CHAPTER V

The colour of the sea and the albedo of the earth

49. To an observer situated on the moon or on one of the planets, the most noticeable feature on the surface of our globe would no doubt be the large areas covered by oceanic water. The sunlit face of the earth would appear to shine by the light diffused back into space from the land and water-covered areas. The character and intensity of the radiation thus sent back would depend on various factors: firstly, sunlight diffused back by the gases of the atmosphere over the whole surface of the earth; secondly, the sunlight incident on the oceans and returned partly after reflexion at the surface of the water, and partly after diffusion within its body; thirdly the light reflected back from cloud-covered areas and the lower dusty levels of the atmosphere; and fourthly, the light scattered by the land masses. When we consider the fact that nearly three-quarters of the surface of the globe is covered by oceanic water, we begin to realise that the molecular scattering of light in liquids may possess an astronomical significance, in fact contribute in an important degree to the observed albedo of the earth. The "earthshine" on the moon for instance may owe not a little to the light diffused out from the oceanic water as the result of molecular diffraction.

50. In intimate relation with the problem of the albedo of water stands the question of the colour of the sea. A detailed discussion of the subject is appearing in a separate paper* and it is sufficient here to deal with the matter only so far as it illustrates the theoretical principles of our subject.

Colour and polarisation of the light scattered in the sea

51. The method of observation used by the writer is sufficiently described in a preliminary communication that appeared in *Nature*†. As Tyndall and others have remarked, the reflection of sky light at the surface of the water is an embarrassing feature in making observations of the colour of the sea. Its influence

through a suitably oriented Nicol. Hence by observing a tolerably smooth patch of water through a Nicol at the polarising angle, the surface-reflection may be got rid of. The Nicol may be mounted at the eye-end of a cardboard tube so that it can be conveniently held at the proper angle with the surface of the water and rotated about its axis so as to get the correct position for extinction of the reflected light. During a recent voyage, the writer made some observations by this method in the deeper waters of the Mediterranean and the Red Seas and found that the colour of the sea so far from being extinguished when the sky-reflection is cut off, is seen with wonderfully improved vividness and with saturated hues. Even when the water is ruffled or when it is viewed more obliquely than at the polarising angle, the Nicol helps to weaken the sky-reflection. Further, as is well known, the light of the sky is itself strongly polarised, and this fact may, in favourable circumstances be used to practically eliminate sky-reflection from the whole surface of the sea. For this purpose, the time most suitable is when the sun has reached its maximum altitude and the observer should stand with his back towards the sun and view the surface of the sea through a Nicol. The part of the sky facing the observer has then its maximum polarisation, especially the low-lying parts, and the amount of polarisation is further enhanced when the light is reflected from the water at various angles of incidence. By turning the Nicol about its axis, the best position for extinction should be found and the whole surface of the sea will then be found to glow with a vivid blue light emerging from inside the water. Part of this improvement is also due to the fact that the Nicol in great measure cuts off the atmospheric haze which covers the more distant parts of the sea.

52. The obvious way of testing the light from the sea for polarisation, that is, viewing it through a Nicol and turning the latter about its axis, is interfered with by the fact that the intensity of the reflected light also varies at the same time and obscures the variation in the intensity of the light diffused from inside the water. Even thus however, it is possible to observe the polarisation of the scattered light, the surface of the water appearing *less* blue when seen through the Nicol in one position than when viewed directly. Much the better way of detecting the polarisation of the diffused light, however, is to hold the Nicol at the proper angle for extinguishing the surface-reflection from the water and vary the *azimuth* of observation relatively to the direction of the sun's rays entering the liquid. Striking changes in the colour and intensity of the light diffused by the water will then be noticed. The best time for making this observation is when the altitude of the sun is moderately large but not too great. Obviously, if the sun's rays are too nearly vertical, varying the azimuth of observation can make no difference. But when the sun's rays inside the water proceed at an angle to the surface, the variation of the azimuth of observation alters the relation between the direction of the primary beam and the scattered rays under test. When the observer has his back to the sun, he looks down practically along the track of the rays inside the

is not extinguished in any position of the Nicol. The colour of the scattered light is then seen as a vivid but comparatively lighter blue. As the azimuth of the plane of observation is swung round, the intensity of the scattered light diminishes and its colour changes to a deeper blue, until finally when the observer nearly faces the sun,* the intensity of the scattered light is very small and it appears of a dark indigo colour. If the polarisation of the scattered light were complete and the direction of observation exactly transverse to that of the primary beams inside the water, the Nicol would have completely quenched the light. This is however not actually the case, evidently because we have to deal not only with the scattering of the sun's direct rays inside the water, but also with multiply-scattered light and also with the blue light of the sky which enters the water and is then rescattered within it. It is evident that these contributions to the luminosity of the water would diminish the perfectness of the polarisation† and would give a much darker blue than the primarily scattered rays.

53. The relatively deep colour of the secondarily scattered rays mentioned in the preceding paragraph is also prettily illustrated by observing the water on the shadowed side of the ship where the sun's rays do not strike it directly. Such water shows a much darker and deeper colour than the contiguous parts exposed directly to the sun's rays. A similar explanation may be given of the deepening of the colour of the sea as the sun goes down. The lower the altitude of the sun, the more important is the contribution of sky-light rescattered within the water to the observed luminous effect. The blue colour of the sea as observed with the aid of a Nicol when the sky is completely overcast by clouds also appears of a distinctly deeper tint than sunlit water. It is probable that this may, at least in part, be due to the importance of multiple scattering in such cases.

54. The difference between the colour of the parts of a wave sloping towards and away from the observer is a very interesting feature. When the surface of the sea is viewed through a Nicol, the degree of contrast varies enormously as the Nicol is rotated about its axis. The precise effect, of course, depends upon the relative intensity, colour and polarisation of the light reflected from the surface of the water at different angles and of the light emerging from inside the water. Broadly speaking, the phenomenon observed is that in one position of the Nicol the sea appears almost flat and undisturbed and in another position ruffled and full of ripples. The visibility of the horizon which depends on the contrast between sea and sky also varies, in some cases very greatly, as the Nicol is rotated.

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*He cannot of course exactly face the sun as the reflection of the sun's rays from the surface of the water would then interfere with the observations. It is advantageous to choose a time when the altitude of the sun is such that these reflections are also quenched by the observing Nicol.

†Much in the same way as the polarisation of sky-light even at 90° from the sun is incomplete. The imperfectness of the polarisation of the molecularly-scattered light (due to asymmetry of the

The albedo of deep water

55. The phenomena described above make it perfectly clear that the light molecularly diffused from within the water is the principal factor to be taken into account and that the colour of the deep sea is not due to reflected sky-light as has sometimes been suggested. That the reflection of skylight is at all noticeable arises from the fact that the observer on the deck of a ship views by far the greater part of the surface of the sea at a very oblique angle. The position would be entirely different in the case of an observer at a great height above the surface of the water, e.g. when flying in an aeroplane. Since the reflecting power of water at normal incidence is quite small (only 2%), the luminosity of the sea to such an observer would be almost entirely determined by the diffusion of light within the water.

56. That such diffusion must, in the case of the deeper oceanic waters at any rate, be due to *molecular scattering* and not to any suspended matter may be inferred from the known great transparency and freedom from turbidity of such waters. It is extremely unlikely that, under normal conditions at any rate, any colloidal matter would remain for long in suspension in salt water. Further, it should be remarked that if sea-water did contain any "motes" in suspension, they would not appreciably influence the observed results. For, "motes" scatter light in an unsymmetrical manner, that is far more in directions approximating to that of the primary rays, and very little in the opposite direction which, to an observer above the surface of the water, is the direction that really matters.

57. A simple calculation may be easily made of the albedo of oceanic water. Since in round numbers, water diffuses light 150 times as strongly as an equal volume of air, a layer of the liquid 50 meters deep would scatter approximately as much light as $7\frac{1}{2}$ kilometers of homogeneous atmosphere, in other words, it should appear nearly as bright as the zenith sky. This calculation however omits to take into account two important factors, the diminution in the intensity of sunlight before it reaches the level of the water and its further attenuation in the passage through the liquid and also the loss in intensity of the scattered light before it reemerges from the depths. It is the two last factors just mentioned which together with the magnitude of the scattering itself ultimately determine the total observed luminosity of an ocean of liquid of very great depth. Neglecting the effect of self-illumination within the liquid and also the contribution which is made by diffuse sky-light which enters the water and is then subsequently rescattered within the liquid—both of which may, in certain circumstances, rise to importance—the observable luminosity of a very deep layer of liquid may be readily calculated. For simplicity, we shall consider a case in which the altitude of the sun is sufficiently great to enable its rays within the water to be treated as approximately vertical in direction, and the intensity of the light scattered will also be assumed to be observed in an approximately vertical direction, e.g. by an observer in an aeroplane flying at some height above the water. The coefficient of

laterally. Denoting it by $2B/\lambda^4$ and the coefficient of absorption of light in water by γ, the total observed luminosity is given by the integral

$$\frac{2B}{\lambda^4}\int \exp(-2\gamma x)\,\mathrm{d}x$$

x being the depth of any layer. For a sufficiently great depth this reduces to $B/\gamma\lambda^4$. For the case of pure water, the values of γ are taken from the determinations of Count Aufsess for wavelengths up to 522 $\mu\mu$, and for shorter wavelengths we may take them to be the same as the value of coefficient of attenuation α given by theory. The value of B is in round numbers 140 times the coefficient of lateral scattering by dust-free air. From these data and making an allowance for the diminution of the solar intensity in transmission through the atmosphere as on an average day, the total luminosity of deep water for different wavelengths is expressed in Table 3 in terms of the kilometers of dust-free air at atmospheric pressure which would by lateral scattering of full sunlight give an equal effect.

Table 3. Albedo of deep water

λ in $\mu\mu$	658	622	602	590	579	558	522	494	450	410
Equivalent kilometers of dust-free air	0·4	0·5	0·6	1·3	2·4	2·8	45	36	22	14

58. If we take the scattering by 8 kilometers of dust-free air as the standard and compare with it the figures shown in Table 3, it is seen that in the light returned by the water, practically all the red is cut out, the orange and yellow are quite feeble, but the green is greatly enhanced, and also the blue, indigo and violet but to a considerably less extent. The standard of comparison, (scattering by dust-free air) being itself of a blue colour, it is clear that the cutting out of the red and the enfeeblement of the orange and yellow would result in the colour of the light scattered by the water being a highly saturated blue. The enfeeblement of the orange and yellow would however considerably diminish the visual intensity which at a rough estimate would probably not exceed two or three times that of the zenith sky.

59. It will be understood from the figures given in Table 3 that the blue colour of the light scattered by the water arises primarily from the operation of the Rayleigh λ^{-4} law, the absorption of the red and yellow regions of the spectrum in the water resulting merely in the colour being more *saturated* than it would otherwise be. If the figures entered in the columns of Table 3 had represented ratios of comparison with *white* light, the presence and predominance of the green would result in the perceived colour being a greenish-blue and not a deep blue

diffraction, the selective absorption of the water only helping to make it a fuller hue.

60. In connection with the foregoing calculations, it should be remarked that certain disturbing factors may arise. If owing to the presence of organic or other dissolved matter in the sea with a marked absorption in the green-blue region of the spectrum the transparency of the water in this region be greatly diminished, the albedo of the deep water may show a great falling off. This is a possibility that should not be overlooked, and how far it does actually arise can only be determined by actual observation. But the considerations set out above make it clear that the light molecularly scattered in the oceanic waters must play an important part in determining the total fraction of the sunlight incident on the earth's surface that is diffused back into space. A fuller discussion of the matter would obviously be of great interest.