ON THE COLOR OF THE SEA. II[1]

By Was. Shoulejkin

Abstract

Color of the sea.—*Spectrophotometric observations of the inner light diffused up from polar seas* were made, using a special instrument which enabled a direct comparison at various wave-lengths of the light diffused vertically up from the sea with the direct light from the sun and sky. The curves obtained agree well with the formula derived in the previous paper. *Measurements of the coefficient of diffusion made with the Secchi disk*, by means of the author's theory, agree with values of the coefficient α determined from laboratory data for the Indian ocean (by Ramanathan) and for the pure water of the Sargass Sea (compared with α for distilled water according to data given by Martin). Recent papers by Raman and by Ramanathan, who consider exclusively molecular scattering, are discussed. When the intensity of the diffused inner light is small, the color of the sea depends almost entirely upon light reflected from the sky.

Complementary relation of the color of deep-sea plants and corals to that of the light transmitted to them.—The coefficient of reflection of a leaf of *laminaria* from the bottom of Warneck Bay varies with wave-length very closely in proportion to the reciprocal of the intensity of the illumination at that depth computed from spectrophotometric data. In the case of *Mediterranean coral* from a depth of about 70 meters, good agreement was also found up to .59μ above which the illumination is extremely weak.

In my preceding article published in this journal[2] it was shown that the bright color characteristic of every sea or lake can be quite easily explained by certain well known optical phenomena taking place in the sea-water and on its surface. Necessary correlations were also drawn which enabled an observer looking at the sea to calculate the spectrum of light, using coefficients easily determined from the experiment. Thus if both the dependence of the coefficient of absorption of rays in pure water $f(\lambda)$ upon the length of the wave corresponding to the given part of the spectrum (given in graphical form), and the Rayleigh's coefficient α of light scattering in sea-water for wave-length μ and for a depth z of 1 meter are known, then the spectrum can be calculated by means of a formula, reproduced here below, after having made some transformations

$$\frac{M_0}{S_0+H_0}=\frac{1}{\pi}\,\frac{\frac{1}{4}\,\alpha/\lambda^4}{\frac{1}{4}\alpha/\lambda^4+f(\lambda)}\,. \tag{4}$$

The fraction on the left side of this equation represents the ratio, which is sought, of the intensity of illumination of the sea from below

[1] Communicated to the Scientific Institution of Moscow, October 2, 1922

[2] Shoulejkin, Phys. Rev. **22**, 85 (1923)

by the inner diffused light (M_0) to that from above by the sun (S_0) and the sky (H_0).

Eq. (4) relates to the case of particles suspended in the sea-water which are so very small that they cause only a scattering of light according to the law of Lord Rayleigh. But if, together with such particles, there are bigger particles of the second kind in the water which cause a selective reflection and selective absorption of light, the calculations of the spectrum must be carried out by means of a more complicated formula

$$\frac{M_0}{S_0+H_0}=\frac{1}{\pi}\,\frac{(1-\beta)\frac{1}{4}a/\lambda^4+\beta\frac{1}{2}\varphi(\lambda)}{(1-\beta)\frac{1}{4}a/\lambda^4+f(\lambda)+\beta[1-\varphi(\lambda)]} \tag{5}$$

where φ (λ) represents the coefficient of reflection (given in a graphical form) for the substance forming the particles of second kind, and β a coefficient dependent upon their concentration.

In the preceding article I have already described the first experiments which served for the proof of the theory by tests in the laboratory. It was desirable to verify the theory on a larger scale, directly in the sea. For this purpose a special sea spectrophotometer was designed by the author and constructed in the workshop of the Physical Institution.

The Sea Spectrophotometer

The general appearance of the apparatus is shown by Fig. 1. The tripod S on which it is fastened is screwed to the deck in such a manner that the objective M of the apparatus is stretched out overboard and directed perpendicularly to the surface of the sea. The diffused inner light emitted from the latter, reaches the objective and after passing through a system of total reflection prisms and of lenses (a system resembling the periscope of a submarine), enters one of the slits k'' of the double collimator $k'k''$. Into the other slit of this collimator enters the light from the ground-glass which covers the camera H at the top and which is illuminated from above with the same light from the sun and sky as is the sea. Then the two rays to be compared pass from the collimator through the usual optical system of a spectrometer, being refracted by a Wollaston prism inclosed in a cylindrical camera P. An observer looking through the eyepiece O sees two spectra lying directly one above the other, the spectrum of the light falling on the sea from above (S_0+H_0) and that of light coming from the depth of the sea (M_0).* With the aid of a special slit inclosed in the ocular tube, a monochromatic strip can be selected from both spectra of wave-length easily determined with the aid of the vernier of an alidade sliding on

* The apparatus was shielded from reflected skylight by means of a screen.

the limb L and attached to the tube O which can rotate about a vertical axis, and thus monochromatic spectral rays be directed to the eye of an observer. Making the well known simple calculations for the different positions of the tube O corresponding to the different wave lengths λ, we shall find the experimental spectrum curve for the given sea.

Experiments at Sea

Preliminary measurements, with the aid of the apparatus just described were made by the author in the Black Sea near Sebastopol on board the cutter *Aj-Phoka*, in June 1922. The results of observations

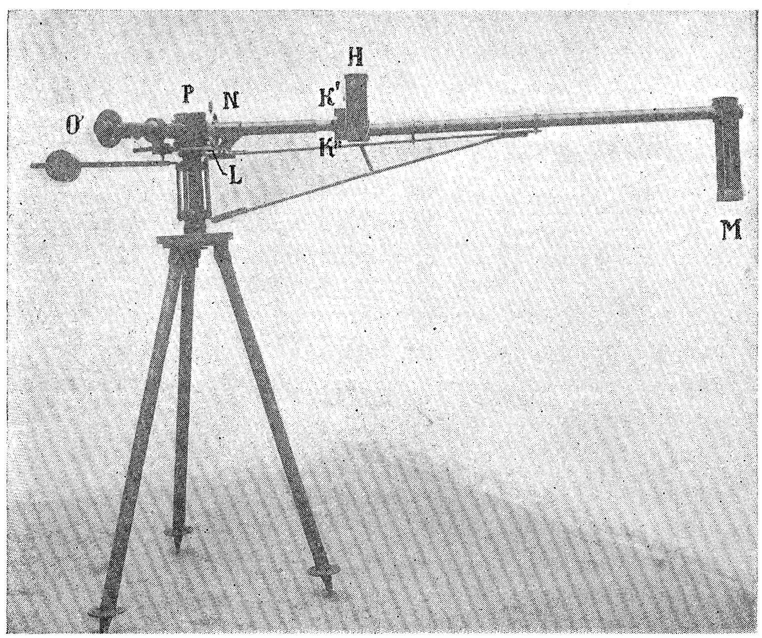

Fig. 1.

agreed sufficiently with the theory, but, unfortunately, the weather was extremely unfavorable, and owing to the violent rolling, the observations were but little trustworthy for plotting accurate curves.

Under far more favorable conditions I succeeded in making experiments on board the hydrographic ship *Pakhtusov* which left Archangel on August 22 1922 for the purpose of supplying the radio stations of Jugorsky-Shar on the north shores of the Island Vajgatsh and the peninsula Jamala on the cape Nare-Sale. Along with the spectrophotometric measurements there was made an approximate determination of the coefficient of scattering by means of a Secchi disk, on the basis of considerations indicated in my first article. But the latter must be regarded in some measure as provisional, for in polar seas, together with the particles of first kind there must be supposed a considerable quantity of particles of the second kind which introduce errors in the results of observations. However, these errors should not be considerable for it is likely that there are plenty of particles of the second kind in certain Bavarian lakes explored by O. v. Aufsess, and yet the depth of disappearance of the Secchi disk in these lakes (given by that author) coincides sufficiently with the depth calculated according to our theory as was noted in my preceding article.

The data obtained on four stations of observation are collected in the following table as examples.

No.	Situation of Station	Time	Depth of disappearance of the Secchi disk	α
1	Extreme north part of White Sea, Lat. 66°34′N; Long. 41°24′ E	9 A.M.	8 meters	0.09
2	Jongorsky-Shear, Warneck Bay	3 P.M.	5	0.23
4	Kara Sea, near Isle of Voronov	10 A.M.	12.5	0.03
5	Kara Sea, Lat. 69°52′ N; Long. 62°45′ E	10 A.M.	11	0.05

The spectral curves obtained at these four stations* are shown in Fig. 2. Two dotted curves lying one above and another below the experimental ones, are constructed theoretically for two different assumed values of α and β. As may be seen, the group of experimental curves lie quite well within the limits of theory. As a matter of fact the absolute intensities of the inner diffused light are everywhere less than given (for instance curve 8, which was constructed in the first article for the White Sea, supposing that only particles of first kind uniformly distributed in the water are present), but such systematic divergence is fully explained by the mere fact of the presence of particles of the second kind which selectively absorb the light. There could even be found an assumed value of β for which the theoretical curve would go exactly through the experimental points, but there is no special interest in this, for we know that the distribution of particles of both kinds is *not uniform* in layers of sea-water at different depths.

* It would have been very interesting to make measurements in the Barentz Sea northward of the Island Kolgujev, but unfortunately it was impossible owing to the very violent rolling.

Application of the Theory to Investigation of the Coloring of Deep-Sea Animals and Plants

Long ago it was noted that the greater the depth at which a given species is found the redder is its color, and the assumption was made that such a color is just complementary to the light which reaches this depth. It is obvious that having the optical constants characteristic of given waters, it is possible to calculate the spectrum of light falling on the given animal or plant after having passed through a layer of sea-water of more or less depth.

If the color of an animal or plant is complementary, then the coefficient of reflection for its surface must be inversely proportional to the intensity of each corresponding spectral ray which reaches the depth. This is in fact the case as is shown by the results of our experiments.

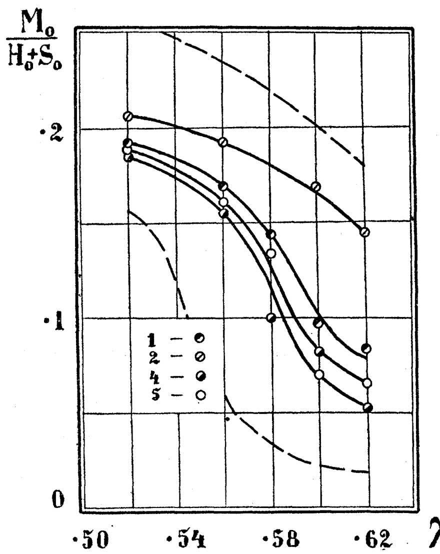

Fig. 2. Spectral curves for four stations.

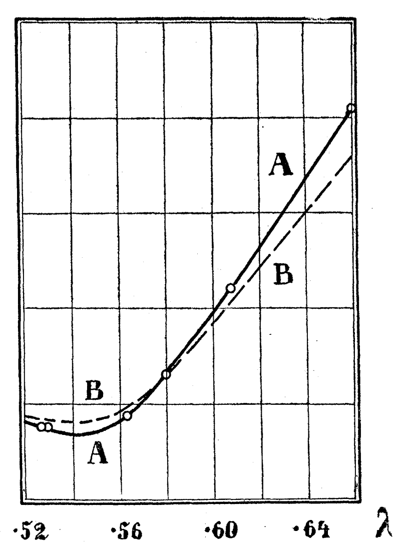

Fig. 3. Coefficient of reflection for Laminaria.

Let us for example take the curve AA, Fig. 3 which represents the coefficient of reflection found for a leaf of the plant *Laminaria*, taken from the bottom of the Warneck Bay. In the same figure a calculated curve BB shows by a dotted line the ordinates which are inversely proportional to the intensity of rays reaching the bottom of the bay. As can be seen, both curves lie very near one another, and therefore taking into consideration the above mentioned correction, we must conclude that this leaf of *Laminaria* is really colored in the complementary color.

Unfortunately there were no arrangements for dragging on board the *Pakhtusov*, and I could not get different animals and plants to examine their colors. Therefore I shall give some spectrophotometric data concerning coral of the Mediterranean, that was supplied to me. In Fig. 4 a continuous curve is shown representing its coefficient of reflection determined experimentally. In the same figure are seen two dotted curves, the ordinates of which are inversely proportional to the intensities of spectral rays reaching the depth, one corresponding to the depth 50 meters and the other to 100 meters. As can be seen, the experimental

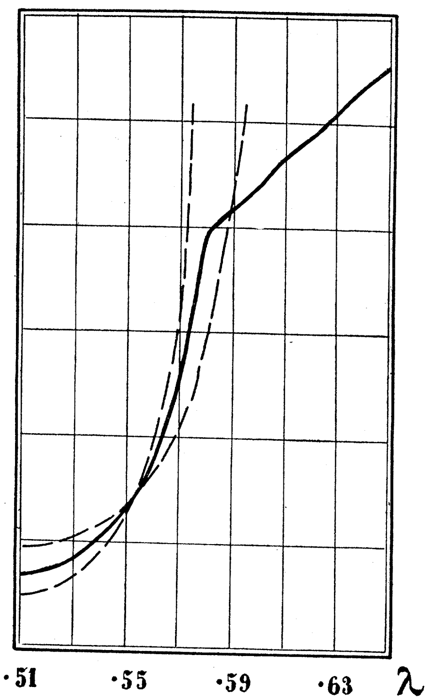

Fig. 4. Coefficient of reflection of Mediterranean coral.

curve to wave-length 59μ runs between these limiting curves, which confirms our hypothesis, for the given specimen, it appears, was found at a depth between 50 and 100 meters. It is particularly interesting to note that the coral follows the spectrum of light falling upon it to wave-length .59μ, but beyond this where the intensity of the falling light rapidly decreases towards the red end of spectrum and the ordinates of the dotted curves, being inversely proportional to the same, rapidly increase, we see that the curve of coefficient of reflection bends aside and no longer increases regularly.

Discussion of Papers by Raman and Ramanathan

After the first account of my investigations had been sent to the Physical Review, an article of Prof. Raman[3] of Calcutta upon "The Color of the Sea" was received, and I also became acquainted with the experimental investigations of Mr. Ramanathan[4] concerning the same problem. Raman and Ramanathan consider exclusively the molecular dispersion in the waters of the sea and they deduce a formula for the emitted diffused light, disregarding secondary diffusion, which leads to a distorted spectral curve.

In seas which I have studied, the molecular scattering is only a very small and negligible part of the whole scattering of light, which is chiefly caused by more active agents. Thus for the most transparent, the Black Sea, the coefficient of diffusion is $\alpha=0.004$ ($\lambda=1\mu$; $z=1$ meter) whereas the molecular diffusion gives only $\alpha=2.9\ (10)^{-4}$.

I am studying now by laboratory methods the different types of scattering in natural waters, a study whose results will be published later. Here I should like to mention only that I cannot agree with Ramanathan who thinks that particles of matter suspended in water do not influence noticeably the color of the sea, reflecting most of the energy of light downwards. It is easy to see that the unsymmetrical diffusion discovered by him does not alter the line of arguments leading to my fundamental equation (4). Actually, the coefficient α is determined experimentally, taking into account only the part of the light energy which is reflected backwards in relation to the falling rays, but this part influences the color of the sea. The coefficient α thus loses perhaps the exact meaning given to it by Rayleigh.

The correctness of this view is confirmed by Fig. 6 of my first article, obtained experimentally with particles very much coarser than those in the sea-water. My theory of the Secchi disk is also confirmed in the article of Ramanathan himself. Calculated from his data, the coefficient α comes out 0.002, which according to the curve of Fig. 5 of the first article gives for the depth of disappearance of the Secchi disk $z=50$ meters, and at this depth, according to J. Shokalsky, the disk really disappears in the waters of the Indian ocean. The greatest depth of the disappearance of the disk was observed in the Sargass Sea, where it reached $z=66$ meters, corresponding according to my theory to $\alpha=1.3\ (10)^{-3}$. A figure of the same order was obtained by me from the data of Martin[5] for distilled water.

[3] Raman, Proc. Roy. Soc. London **A101** (1922)
[4] Ramanathan, Phil. Mag. (1923)
[5] W. H. Martin, Journ. Chem. Soc. 1922

Therefore both for the most turbid Bavarian lakes investigated by O. v. Aufsess and for the most transparent point of the ocean my theory gives correct results, although the coefficient α varies from $1.46(10)^{-1}$ to $1.3(10)^{-3}$.

Returning to the case of molecular scattering I should point out that where it happens in its purest form (in the most transparent parts of the ocean), the energy of light emitted from the sea is very small in comparison with the energy of light *reflected by the surface of the sea* (as by the surface of a black mirror), and the color of the sea will depend here chiefly upon the color of the sky (see section 5 of the first article.)

In conclusion I wish to give my thanks to the Commitee of the Floating Marine Scientific Institute which gave me the opportunity to do experimental work in the polar Seas, and to all establishments and persons who helped me in my work either on the polar seas or in the Black Sea.

Physical Department
of the Scientific Institution,
Moscow,
October 27, 1923.

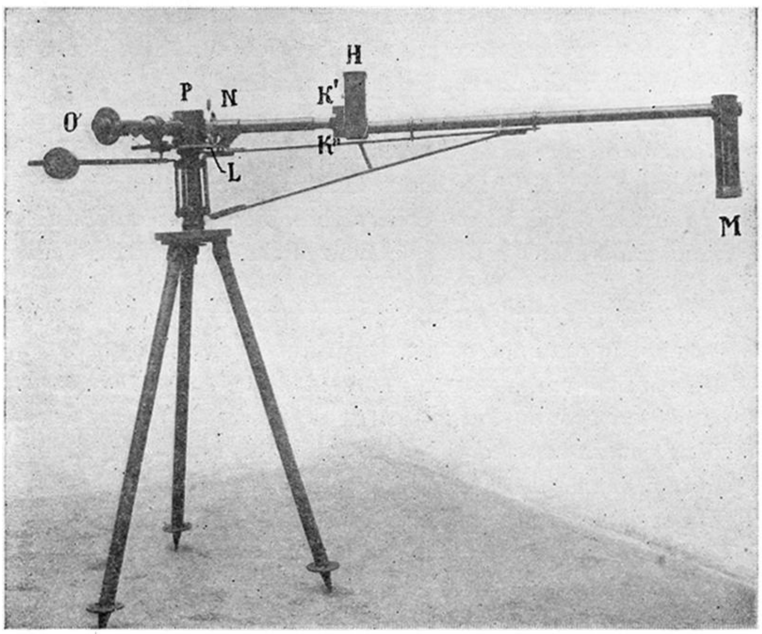

Fig. 1.