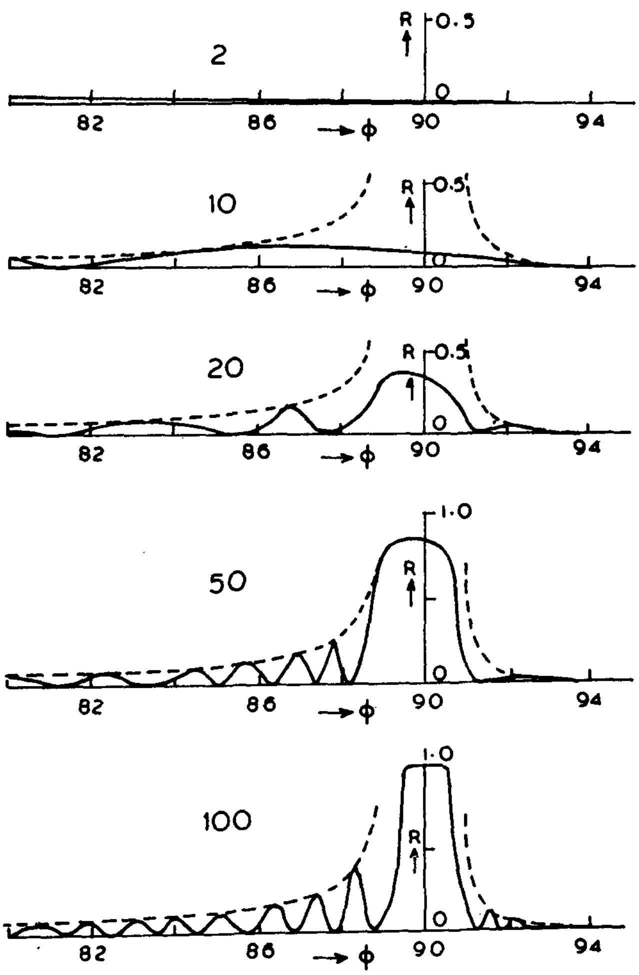


Figure 12. Spectral character of reflection by a regularly stratified medium.

$c = 0{\cdot}9$. The dotted line marks the curve on which the secondary maxima lie, and it shows how the intensity of these is widely different on either side of the principal maximum.

Iridescence of potassium chlorate crystals: Potassium chlorate crystallises in the prismatic class of the monoclinic system, commonly taking the form of flat plates whose faces are parallel to two of the crystallographic axes and are inclined to the third. Twins showing the characteristic re-entrant angles at the edges are not infrequent. The precise circumstances which result in the formation of crystals exhibiting vivid colours are rather obscure. The seat of colour is usually a thin layer within the crystal parallel to its external faces and its power to reflect light appears to be the consequence of a repeated twinning within this layer. It is noteworthy that the coloured reflection vanishes when the plane of incidence of the light coincides with a plane of symmetry of the twinned crystal, while it is of maximum intensity when these two planes are perpendicular. Thus, when a crystal plate is held so as to reflect light obliquely and is turned round in its own plane, the colours alternately appear and disappear twice in each complete rotation. The intensity and colour of iridescence show wide variations. There are some crystals in which the reflections are so weak that they can only be observed with the flake mounted in Canada balsam between two glass prisms so as to eliminate all disturbing reflections. On the other hand, there are cases in which the coloured reflection is so intense that the crystal shines with an almost metallic lustre.

The spectral character of the reflected light is also very variable. In some cases, bands of varying widths are observed covering the whole of the visible spectrum. This is the case when the reflections are feeble and could, therefore, be ascribed to a few twinning planes only being present, possibly at considerable distances from each other and irregularly spaced (see figure 13). The character of the reflections

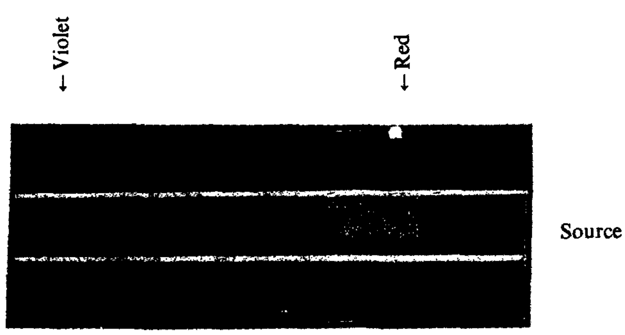


Figure 13. Reflection spectra of potassium chlorate crystals (feeble iridescence).

shown by strongly iridescent crystals is more remarkable, being frequently found to consist entirely of a narrow region in the spectrum (figure 14). It is evident that the reflecting planes are then numerous and are arranged with remarkable regularity. In one such case, L A Ramdas* observed no fewer than eight orders of reflection distributed in a regular sequence in the infra-red, visible and ultraviolet regions of the spectrum, each order of reflection being accompanied by a few

*L A Ramdas, *Proc. Indian Assoc. Cultiv. Sci.*, 1923, **8**, 231.

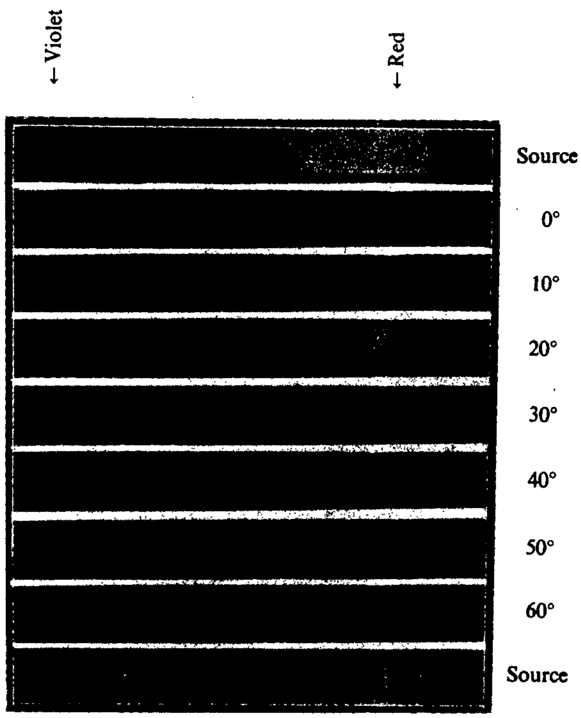


Figure 14. Reflection spectra of potassium chlorate crystals (strong iridescence and varying obliquity).

subsidiary maxima on either side. The general similarity in the appearance of the different orders indicated that these subsidiary bands were of similar origin in each case.

At strictly normal incidence, the twinning planes produce no optical effect, and there is then no hint of colour either by reflection or by transmission. On tilting the crystal even by a few degrees, the reflections appear, and their intensity increases rapidly as the incidence is made more oblique. The transmission colours are scarcely noticeable when the incidence is nearly normal, but rapidly becomes richer at more oblique incidences. The spectra of the reflected and transmitted light are, of course, complementary, a sharp bright band in reflection corresponding to an equally sharp dark band in transmission. (Compare figures 14 and 15) which refer to the same crystal). In the case of the strongly iridescent crystals, the selective reflections are practically total, and the corresponding extinctions in the transmitted light are therefore complete. The effect of varying the obliquity of incidence on the character of the spectra is very striking. The bands shift towards the violet end of the spectrum and at the same time rapidly widen out. The

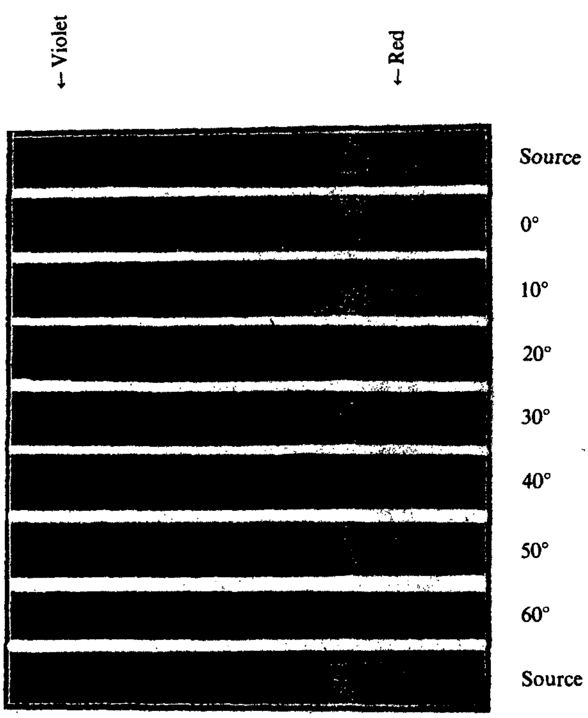


Figure 15. Transmission spectra of potassium chlorate crystals (strong iridescence and varying obliquity).

increased intensity of reflection and the enriched colour of the transmitted light are thus satisfactorily explained. With the particular crystal already mentioned, Ramdas found that the width $\Delta\lambda$ of the principal bands of reflection measured in Angstrom units decreased very markedly with increasing order of the reflection at any particular incidence. $\lambda/\Delta\lambda$ was not far from being the same for the different orders of reflection, but diminished rapidly with increasing obliquity of incidence, being about 150 near normal incidence, about 75 at 23° and 40 at 50° away from the normal.

The increasing width of the spectral bands of selective reflection at oblique incidences is evidently the result of the increased reflecting power of an individual lamina at such incidences, and is thus an illustration of the general theory of reflection by a stratified medium. A similar result may be brought about by keeping the angle of incidence constant, but rotating the crystal in its own plane. We have already remarked that when this is done, the reflection vanishes twice in each complete rotation. Accordingly, we should expect that the width of the spectral bands of selective reflection should oscillate as the crystal is rotated,

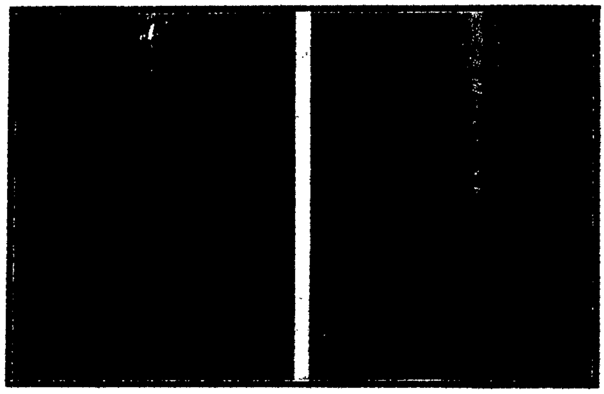


Figure 16. Reflection spectra of potassium chlorate crystals (effect of varying azimuth of reflection).

being least when the reflection is nearly extinguished and greatest when it is most intense. Further, these changes should be the more pronounced the greater the angle of incidence on the crystal. These anticipations from theory are completely confirmed in experiment.* (See figure 16).

A remarkable prediction from theory is that the direction of vibration of the light vector is turned through a right angle in the act of reflection from a twinning plane.† In other words, if the incident light is polarised in the plane of incidence, the coloured reflections should be polarised in the perpendicular plane, and *vice versa.* The late Lord Rayleigh to whom the explanation of the iridescence of potassium chlorate crystals is due, endeavoured to verify this prediction but found he could do so only in the particular case when the incidence of light on the crystal is nearly normal. As pointed out by him, the difficulty in observing the effect at more oblique incidences is the depolarisation of the light in its passage through the crystal before and after reflection at the twinning planes. This difficulty, however, disappears if the coloured layer be sufficiently close to the external surface of the crystal. Observations can then be made even at oblique incidences.‡ One polaroid may be used to polarise the incident light while the reflected light is viewed through a second polaroid and a direct vision spectroscope, the latter serving to eliminate the disturbing reflection at the external surface of the crystal. It is observed, in agreement with the theoretical prediction, that *the spectral bands of selective reflection are strong when the two polaroids are crossed and very weak when they are parallel.* A rotation of one

*Unpublished observations by V S Rajagopalan and the present writer.

†Rayleigh I, *Scientific Papers*, 3, 201.

‡Unpublished observation by the present writer.

polaroid alone when the other is absent makes no difference in the intensity of the coloured reflection. This is also in accordance with the theory.

It may be remarked that the existence of the twinned strata in potassium chlorate is no mere hypothesis, as they can be made visible by suitable sectioning, coupled with the use of polarised light for microscopic observation.* Viewing a crystal plate directly under the polarising microscope also discloses the difference between a twinned and an untwinned specimen. X-ray examination of twinned and iridescent crystals shows a doubling of certain groups of Laue spots which appear single in the untwinned crystals.† A similar behaviour is shown by the crystals in which twinning has been developed by heating up to nearly the fusion temperature and subsequent cooling. The question why twinning occurs with such facility and with such remarkable regularity in many cases in potassium chlorate is of considerable interest and is worthy of fuller elucidation. It is presumably connected with some special feature in the crystal structure of the substance.

Structure and colours of opal: Precious opal exhibits a striking play of colour. The finest specimens give brilliant monochromatic reflections over large areas, the colours ranging over the whole spectrum and altering with the angle of incidence of the light. Some specimens exhibit numerous small glittering spangles of colour, and others again an almost continuous sheen of iridescence. Some very beautiful and valuable opals are grey, blue or black in colour, the iridescence showing up by reflection against the dark background thus provided. Opals of a lighter tint are fairly transparent and in transmitted light exhibit hues approximately complementary to the colour of the reflected light. Opals also usually show a bluish-white opalescence overlying the reflected colours, and if such opalescence is strong, the colour seen by transmitted light tends to a honey-yellow, the complementary tints then being less conspicuous.

In examining the spectra of the reflected and transmitted light, it is important to fix attention upon a limited area of the opal showing a definite colour. The reflected light then appears as a narrow region in the spectrum, the width of which at normal incidence may be as little as 50 Å units or less. Corresponding to the bright band in the reflection, a black band appears in the transmitted light, indicating that the reflection is total (figure 17). On tilting the reflecting surface away from normal incidence, the bands shift towards the violet, broadening as they move. While these features are analogous to those observed with potassium chlorate, in almost every other respect the opal colours behave differently. They do not vanish when the incidence is normal, nor do they vary in intensity or spectral character with the azimuth of incidence. They are also polarised in the

*Rayleigh II, *Proc. R. Soc. London*, 1923, **A102**, 668.
†S C Sirkar, *Indian J. Phys.*, 1930, **5**, 337.

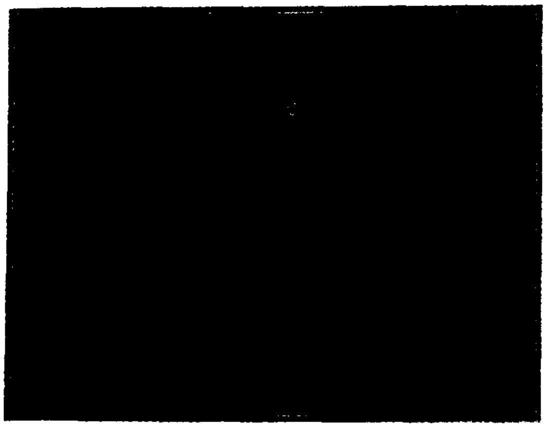
Figure 17. Reflection and transmission spectra of opal.

normal way, as may be shown by immersing the opal in carbon disulphide, thereby enabling the angle of incidence to be increased up to and beyond the angle required for complete polarisation. If polarised light is incident on the opal and the iridescent reflections are observed through a second polariser, they may be extinguished by holding the two polarisers in the crossed position, while in the parallel position the iridescence is seen with maximum intensity.

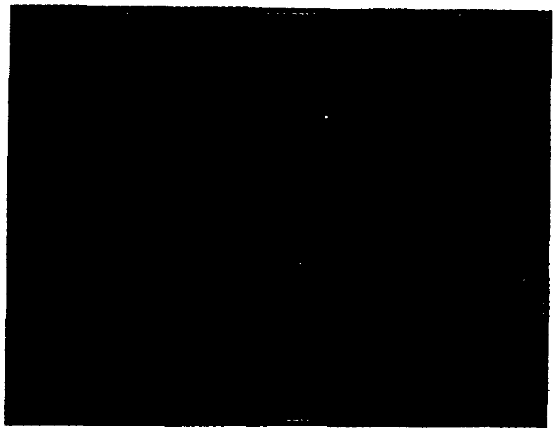
Examination of opal under the microscope reveals that the material possesses a lamellar structure of a remarkable character, there being actually three sets of interpenetrating planes of lamination geometrically related to each other in a manner recalling the rhombohedral cleavages of a crystal of calcite. Each set of laminations is capable of giving a monochromatic reflection of which the wavelength varies with the angle of incidence according to the usual formula. If, in a particular area, all three sets of laminations are exposed, they should be capable of giving reflections of a wavelength determined by the respective angles of incidence of the light upon them. But it is obvious that if the incident light be parallel, it would not be geometrically possible to observe the three reflections simultaneously. Normally therefore, if one set of laminations appears bright by reflection, the two others would, in general, appear dark. If, however, light be allowed to fall on the specimen from different directions at the same time, it should be possible to see the reflections from two or even all the three sets of laminations simultaneously. They would then be visible as sharply divided areas exhibiting different colours in close juxtaposition. The effect is readily observed and is a striking demonstration of the existence of the three sets of laminations.

Figures 18 and 19 are photographs of the same area on a piece of Australian opal, nothing being varied except the direction of illumination. The surface of the specimen was roughly parallel to the exposure of one of the three sets of laminations exhibiting a bright green iridescence. This appears as an extended luminous area in figure 18. The second set of laminations presented exposed surfaces of lesser area appearing as transverse bands and lines cutting across the

(18)



(19)



Figures 18 and 19. Laminated structure of opal.

main luminous area. As seen visually under the microscope, these exhibited a violet reflection. The third set of laminations appears as dark lines crossing the second set obliquely in figure 18. In figure 19 the illumination was so arranged that this third set of laminations appeared as bright yellow lines running through the whole field, the other two sets of laminations being perfectly dark. Effects of this kind may be conveniently studied by placing the specimen on the stage of a microscope, illuminating it from above in any desired direction and rotating the stage.

As the spacing of the stratifications is of the order of the wavelength of light, we can scarcely hope to be able to observe them directly under the microscope except in specially favourable circumstances. Their physical nature and origin is, as yet, an unsolved problem, though numerous studies by X-ray and other methods have been reported in the literature. The spectral character of the reflections indicates that these stratifications are numerous and regular, and also that the reflective power of an individual lamina is not great, thus definitely excluding such crude hypotheses as for instance, the presence of cracks containing air. It appears probable that the material of the stratifications differs little in refractive index from that of the opal substance, or, alternatively, that the reflecting layers are thin even in comparison with the spacing of the laminations. Precise measurements of the polarising angle of reflection may assist in reaching a decision as to the nature of the material present.

Colours of mother-of-pearl: A nacreous layer with a characteristic lustre and iridescence is present in the shells of a great many mollusca. The nature of the material is, however, far from being identical in the different classes of mollusca, e.g., the Bivalves, the Gastropods and the Cephalopods. This is indeed evident from the striking variations in the general appearance of the nacre as well as of its density and other physical properties. Closer examination reveals remarkable variations in the structure and optical properties of nacre, not only of these great classes of mollusca but also of individual genera and species. These facts as well as the ready availability of the material, and the ease with which it can be worked and polished, make mother-of-pearl a substance of considerable interest to the student of optics. Large-sized shells of *M. margaratifera, Turbo, Trochus, Haliotis* and *Nautilus* are easily obtained, and when their nacreous layer is exposed and polished, they make striking exhibits. The iridescence of a large shell of *Turbo* thus prepared may be effectively displayed by placing an electric bulb inside it. The soft and glowing colours of the light which then diffuses out of the shell make an impressive demonstration of its optical properties.

A convenient way of examining the colours of mother-of-pearl is to cut out a piece of the shell parallel to its surface and after grinding it down to a suitable small thickness to polish its surfaces and mount it in Canada balsam between two cover slips of glass. To illustrate the influence of the thickness of the piece on the spectral character of the effects, the material may be worked into the shape of a wedge, not very thick at one end and tapering off to extreme thinness at the other. The transmitted light may then be examined by placing the mounted specimen right up against the slit of a pocket spectroscope. The transmission colour as visually observed is very weak at the thin end and becomes more vivid with increasing thickness. The spectroscope indicates that this effect is due to the spectral band of extinction being very narrow at the thin end and widening out with increasing thickness. This widening is evidently the result of small variations in the spacing of the laminations and illustrates the optical principle that a lack of perfect regularity in the stratifications may actually improve the intensity of iridescence.

Mother-of-pearl consists, in the main, of calcium carbonate which, remarkably enough, is present in the optically biaxial form of aragonite together with varying amounts of an organic substance known as conchin which serves to hold the substance together. The laminations characteristic of nacre are, in fact, made up of successive layers of aragonite in the form of very thin crystalline plates which are held together by the cementing material, there being an immense number of such layers, running roughly parallel to the natural surface of the shell. Examination of thin sections under the polarising microscope shows clearly that the aragonite crystallites all lie with their *c*-axes more or less exactly normal to the general direction of the laminations. The *c*-axis is the direction of vibration for which the refractive index of aragonite is least (1·530), while the refractive indices corresponding to the other axes are larger and nearly equal (1·680 and 1·685). For directions of incidence of the light not far from the normal, the effective refractive index of the crystalline plates is, therefore, in the neighbourhood of 1·68. The refractive index of conchin is probably about the same as that of solid gelatin (1·53), and the difference between this and the index of aragonite (1·68) is fairly large. Hence, if the thickness of the conchin films were at all comparable with those of the aragonite layers, the reflecting power of the individual laminae would be so large that the reflections by a large number of them would not exhibit any very marked spectral selectivity. A consideration of the relative densities of aragonite, mother-of-pearl and conchin, however, indicates that the conchin layers should be very thin in comparison with the aragonite crystals, and this conclusion is independently supported by a microscopic examination of the material. It follows that the reflecting power of an individual lamination should be small, and the fact that mother-of-pearl gives monochromatic reflections and extinctions in much the same way as potassium chlorate and opal thereby becomes intelligible. It is also evident that the relative thickness of the conchin and aragonite layers in different varieties of nacre should influence its optical properties quite as much or even more than the variation in the spacing of the laminations. This view is supported by spectroscopic studies which reveal that the greater vividness of colour exhibited by the mother-of-pearl from certain mollusca, e.g., *Haliotidae*, is largely a matter of the greater width of the spectral bands of extinction and transmission.

The angle at which the laminations meet the surface of the shell varies but is usually small; it may be adjusted to any desired value by suitably cutting and polishing the material. Unless the polishing has been unduly prolonged, the structure of nacre becomes evident under the microscope when its surface is illuminated in such manner that the direct reflection does not enter the field of view. Numerous sharp bright lines on a dark background are then seen (figure 20); these are the intersections of the conchin layers with the surface of the shell, and their configuration depends upon the curvature of the intersecting surfaces and the angle at which they meet. The sharpness of the lines and the character of the optical effects observed makes it evident that the conchin layers

Figure 20. Surface of mother-of-pearl under dark-ground illumination.

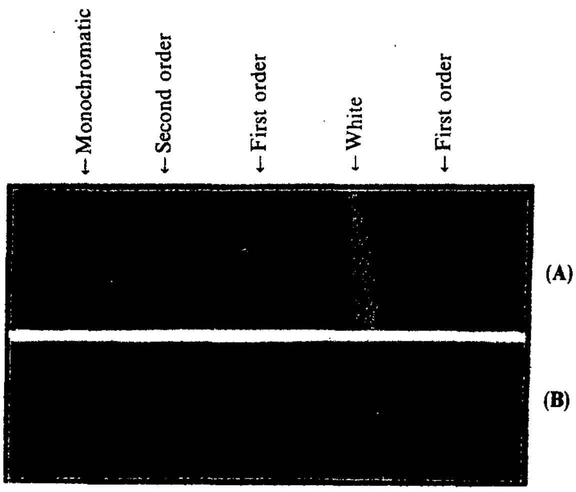


Figure 21. Reflection and diffraction by the surface of mother-of-pearl.

are excessively thin compared with the aragonite crystallites which they separate.

A surface structure such as that illustrated in figure 20 necessarily gives rise to diffraction effects when a pencil of light falls upon it and reflected by it. Figure 21 (A) exhibits the group of diffraction spectra given by a moderately well-polished surface and received on a screen, while figure 21 (B) is the effect observed when the surface is covered by a little Canada balsam and a glass cover-slip. It will be noticed that the diffraction spectra seen in figure 21 (A) have all vanished in figure 21 (B), except the third order on the left which persists with undiminished intensity and in an unaltered position. This is evidently the monochromatic reflection by the internal laminations.* As we shall see in a later lecture, it is a simple consequence of diffraction theory that the directions in which the spectrum of a particular order and wavelength and the selective internal reflection of the same order and wavelength appear, coincide. This fact enables us readily to evaluate the spacing of the laminations optically and to connect their separation as seen on the surface with that directly observed (though with difficulty) in transverse sections under the microscope.

Mother-of-pearl is not only a stratified medium but also a heterogeneous one. This results in a diffusion of light which increases with the thickness of the material and exhibits itself in several ways. While a part of the incident light is selectively reflected, the rest is diffused backwards, forwards and laterally, while the regularly transmitted light progressively suffers extinction. The diffusion backwards, i.e., towards the source of light, results in mother-of-pearl exhibiting a body-colour which is *complementary* to the iridescence. The effect is conspicuously seen when the material is viewed in directions in which the iridescence is not visible. Indeed, the body-colour is also present superposed on the iridescence, thereby diluting its spectral purity. How great such dilution is can best be realised by viewing the shell under the light of the open sky. The iridescence and body-colour then completely overlap, and the shell appears dead-white, even though under directed illumination it may be strongly iridescent. In certain cases, however, as for instance, some of the Californian Haliotidae, the iridescence is very striking even in diffuse light. It would appear that in such shells the body-colour is suppressed by the presence of a strongly absorbing material in the conchin layers.

The diffusion of light in nacre is, at least in part, due to the aragonite crystallites which give the substance a granular structure. This may be demonstrated by viewing a distant source of light through a thin piece of mother-of-pearl polished and mounted in Canada balsam between glass cover-slips and held normally in front of the eye. A diffusion halo is then observed surrounding the source of light, its form being radically different with the mother-of-pearl from the three classes of mollusca, namely the Bivalves, the Gastropods and the Cephalopods.† The haloes differ in detail while retaining the general features of the class for the different individual genera and species. Their configuration is determined by the size, shape, orientation and spacing of the aragonite crystallites and is illustrated for three typical cases in figure 23. The conclusions regarding the structure of mother-of-pearl in the three classes of mollusca reached from a study of the diffusion haloes are independently confirmed by various other methods, viz., by a microscopic study of thin sections,‡ by their X-ray diffraction patterns§ and by

*C V Raman, *Proc. Indian Acad. Sci.*, 1935, **A1**, 574.
†C V Raman, *Proc. Indian Acad. Sci.*, 1935, **A1**, 859.
‡V S Rajagopalan, *Proc. Indian Acad. Sci.*, 1936, **A3**, 572.
§S Ramaswamy, *Proc. Indian Acad. Sci.*, 1935, **A1**, 871; and 1935, **A2**, 345.

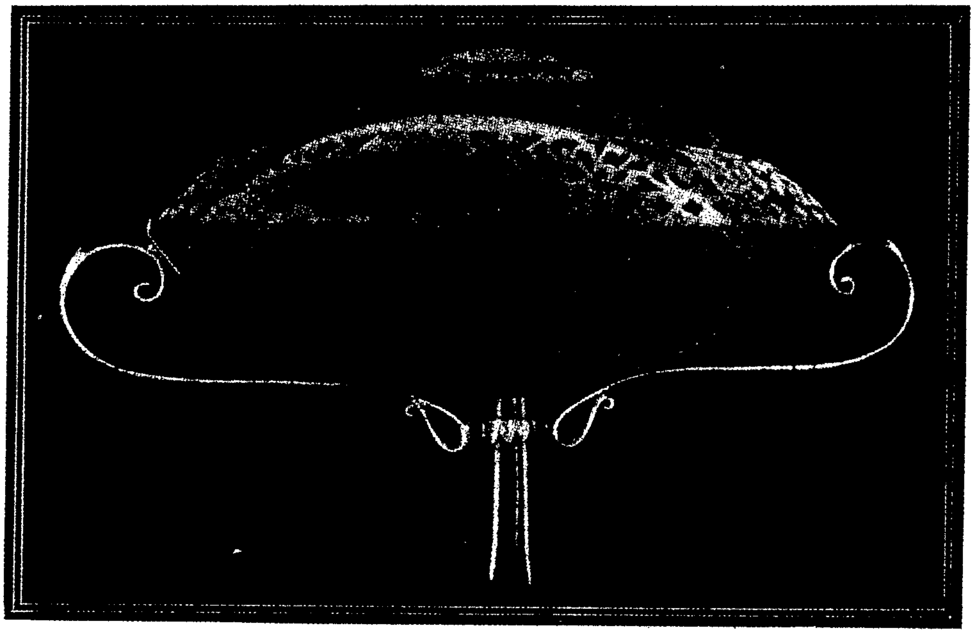


Figure 22. Bands of body-colour in a polished shell of *Turbo*.

observations of the birefringence, the magnetic anisotropy* and the elastic behaviour of nacre† from the different sources. We shall not enter into further details here, as this would take us beyond the limits of our present subject.

A lamination spacing of about 0·5 μ may be taken as roughly representative of the strongly iridescent varieties of mother-of-pearl; this would give a third-order reflection in the brightest part of the visible spectrum, the second order being in the near infra-red, while the fourth order would be at the violet end of the spectrum. A tenth of a millimeter would accordingly be sufficient to include about 200 laminations, and if these were all uniform and equally effective, the bands of reflection and extinction would have a width of only 10 Å, while at the same time, the effect of diffusion would be minimised. The advantage of using a relatively thin piece of the material for spectroscopic observations is thus apparent. With selected specimens and holding the slit of the spectroscope parallel to the contour lines of colour, reflection and extinction bands fully as sharp and straight as those observed with potassium chlorate crystals and with opal may be seen with mother-of-pearl.

*P Nilakantan, *Proc. Indian Acad. Sci.*, 1936, **A2**, 621.
†P S Srinivasan, *Proc. Indian Acad. Sci.*, 1937, **A5**, 463.

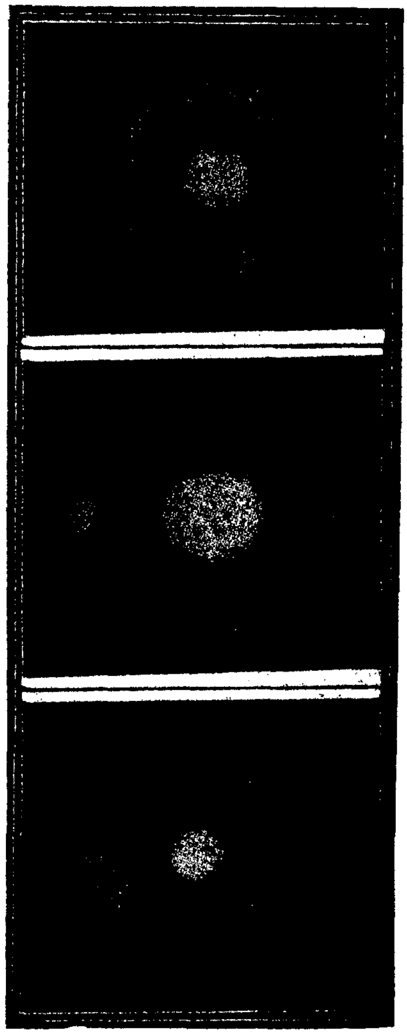


Figure 23. Diffusion haloes of mother-of-pearl.

The extinction of the transmitted light due to diffusion in traversing the nacre varies greatly with the class of mollusc. The mother-of-pearl from *Trochus*, for instance, is remarkably opaque even in thin layers, while the shells of *Turbo* and *M. margaratifera* are much more transparent than those of *Haliotis* or *Nautilus*. As is generally the case with turbid media, the extinction coefficient increases rapidly as the wavelength is diminished, becoming very great in the violet and ultra-violet regions of the spectrum. The colour of the transmitted light which at

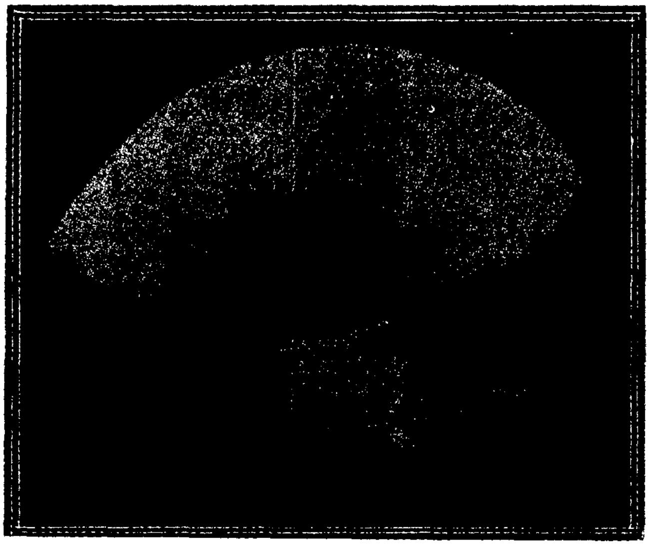


Figure 24. Shell of *Nautilus* photographed as a translucency.

first is complementary to the selective reflection, assumes a reddish tinge and ultimately becomes a deep red with increasing thickness of the plate. One curious result of this is that specimens which selectively reflect at the red end of the spectrum are more opaque than those which give green or blue reflections. With thicknesses greater than a few tenths of a millimetre, light does not penetrate but only diffuses through; the colour of the diffusing light at first is complementary to the selective reflection only for moderate thicknesses and assumes a reddish tinge with increasing thickness. One remarkable property characteristic of nacre is that light can diffuse *in a direction parallel to the laminations to a distance of some centimetres*, while the diffusion normal to the laminations is limited to a few millimetres at the utmost. This effect is illustrated in figure 25 in which an extended area of the nacre appears luminous though only a small region at its centre was illuminated.*

This effect illustrated in figure 25 is no doubt a consequence of the special structure of nacre. The shape and size of the aragonite crystallites vary with the class of mollusc, the smallest dimension being from 2 to 8 μ as shown by the angular diameter of the diffusion haloes, while their thickness is of the order 0·5 μ. The number of reflecting boundaries traversed per unit path of the light is thus many times greater transverse to the laminations than parallel to them. The difference in refractive index between the aragonite and the conchin also

*C V Raman, *Proc. Indian Acad. Sci.*, 1935, **A1**, 859.

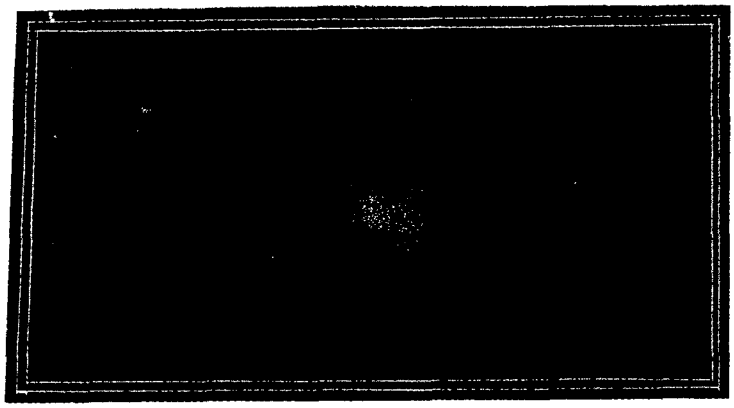


Figure 25. Diffusion of light in *Margaratifera* parallel to laminations.

effectively vanishes for light travelling parallel to the laminations with its electric vector normal to them. These features conspire to enable the light to penetrate to great depths along the aragonite layers.

Iridescence of decomposed glass: Ancient glassware excavated from archaeological sites is often distinguished by a beautiful iridescence. It is frequently possible to detach iridescent flakes from such glass, exhibiting rich colours by transmitted light complementary to those seen by reflection. The laminar structure of decomposed glass becomes evident on examining the edges of the flakes under the microscope. It is noticed also that the flakes are often not plane, but consist of shallow cups like watch-glasses fitting together perfectly and dividing the area into a larger number of polygons. These exhibit rich colour which is uniform over a large area but differs slightly at the margin and centre of each cup, owing to the difference in obliquity of observation. The beautiful regularity in curvature and the sharpness of the polygonal edges are evident in figure 26 which reproduces the interference rings in monochromatic light seen by transmission between the upper surface of the flake and a sheet of mica laid above it, and viewed under a microscope.*

Deeper cavities are sometimes seen which may be spherical or ellipsoidal in shape. Seen between crossed micols in the polarising microscope, such cavities exhibit a dark cross (figure 27) intersected by rings of colour due to the varying obliquity of the surface.

From the fact that the laminations in an iridescent flake adhere pretty firmly to each other, it is evident that they are *ordinarily in optical contact and are not*

*C V Raman and V S Rajagopalan, *Proc. Indian Acad. Sci.*, 1940, **A11**, 469.

Figure 26. Polygonal sub-divisions in iridescent glass.

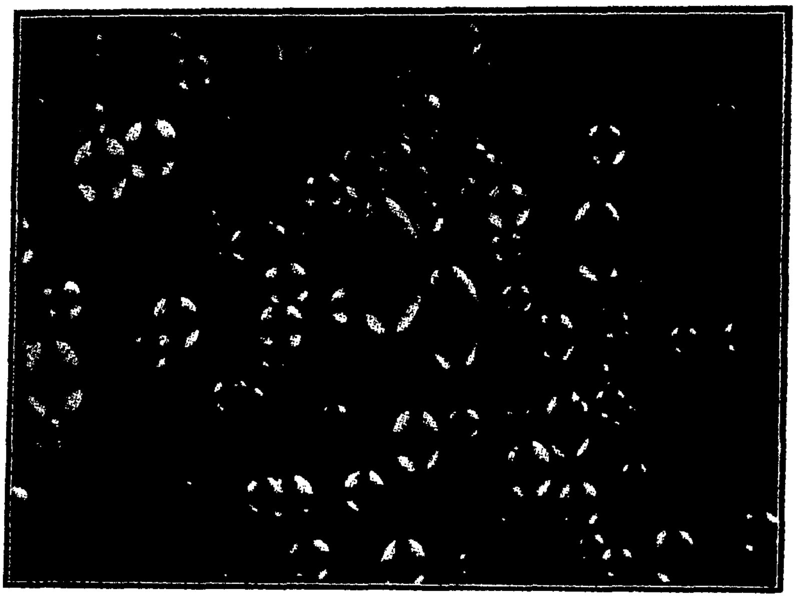


Figure 27. Deep cavities in iridescent glass under polarised light.

separated by films of air. When the flakes are viewed under the microscope in monochromatic light, the areas of colour appear uniform in intensity, but in those cases where a film of air has entered and broken optical continuity, it reveals itself immediately by the appearance of bright and sharply defined interference fringes

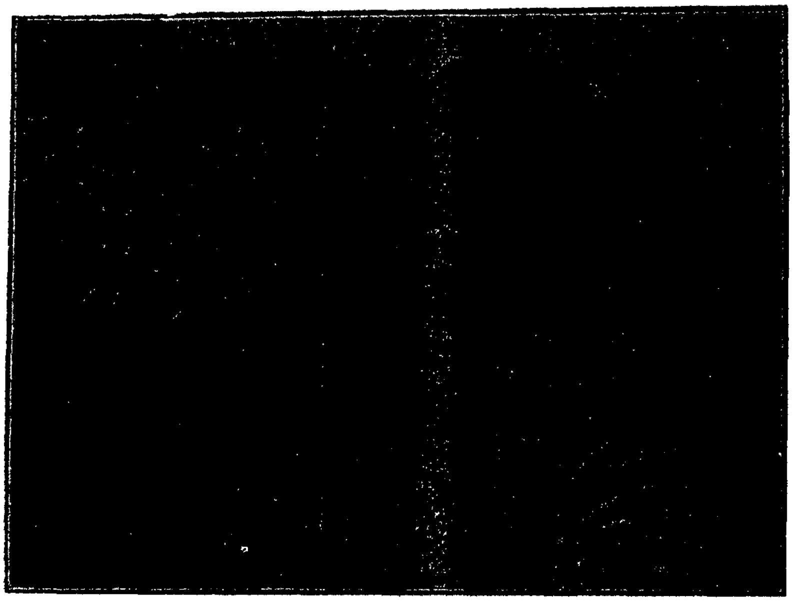


Figure 28. Fringes due to intruding air films.

on a dark ground (figure 28). Such fringes move about when the flake is lightly pressed and recover their shape when the pressure is removed. The presence of films of air also disturbs the uniformity of colour of the flakes as seen in white light under the microscope.

An insight into the nature of the laminations is obtained on immersing a flake in a cell of liquid and gradually varying the refractive index of the latter. The transmission colour disappears immediately, but the reflection colour continues to be visible though weakened, provided the refractive index of the liquid is either lower or higher than of the glass ($\mu = 1{\cdot}46$). It is noticed, however, that the colour of the flakes when immersed in carbon disulphide ($\mu = 1{\cdot}63$) is decidedly different from the colour when immersed in water ($\mu = 1{\cdot}33$). These observations indicate that the decomposed flake, though optically a continuous medium, has an open or porous texture into which liquid can penetrate, the distribution and size of the cavities varying in such manner as to give the material a laminated structure. A striking proof of this is given by the appearance of the flake when it is removed from the immersion liquid and allowed to dry. When still saturated with liquid, it appears quite colourless. But immediately the drying commences, it becomes almost perfectly opaque and transmits no light, while it is silvery white as seen by reflection. The opacity then slowly clears up, the flake exhibiting the usual colours when completely dry. These observations indicate that in drying, the liquid withdraws first from the largest cavities, while it continues to fill the finer pores; as a consequence, the optical stratifications are actually intensified in the first stage of drying and their reflecting power is enhanced as compared either with the perfectly dry or with the completely saturated flake. The porous structure of ancient glass is also shown by placing a small flake covered with a piece of cellophane on the stage of the microscope, and then pressing or rolling a blunt steel point firmly on its surface. The colour is then observed practically to disappear from the area of pressure and does not recover on its removal.

It would seem that the laminations responsible for the colour are tolerably regular. This is indicated by a spectroscopic examination which shows that the flakes may be roughly classified in two divisions. Flakes of the first kind appear red or orange red by reflected light and blue or bluish-green by transmission; while flakes of the second kind show the complementary colours in each case. Typical spectra of the two groups are reproduced in figures 29(A) and 29(B). Spectra of the first kind are roughly analogous to those obtained with the

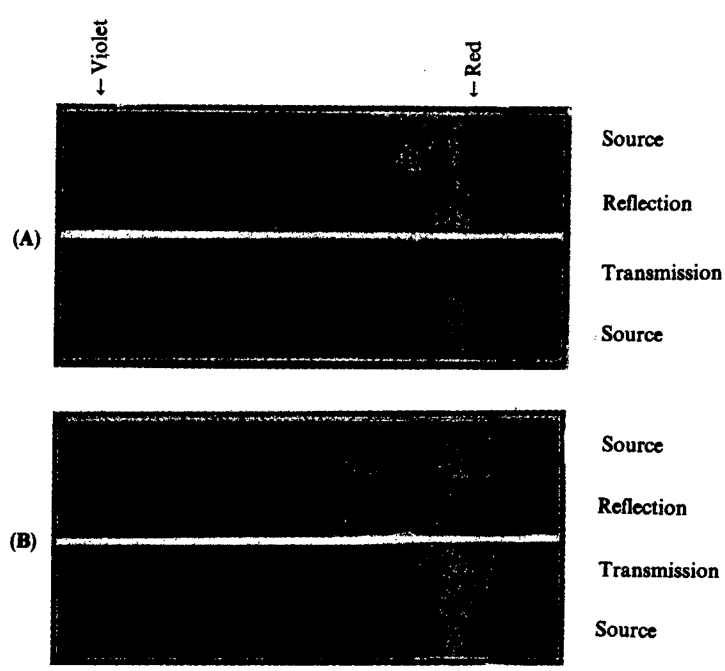


Figure 29. Spectrograms of ancient decomposed glass.

stratified media already discussed. The spectra of the second kind are evidently of a different nature. They are analogous to those encountered when we examine the light transmitted by a thin film enclosed between highly reflecting surfaces, in which case most of the light is reflected except certain narrow regions in the spectrum which are transmitted. It would appear that in such cases the laminations have a specially large reflecting power.

Modern glassware when buried underground or exposed to chemical action often develops iridescence. But this is superficial and the transmission colours are poor. Examined by reflected light under the microscope, however, some beautiful effects may be observed. A distinctive type of decomposition often seen is one in which the surface of the glass is divided up like a map into areas of uniform colour with sharply defined boundaries. In other cases, again, we have numerous small cavities pitting the surface and appearing by reflected light as circular rings of colour. These may be separate but may and indeed often also appear closely grouped together over extensive areas. Glass which has been attacked severely frequently exhibits numerous hollow cup-like cavities adjoining each other, the walls of such cavities being in many cases themselves pitted by still smaller depressions. Some particularly remarkable cases may be seen in which the decomposition has proceeded symmetrically outwards from a nucleus on the surface and has at the same time spread downwards into the glass, forming a succession of thin concentric laminae. The cavities formed by the removal of the decomposed material in such cases appear like circular craters which go down in

Figure 30. Crater-like forms in decomposed glass.

a series of terraces to the deepest area at the centre, these terraces exhibiting brilliant colours by reflected light. Numerous such craters may be seen adjoining each other in figure 30 in which a few craters are also visible in which the material resulting from decomposition is still *in situ*.*

The porous texture of glass which has been chemically rendered iridescent may be prettily shown by placing a small drop of monobrom-naphthalene on the

Figure 31. Adsorption of monobrom-naphthalene by iridescent surface.

surface and observing it by reflected light (figure 31). Surrounding the drop appears a circular area of film saturated with liquid, while beyond this is seen a succession of dark and bright rings which indicate a variation in the quantity and distribution of the liquid adsorbed by the film. These rings exhibit varied colours which are even more striking than the colour of the part of the film free from liquid. Monobrom-naphthalene being non-volatile, the pattern seen round the drop of it is static. The case is, however, different when a quickly-spreading and volatile liquid such as benzene is used; the colour patterns due to its adsorption and subsequent evaporation change with great rapidity.

The Lippmann photographic films: Besides the four examples of a laminated structure giving iridescence which we have dealt with in detail, there are several others which would have been well worthy of discussion in these pages, had space permitted. For instance, the metallic colouration of many beetles has been shown to be due to the presence of stratified layers in their wing cases.† The brilliant

*C V Raman and V S Rajagopalan, *Proc. Indian Acad. Sci.*, 1939, **A9**, 371.

†Rayleigh II, *Proc. R. Soc. London*, 1923, **A103**, 233.

colouration exhibited by many birds, insects and fishes may, at least in some instances, be of the same general nature. Amongst artificially produced periodic structures, pride of place must be given to the well known Lippmann films in natural colour obtained by the action of stationary light waves on photographic films. The theory set out in the preceding pages gives a satisfactory explanation of the experimental facts observed with such films. The appearance for instance, of subsidiary bands *on one side only* of the principal maximum in the spectrum with films intended to exhibit a monochromatic reflection is clearly in accord with the theoretical expectations* (see figure 12).

The frequency with which laminated structures are forthcoming in nature is rather remarkable. The mechanism giving rise to such structures appears to be of a varied nature, viz., rhythmic crystallisation, multiple twinning, periodic precipitates, colloidal aggregation, and the natural processes of biological growth. Perfect regularity in the laminations is not always to be expected, nor is it essential for the production of vivid colour. Indeed, a lack of regularity may enable the medium to give a sensibly total reflection and a corresponding extinction over a wider range of wavelengths than would otherwise be possible, and thereby to enhance the intensity of the colours observed without notably diluting their purity. This feature is of particular importance in those cases where the reflecting power of the individual laminations is small and a great many of them are present.

*R V Subramanian, *Proc. Indian Acad. Sci.*, 1941, A13, 467.