CHAPTER III

Atmospheric scattering and twilight phenomena

21. Following upon the publication by the late Lord Rayleigh of his brilliant idea that the scattering of light by the molecules of air accounted in large measure both for the blue light of the sky and the observed degree of transparency of the atmosphere, the subject was taken up by Lord Kelvin* and by Prof. Schuster† and it was shown that the suggestion was in quantitative agreement with the facts. The subsequent development has been largely a matter of detail and owes its interest to the importance of the problem from the standpoint of solar and terrestrial meteorology rather than that of theoretical physics. Among the principal contributions subsequent to the pioneer investigations referred to above may be mentioned especially the work of Abbot and Fowle‡ and the theoretical researches of Prof. L V King§ in which an attempt is made to take secondary scattering into account and to discuss the disturbing effects produced by atmospheric "dust." A large amount of detailed work, chiefly of an observational kind on the character and intensity of sky-radiation and on atmospheric absorption has also been published. The main result has been the confirmation of Rayleigh's theory, but nothing essential has been added to it except perhaps the recognition of the importance of taking into account the selective absorption in certain regions of the spectrum exercised by the gases of the atmosphere and by the water-vapour present in it.

22. The newer work of Cabannes and of the present Lord Rayleigh in their laboratory experiments on molecular scattering by gases and the subsequent theoretical discussions of their results have however opened up novel issues. Two new facts have emerged, namely, the imperfect polarisation of the transversely diffracted light, and the influence of this imperfect polarisation on the intensity of the scattered light. A third point is also suggested by theory that the magnitude of the imperfect polarisation may depend to an appreciable extent on the wave-length of the incident light. It is natural to ask the question, is there any evidence of these effects to be found in the observations on sky-radiation? Then again, a perusal of the literature shows that several interesting problems relating to

molecular diffraction in the atmosphere have not as yet been the subject of mathematical treatment. Notable amongst these is the explanation of twilight phenomena regarding which very little theoretical work has been done. It is proposed in this chapter briefly to review the outstanding problems relating to atmospheric scattering which are of interest from the standpoint of theoretical physics and to indicate the lines of advance.

The polarisation of skylight

23. As mentioned above, the first novel issue which is raised by the newer work is the extent of polarisation of molecularly diffracted light. As is well-known, the light of the sky observed in a direction 90° remote from the sun is strongly but not completely polarised, the degree of such polarisation depending not only on the wavelength of the light under consideration but also to a large extent upon the altitude of the sun, the meteorological condition of the atmosphere and other factors. The defect of polarisation under ordinary conditions is in fact so considerable that not more than a small fraction of it, if at all, is that inherent in molecular diffraction. Much of the larger part arises from disturbing factors, such as dust, thin clouds or haze, secondary scattering due to the self-illumination of the atmosphere and light reflected from the earth's surface. We may ask, is it at all possible to eliminate these factors altogether or to disentangle their effects and establish the imperfect polarisation to molecular anisotropy by observations of skylight? At first sight this may seem very difficult, but a little consideration will show that the attempt is not quite so hopeless as may be thought. As is well-known, dust and haze are largely confined to the lower levels of the atmosphere. This is beautifully illustrated by the aeroplane photographs secured by Luckiesh* which show a well-marked dust or haze horizon lying at an altitude of about a mile above the earth's surface. Mr Evershed has mentioned to the author in conversation that from the observatory at Kodaikanal which is above the dust-level, its rise and fall with the change of seasons can be seen against the dark background provided by a distant mountain. It is clear therefore that by making the observations on a high mountain on a bright clear day, it should be possible practically to eliminate the effect of dust and haze on the polarisation of sky-light. The disturbing factors then left to be dealt with would be the secondary scattering and earthlight. The influence of secondary scattering may be reduced very considerably by making the observations at the extreme red end of the visible spectrum. On a clear bright day, the sky as seen at a mountain observatory through a deep red glass appears almost perfectly black, but there is ample

illumination, if the observer's eyes are carefully screened from extraneous light, to allow the extent of polarisation to be determined with the help of a double-image prism and a nicol. The effect of earthshine on the polarisation may be estimated by utilizing the data obtained by Luckiesh* on the albedo of different types of landscape from aeroplane observations. Under such conditions it should evidently be possible to eliminate the disturbing influences and to detect the residual effect due to molecular anisotropy.

24. In order to make a test on these points, the writer made the ascent of Mount Dodabetta (8750 feet above sea level) in the Nilgiris on the forenoon of the 4th December, 1921. The sky was beautifully clear, free from cirrus clouds and almost completely black as seen through a red filter. The weaker component of polarisation was found to have 13% of the intensity of the stronger component. According to Luckiesh, the albedo of landscape covered by grass or fields varies from 0·05 to 0·10, and of landscape covered by woods from 0·03 to 0·05. That of barren land is greater, ranging from 0·10 to 0·20. It was estimated that the average albedo of the Nilgiris and the surrounding country could be taken as 0·08. As an outside estimate therefore, earthshine when the sun is 45° above the horizon would not give rise to an imperfect polarisation exceeding 4%. L V King has calculated the imperfect polarisation due to secondary scattering at the level of Mount Wilson (5886 feet) and found it to be 5% at the red end of the spectrum. The level of Mount Dodabetta is much higher (8750 feet) and the disturbing factors are therefore less, but some allowance must be made for the fact that the region of spectral transmission of the filter used extends to slightly shorter wavelengths, and we therefore retain King's figure of 5% as the effect due to secondary scattering. A total of 9% out of the 13% actually observed is thus accounted for, and the remaining 4% is ascribable to molecular anisotropy. This is in good agreement with the latest experimental results of Lord Rayleigh obtained in the laboratory.

Polarisation of twilight

25. Another very interesting way in which the problem may also be dealt with is by observations on the polarisation of the sky immediately after sunset. In this case, it is not necessary to use any light-filters or to work at a mountain observatory, and the measurements may be made on any clear evening at a low-level station. If the polarisation of the light of the zenith sky in the evening is determined from time to time, it will be found that as the sun approaches the horizon and sinks below it, there is a rapid improvement in the completeness of polarisation, followed subsequently by a slow and steady deterioration with

deepening twilight. Kimball* who observed the phenomenon suggests that the improvement of the polarisation is due to the earth-illumination being cut off when the sun sets. This explanation does not appear to be adequate as it does not account for the large magnitude of the effect or the rapidity with which it occurs. For instance, in some observations made at Calcutta by the author and by Mr K R Ramanathan, it was found that 40 minutes before sunset the ratio of the intensities of the components of polarisation was 30%, 20 minutes before sunset it was 20%, at sunset it was 14%, 20 minutes later it was 15%, and then gradually rose again to 30%. In view of the low albedo of landscape already quoted above, we can hardly suppose that such effects could be merely due to the cutting off of earthshine. The greater part of the effect really arises in another way. As the sun approaches the horizon, the thickness of the atmosphere which has rays have to traverse rapidly increases, and the actual intensity of illumination of the first kilometer or two of the atmosphere above the observer becomes exceedingly small. At higher levels, however, the weakening of the sun's rays is not so great, and as we proceed upwards to the layers of the atmosphere in which the barometric pressure is considerably smaller than the sea-level value, the intensity of the sun's rays rapidly increases, until finally at a great height it reaches practically its noon-day value. The effective scattering layers of the atmosphere are thus its high-level dust-free portions. Thus immediately after sunset, the effect of the low-lying dust and of the earthshine is automatically eliminated. Further, the great diminution in the effective mass of air and the increase in the effective wavelength of the transmitted rays which illuminate it should result in a considerable diminution of the effect of secondary scattering. It should also be noticed that the illuminating rays being horizontal, and the extension of the earth's atmosphere being chiefly horizontal, secondary scattering should have a much smaller influence than when the sun is at a high altitude. This is easily seen on considering the directions of vibration in the incident light, in the primarily scattered light which reaches the observer, and in the scattered light arriving from different directions which after a second scattering also reaches the observer. In fact, a careful consideration shows that if the molecules of the atmosphere were spherically symmetrical. the zenith sky *immediately* after sunset should be almost completely polarised, the defect of polarisation if any, not exceeding 5% or 6%. Actually, however, a defect of about 10% is observed even on the clearest days, showing that there is a residual effect of 4% or 5% arising from molecular anisotropy.

26. When the sun sinks very far below the horizon, much the greater part of the atmosphere above the observer enters the region of shadow and the influence of secondary scattering on the polarisation again becomes prominent. Some very curious effects may be observed, one of which is that the region of strongest polarisation in the sky, instead of following the movement of the sun, actually recedes from it.

The problem of secondary scattering

27. In attempting to extend the work described in the preceding pages to different wavelengths in the spectrum and to put it on a very precise quantitative basis, we naturally come up against the problem of evaluating the effect of secondary scattering on the polarisation. This had been attempted by Soret in order to explain the existence of "neutral points" in the sky.* More recent work is that of L V King already quoted in which he has used the theory of integral equations in order to find the result of self-illumination of the atmosphere. In order to apply his method to the determination of the state of polarisation of sky-light, King had to make two simplifying assumptions: firstly, that the effect of the curvature of the earth may be neglected: secondly, that the portion of the scattered radiation due to self-illumination is independent of the angle of polarisation of the incident radiation. As regards the first assumption, it should be remarked that it is the curvature of the earth that determines the horizontal extension of the portion of the earth's atmosphere which contributes the primarily scattered light which is again re-scattered by the part of the sky under observation. Its neglect is thus *prima facie* justifiable only if it can be shown that the actual brightness of the sky in a horizontal direction is the same as for an infinitely extended atmosphere. As regards the second assumption, we have only to remember the case just discussed—that in which the sun's rays are nearly horizontal—to see that it may lead to results which do not agree with facts. It would seem therefore that there is a real need for a discussion of secondary scattering in which the curvature of the earth is taken into account and the result is fully worked out without any assumptions except perhaps the negligibility of multiple-scattering of the third and higher orders. If such calculations were made, it may prove possible to establish the imperfect polarisation for different wavelengths due to molecular anisotropy by comparison with observations made at high level stations. Perhaps the use of a simpler mathematical method than that adopted by Prof. King may render the problem tractable.

The influence of atmospheric dust

28. The curves showing the brightness of the zenith sky as a function of the wavelength obtained by the observations made at Washington and figured in Prof. King's paper show a sudden kink amounting practically to a discontinuity at a wavelength of 0·61 μ. A similar jump also occurs in the curves for polarisation of the zenith sky. In the curves for the Mount Wilson observations, undulations also occur but at a shorter wavelength, about 0·45 μ. These effects are clearly due

to the influence of "dust," but precisely how they arise does not appear to have been fully explained. The suggestion may be ventured that the effect is due to diffraction, the wavelength at which the bend occurs being determined by the average size of the dust particles. In this connection, some interesting observations made by the author and by Mr Bidhubhusan Ray may be quoted.* When suspensions of sulphur are used containing particles comparable in size with the wavelength, both the transmitted light and the scattered light show oscillations of intensity depending on the relation of size between the particles and the wavelengths used, and the polarisation of the scattered light also shows striking fluctuations. It seems possible that dust may give rise to somewhat similar results in relation to atmospheric extinction, scattering and polarisation. At a higher level such as Mount Wilson, the average size of the particles remaining floating in the atmosphere would naturally be smaller and this would explain the occurrence of the bends at smaller wavelengths in this case.

29. The foregoing suggestion is put forward for what it is worth. Careful experimental determinations of the average size of atmospheric "dust" at different levels would be necessary in order to establish its correctness.

Twilight and afterglow

30. A very interesting application of the theory of molecular diffraction is in the explanation of the various phenomena attending twilight or dawn, especially the manner in which the total illumination due to twilight diminishes with the movement of the sun below the horizon, the distribution of brightness in the different parts of the sky and its variation with the altitude of the sun and so on. The impression appears to prevail that twilight phenomena are so complex in their nature that no simple calculations concerning them are possible. Thus for instance, Prof. W J Humphreys in his book on the Physics of the Air remarks, after giving an account of the various effects observed—"The foregoing descriptions which of course apply equally to dawn are by no means universally applicable. Indeed, the sky very commonly is greenish instead of purple, probably when the atmosphere is but moderately dust-laden. Furthermore, the explanations are only qualitative. A rigid analysis, even if the distribution of the atmosphere and its dust and moisture content were known—which they are not, nor are they constant—would be at least difficult and tedious." With reference to these remarks, it may be pointed out, that twilight really arises from the illumination of the higher levels of the atmosphere which may be regarded as dust-free, at least under normal conditions. Further, as we have seen in considering the explanation of the polarisation of twilight, the transmission of

sunlight through the lower dusty levels is really negligible under these conditions, and practically the whole of the observed effect arises from light which has *throughout its course* passed through the higher levels. Hence, we are entitled to regard the problem as one of practically simple molecular diffraction, and the complications arising from secondary scattering are far less important than might be imagined. The possibility of giving a quantitative theory of twilight is therefore much less remote than has been suggested by various writers on the subject.

31. Kimball and Thiessen* have given data based on photometric measurements of clear sky, twilight and other natural illumination intensities on a fully exposed horizontal surface. These values are given in Table 1.

Table 1

Relative illumination intensities surface of illumination horizontal	Intensity in foot candles
Zenithal sun	9600·0
Twilight at sunset or sunrise	33·0
" centre of sun 1° below horizon	30·0
Twilight centre of sun 2° below horizon	15·0
" " 3° "	7·4
" " 4° "	3·1
" " 5° "	1·1
" " 6° "	0·40
(End of civil twilight)	
7°	0·10
8°	0·04
8° 40′	0·20
9°	0·015
10°	0·008

The above table shows that the brightness of twilight changes rapidly when the sun is more than about 4° below the horizon. The author has attempted to explain the observations of Kimball and Thiessen quoted in Table 1 quantitatively on the basis of molecular scattering. The method adopted is to divide up the whole atmosphere above the observer into a series of horizontal layers, and to find the effective mass of air in each layer illuminated by the direct rays of the sun, secondary scattering being neglected. In making the calculation, allowance must be made for the diminution of intensity of the sun's rays before they reach the air-mass under consideration, and the cosine of the angle at which the diffracted rays illumine the horizontal surface of the photometer must also be included as a factor. Approximate methods of numerical quadrature were used, and it was found that the observations of Kimball and Thiessen were quite satisfactorily explained, at least as regards the relative values of the illumination for different altitudes of the sun after sunset. But as regards the ratio of full sunlight to the intensity of twilight a discrepancy appears which has not up to the time of writing of this volume been cleared up. It is possible that the discrepancy is in some way due to refraction of the sun's rays in passing horizontally through the earth's atmosphere. But this can only be settled by further investigation. Sufficient work has been done, however, to show that the problem of twilight at least in its essential features, is capable of being subjected to numerical computation of intensities from theory of detailed comparison with the observations.