THE TRANSPARENCY AND COLOR OF THE SEA

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Abstract

The theory of the Secchi disk given by Shoulejkin[1] is discussed and a correct expression derived for the depth to which the disk, painted white, should be sunk in an ocean of pure dust-free water so as to be just visible. With ordinary paint the maximum depth is computed to be about 120 meters, whereas the greatest observed depth in the ocean is about 60 meters. The difference is due (1) to the presence of suspended matter and (2) to a possible extra absorption in the blue and violet. Contrary to the opinion expressed by Shoulejkin, it is shown that in the blue region the *brightness* due to molecular scattering alone would be appreciable, in fact about one-sixth that of blue sky. This is confirmed by rough observations made in the Bay of Bengal.

IN two recent papers,[1] Prof. Shoulejkin has discussed the question of the color of the sea and has published interesting experimental observations in connection with them. He is of the opinion that the return of light from the sea is mainly due to the scattering of light by small particles suspended in it, the color and intensity of the returned light being modified by the selective absorption of the water. While agreeing with Prof. Shoulejkin that in many cases the scattering of light by suspended particles is of primary importance, the writer wishes to point out that it is not always so. Shoulejkin has also derived an expression for the relation between the scattering and absorption coefficients of sea-water and the maximum depth to which a disk (painted white) should be sunk in order to be just visible. Making use of this relation, he concludes that in seas where water occurs in its purest form, and hence where molecular scattering[2] is mainly responsible for a return of light, there would be very little light returned from within the ocean and that the color and the brightness of such seas would depend mainly on the state of the sky at the time. Since this is contrary alike to theory and observation, it is felt desirable to examine Shoulejkin's paper in some detail.

Shoulejkin's arguments rest on his theory of the Secchi disk[1a] and on the expression for the brightness of the sea which he derived[1a]. It seems to the writer that serious errors have been made, especially in connection with the theory of the Secchi disk. Both on that account and on account of its intrinsic interest, it is proposed to discuss the problem afresh.

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[1] Shoulejkin, (a) Phys. Rev. **22,** 85 (1923) and (b) **23,** 744 (1924).

[2] C. V. Raman, Proc. Roy. Soc. A **101,** 64 (1922) and
K. R. Ramanathan, Phil. Mag. **46,** 543 (1923)

When a plate is gradually lowered in water to such a depth that it ceases to be visible, what we look for is the difference in *brightness* between the plate and the surrounding column of water. In a transparent medium, the brightness of an object which subtends a finite angle at the eye is independent of its distance, while in an absorbing medium, the brightness varies as $e^{-\gamma r}$ where γ is the coefficient of extinction in the medium and r is the distance.[3] When a matt surface of albedo A is sunk in water to a depth z, it will have a brightness $AI_0e^{-2\gamma z}/\pi$ where I_0 represents the intensity of the normally incident light at the surface of the sea. To get the apparent brightness of the disk, we have also to add to this the brightness of the superincumbent column of water due to scattering. If $2B/\lambda^4$ represents the scattering per unit solid angle by unit volume of water against the direction of the incident light, this amounts to

$$\frac{2BI_0}{\lambda^4}\int_0^z e^{-2\gamma x}dx=\frac{BI_0}{\gamma\lambda^4}(1-e^{-2\gamma z})$$

and the total apparent brightness of the disk is therefore

$$(A/\pi-B/\gamma\lambda^4)I_0\,e^{-2\gamma z}+BI_0/\gamma\lambda^4\ . \tag{1}$$

The brightness of the surrounding unobstructed column of water is $I_0B/\gamma\lambda^4$ and the relative contrast is therefore

$$(A/\pi-B/\gamma\lambda^4)e^{-2\gamma z}/(B/\gamma\lambda^4)\ . \tag{2}$$

In estimating what minimum relative difference in brightness we may reasonably expect to detect, we have to remember that at the depths at which the disks usually disappear in tropical waters, practically all the red, yellow and green have been cut off and the light is mostly indigo and violet where the sensitiveness of the eye in detecting differences of brightness is small and the fatigue is rapid; the disk is but a small patch in an otherwise continuous and uniformly bright area; and moreover, the observations are made from an unsteady support so that the eye cannot be properly focussed. Ten per cent will not, under these circumstances, be an overestimate for the minimum contrast necessary for proper seeing. Indeed, according to Buchanan,[4] the contrast should be very much larger. The value for the least perceptible difference in brightness adopted by Shoulejkin, 1/133, is decidedly too low. Even in calm days and with

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[3] Shoulejkin's assumption that the coefficient of extinction as measured in transmission experiments is $\frac{1}{2}\alpha/\lambda^4+f(\lambda)$ where α/λ^4 is the coefficient of scattering and $f(\lambda)$ the coefficient of absorption is erroneous. What is measured is $\alpha/\lambda^4+f(\lambda)$.

[4] Buchanan, Nature, July 1910, p. 87.

large disks, it is doubtful if one could detect a difference of less than 5 per cent.

Another point of importance is the value of the albedo for the disk. With white light incident, the albedo for ordinary white paint is about 0.6, but the usual paints exercise an absorption in the blue and violet parts of the spectrum, so that in this region, the albedo is much less. When we go down to depths of 50 meters and more, the transmitted light is mostly of wave-lengths below .5μ and we cannot therefore use the usual value of the albedo. Buchanan's statement that at a depth of 25 fathoms, the brightness of the uninterrupted sea was of much *greater* intensity than that of the disk supports this.

Considering as an ideal case an ocean of dust-free distilled water and taking primary scattering alone into account, the following table gives the values of the brightness of a sufficiently large white disk sunk under different depths of water. The data for scattering and absorption coefficients are the same as those used in my paper on the color of the sea. The value of the albedo has been assumed to be 0.6 for all wave-lengths except the last two for which it has been taken to be 0.4 and 0.3 respectively.

TABLE I.

Proportion of incident light scattered per unit solid angle by a Secchi disk

Depth	.578μ	.546μ	.475μ	.436μ
50m	1.55×10^{-3}	9.1×10^{-3}	2.9×10^{-2}	4.3×10^{-2}
100	1.2	3.0	1.3	2.8
150	1.2	2.8	1.05	2.3
∞	1.2	2.8	1.0	2.1

To get the visual effect of all the wave-lengths taken together, we have to take the radiations in different spectral regions in proportion to the energies of the incident radiations and also to the corresponding luminous efficiencies. Remembering that the luminous efficiencies at .475μ and .436μ are only about 1/8 and 1/35 of that at .550μ (Ives), we can easily see from the table above that the maximum depth at which we can expect to distinguish a sufficiently large disk is about 120 meters.[5]

The greatest observed depth of disappearance of the disk, about 60 meters, is in the tropical parts of the Pacific ocean and in the Sargasso sea. In the transparent parts of the Indian ocean, the depth is about 50 meters. These are decidedly less than the depth calculated for pure

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[5] We have in the above neglected the illumination of the disk and of the water by scattered light. A rough calculation shows that this will not greatly affect the depth of disappearance in pure water. A detailed calculation would however be of interest.

dust-free water; the difference may be due either (1) to scattering by suspended particles, such as were found by the writer to be present in small quantities in the Bay of Bengal, or (2) to an increase in the coefficient of absorption in the violet end of the spectrum, or to both causes combined.

The presence of suspended particles affects the depth of sinking in two ways; it increases the coefficient of scattering which causes the return of a greater percentage of incident light from the water, the contribution of the surface layers being comparatively greater; it also reduces the transparency of the medium. A reference to Eq. (2) shows that both these would reduce the critical depth of sinking. When the quantity of suspended matter is, however, small, the increase in the scattering is mostly on the forward side of the incident light and the scattering against the incident direction is hardly affected. For example, with one of the samples from Bay of Bengal, the scattering was about 1.2 times that of dust-free distilled water between the angles 0° and 60° (measured from a direction opposite to the incident light), 1.5 times between 60° and 90°, 3.0 times between 90° and 120°, and 6 times between 120° and 180°. Since the solid angle contained between each of these limits is the same, namely π, the total scattering is increased to about 3 times that of pure dust-free water. But the total light returned from within the ocean is not increased in the same ratio, because the scattering against the direction of the incicent light is only slightly more than that of the dust-free water, and thus the return of light from within the sea is primarily due to molecular scattering. Although, therefore, the presence of these particles would to some extent diminish the depth at which an immersed white disk can be seen, it cannot account for the entire difference between the observed and calculated depths.

There is evidence to show that the actual absorption of sea-water in the violet end of the spectrum is really greater than that of dust-free distilled water. Even water from the deep-blue portions of the Bay of Bengal shows a very feeble but distinct green fluorescence when excited by blue and violet light. This implied an extra absorption in this region and this is, I think, another important reason why we are not able to see a white disk at depths greater than about 60 meters in even the most transparent parts of the ocean. Actual measurements of extinction coefficients in water collected from the transparent parts of the ocean would be of interest.

In connection with Shoulejkin's statement that molecular scattering by itself cannot give rise to any appreciable brightness of the sea, it may be pointed out that according to the figures given in Table I, the brightness of a dust-free sea when viewed normally is in the blue region of the spectrum about one per cent of the incident intensity of illumination. When secondary scattering is taken into account, this will be raised to about 1.2 per cent. Now it is known that the average blue sky has about 1/7 the brightness of white paper illuminated by the zenith sun.[6] Taking the albedo of white paper to be 0.80, the brightness of the latter is AI_0/π i.e. about 25 per cent of the incident intensity of illumination, and that of the average blue sky is therefore 3.5 per cent. If we confine ourselves to the blue region of the spectrum, the value would be higher, say about 7 per cent. An ocean of dust-free distilled water would thus have a brightness about 1/6 that of the average blue sky, while sky-light normally reflected at the surface of the sea would give rise to a brightness of only 2 per cent of the sky-brightness. Some rough photometric measurements (with a blue filter) carried out by the author from the upper deck of a steamer in the blue waters of the Bay of Bengal between the hours 9 a.m. and 3 p.m. on a day when the sky was *very clear*, showed that the zenith sky was 4 to 5 times as bright as the sea when viewed nearly normally.

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[6] Recueil des Constantes Physiques, p. 209.