ON THE VISUAL AND PHOTOGRAPHIC ALBEDO OF THE EARTH

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ABSTRACT

The visual and photographic albedo of the earth.—This subject, previously treated by H. N. Russell and C. G. Abbot, is here discussed afresh in the light of Luckiesh's recent measurements of the visual brightness of earth-areas as seen from an aeroplane and Raman's theory of the color of the sea as originating from the molecular scattering of light in deep water. The effects of molecular scattering by the atmosphere and the sea are considered in detail with reference to the spectral distribution of the scattered light. The computed visual albedo comes out to be 0.46, and the photographic 0.58, in close agreement with the astronomical values 0.45 and 0.6 respectively.

INTRODUCTION

A valuable discussion of the photometric measures of the albedo of the earth was put forward by H. N. Russell,[1] who came to the conclusion that the visual albedo of the earth according to Bond's definition, as deduced from Very's observations of earth-shine on the moon, was 0.45 and the photographic albedo was 0.6. Further, Abbot[2] from radiation measurements and a consideration of the physical characteristics of the earth, has computed the total energy albedo to be 0.37. The difference between the visual and photographic albedoes is considerable and it has been suggested that this is due to the fact that a part of the light diffused out by the earth arises from the molecular scattering of light in the earth's atmosphere. Since the publication of the papers referred to, two investigations have appeared which make it desirable to consider the problem of the earth's albedo afresh. Luckiesh[3] has published observations made during aeroplane flights of the visual albedo of different kinds of landscape and also inland and oceanic waters. Then again, Abbot, in his discussion of the albedo of water-covered areas, considered only the reflection of light at the *surface* of the liquid. In reality, we have also to consider the important part arising from the diffusion of light entering the water. A theory of the color of the sea as being due to the molecular scatter-

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[1] *Astrophysical Journal*, **43**, 173, 1916.

[2] *Annals of the Smithsonian Astrophysical Observatory*, **2**, 161–163.

[3] *Astrophysical Journal*, **49**, 108, 1919.

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ing of light in deep ocean water has been put forward by C. V. Raman,[1] who has also pointed out the importance of the contribution which the scattered light from the sea would make to the albedo of the earth. In this paper, it is proposed to discuss the problem of the albedo, taking into account the spectral distribution of the molecular scattered light from the atmosphere and the sea.

We may divide the light going out of the earth into space as arising in the following ways:

1. Light molecularly scattered from the atmosphere above the region of dust;
2. Light scattered by the clouds;
3. Light scattered from the unclouded portions of the earth in the lower dusty regions of the atmosphere;
4. Light diffusely reflected from the earth's surface including the oceans.

Of these, the light molecularly scattered from the atmosphere and the sea would be richer in the shorter wave-lengths, and hence, on the aggregate, the returning light would be bluer than the incident.

LIGHT MOLECULARLY SCATTERED FROM THE ATMOSPHERE ABOVE THE REGION OF DUST

The discussions by F. E. Fowle[2] and L. V. King[3] of the extensive measurements of atmospheric transparency made by the Smithsonian Observatory have shown that in the region of wave-lengths shorter than 0.69 μ the loss of light on a clear day above the Mount Wilson level (1730 meters) could be accounted for almost entirely by the molecular scattering of light by the atmosphere.[4] The selective absorption exercised by the oxygen and water-vapor lies entirely in the region of wave-lengths longer than 0.70 μ and hence outside the visual and photographic regions. We shall take Mount Wilson level to be the upper limit of the region of dust. Abbot has given a table of intensities of energy in the normal solar spectrum outside the earth's atmosphere. From these and the values of the yearly mean dry-air transmission coefficients at Mount

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[1] *Proceedings of the Royal Society*, A, **101**, 64, 1922. See also *Molecular Diffraction of Light*, published by the Calcutta University Press, 1922.

[2] *Astrophysical Journal*, **38**, 393, 1913.

[3] *Philosophical Transactions of the Royal Society*, A, **212**, 375, 1913.

[4] Except for a possible small selective absorption between 0.51 μ and 0.65 μ.

Wilson,[1] we can determine graphically, from the areas of the energy wave-lengths curve, the percentage of light lost in transmission in different regions of the spectrum. Between 0.45 μ and 0.68 μ which we may take to be the effective visual region, I find the percentage of energy lost on normal transmission to be 10, and, in the region between 0.35 μ and 0.45 μ which we may take to be the effective photographic region, the percentage is 24. We have now to consider the actual loss that occurs, taking into account the facts that at a large portion of the earth's surface the light is incident obliquely and that, on the average, a portion of the atmosphere above Mount Wilson level is always clouded. At the place where the sun's rays meet the earth at an angle i, the transmission coefficient is $a^{\sec i}$ where a denotes the same quantity for normal incidence. The quantity of light falling on the surface of a sphere of radius r between the angles i and $i+di$ is

$$2\pi r^2 I \sin i \cos i \, di \, ,$$

where I is the intensity of the incident light. The amount of light transmitted in the same range is this quantity multiplied by $a^{\sec i}$, and this, taken over the whole sphere is

$$2\pi r^2 I \int_0^{\frac{\pi}{2}} \sin i \cos i \, a^{\sec i} \, di \, . \tag{1}$$

The integral does not seem to be capable of being easily evaluated; instead, it was done by graphical integration and the total loss in the visual region was found to be 17 per cent and in the photographic region 38 per cent. Assuming that half this amount would be reflected back to space, we get 8.5 per cent to be the visual, and 19 per cent to be the photographic albedo of the atmosphere above Mount Wilson, if it were entirely unclouded. Actually, however, according to Abbot,[1] about 60 per cent of the earth's cloudiness is above Mount Wilson level and since, on the average, 52 per cent of the earth's surface is always clouded, 31 per cent of the skies above Mount Wilson will be always covered by clouds. The distribution of clouds with height as given in Humphreys' *Physics of the Air*[2] is as follows:

1. Cirrus level—height above surface about 10 km
2. Cirro-stratus level—height above surface about 8 km

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[1] Fowle, *Smithsonian Miscellaneous Collections*, 69, No. 3.

[2] P. 309.

3. Alto-cumulus level—height above surface about 4 km
4. Cumulus level—height above surface about 1.5 km
5. Fog-level—ground

Of these, the first two would be comparatively thin and would transmit a large portion of the light. We may take the average cloud-height above Mount Wilson to be $5\frac{1}{2}$ km, corresponding to a level at which the pressure is half the sea-level pressure. Thus, the albedo due to the molecular scattering of the atmosphere above the dust-level would be as is shown in Table I.

TABLE I

	Visual	Photographic
From cloudless portion..........	0.69×8.5	0.69×19
From clouded portion...........	$0.31 \times \frac{38}{63} \times 8.5$	$0.31 \times \frac{38}{63} \times 19$
Total.....................	7.5 per cent	17 per cent

We have assumed the fraction scattered from the clouded portion to be less than that from the unclouded, in the ratio of the pressure above the average higher cloud-level to the pressure at Mount Wilson. We have also neglected the scattering due to the moisture in the dustless region.

LIGHT REFLECTED FROM THE CLOUDS

According to Abbot's energy-measurements and Luckiesh's photometric observations, we shall take the average reflecting power of clouds to be 65 per cent. Since the average cloudiness of the earth is 52 per cent, we get, for the percentage of light reflected back from the clouds, the values given in Table II.

TABLE II

	VISUAL		PHOTOGRAPHIC	
	Percentage Incident	Percentage Reflected	Percentage Incident	Percentage Reflected
From higher clouds (average level 5.5 km)	$100-\frac{38}{63} \times 8.5$ $=95$	$0.31 \times 95 \times 0.65$ $=19.1$	$100-\frac{38}{63} \times 19$ $=88.6$	$0.31 \times 88.6 \times 0.65$ $=17.9$
From lower clouds (average level 1.7 km)	$100-8.5$ $=91.5$	$0.21 \times 91.5 \times 0.65=12.5$	$100-19$ $=81$	$0.21 \times 81 \times 0.65$ $=11.1$
Total..........	....	31.6	....	29.0

Very little need be allowed from this for loss in transmission upward, for the diminution is due to scattering, and the scattered light would either go up or again get reflected from the clouds.

LIGHT SCATTERED FROM THE LOWER ATMOSPHERE

The light reflected from the lower atmosphere below the Mount Wilson level can be calculated as follows. From Abbot's data[1] for the mean coefficients of normal atmospheric transmission at Mount Wilson and Washington, the percentage of energy lost between the levels of the two stations is calculated for different wave-lengths, and an energy wave-length curve constructed with these data. From the area of the curve, it is found that in the region $0.45\ \mu$–$0.68\ \mu$, 14 per cent of the energy is lost, and practically the same percentage between $0.35\ \mu$ and $0.45\ \mu$. Assuming 20 per cent of this to be absorbed and half the remainder to be sent to earth and the other half back, we get 6 per cent to be the ratio of the light reflected back at normal incidence. Taking into account the fact that at a considerable portion of the earth the light is incident obliquely and that only 48 per cent of the earth is unclouded, the contribution of the lower atmosphere comes out to be nearly 4.5 per cent.

The above estimates agree very well with the careful visual photometric measurements of Kimball,[2] who found a mean transmission coefficient of 0.77 in clear weather, corresponding to the estimate here made of a loss of 10 per cent above Mount Wilson and 14 per cent below it.

LIGHT REFLECTED FROM THE EARTH'S SURFACE

Since more than three-fourths of the earth's surface is covered by seas, the most important contribution of the albedo from the surface of the earth would come from them. The deep blue color of the ocean waters has been explained by C. V. Raman[3] as originating from the molecular scattering of light within the water. The fraction of the incident energy scattered by unit volume of a homo-

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[1] *Astrophysical Journal*, 34, 203, 1911.

[2] *Monthly Weather Review*, 43, 650, 1914; also H. N. Russell's article, *loc. cit.*

[3] *Proceedings of the Royal Society*, A, **101**, 64, 1922.

geneous fluid like water is, for the most part, given by the Einstein-Smoluchowski expression

$$\frac{8\pi^3}{27}\frac{RT\beta}{N\lambda^4}(\mu^2-1)^2(\mu^2+2)^2 , \tag{2}$$

where β is the isothermal compressibility of the medium, μ its refractive index, N the Avogadro constant and λ the wave-length of the incident light. R and T have their usual meanings in kinetic theory. Since the amount of scattered light varies inversely as the fourth power of the wave-length, we can easily see why the blue end of the spectrum should predominate in the light returning from the water. Two other factors go to make the scattered light even a richer blue: one is the greater absorption in water of the red and yellow regions of the spectrum, and the other is an addition, to the light scattered in accordance with (2), of some unpolarized light which is greater in the violet end of the spectrum.[1] In his paper, Raman has given a table of the luminosity of deep ocean water for different wave-lengths in terms of the luminosity of a layer of dust-free air one kilometer thick when viewed transversely to the incident light. In calculating these values, he made use of the absorption coefficients of water obtained by Count Aufsess. Recently, W. H. Martin[2] has obtained fresh values for the absorption coefficients with pure, dust-free water, and Table III gives Raman's revised values for the luminosity of ocean water in terms of that of an atmosphere of dust-free air which would give an equal effect by lateral scattering.

TABLE III

LUMINOSITY OF OCEAN WATER

	Wave-Length in μ						
	0.658	0.602	0.590	0.578	0.546	0.499	0.436
Equivalent atmospheres of dust-free air....................	0.06	0.09	0.23	0.35	0.65	0.90	2.0

Confining ourselves to the region 0.45 to 0.68 μ, the fraction of incident light scattered comes out to be 0.06. Luckiesh's direct

[1] C. V. Raman, *Molecular Scattering of Light*, p. 55.

[2] *Journal of Physical Chemistry*, May, 1922.

determination of the "reflecting" power of the Atlantic, as measured from an aeroplane, gave an average value of 3.5 per cent. The difference is no doubt to be attributed to the fact that, in the above calculation, the absorption coefficient has been assumed to be equal to that of dust-free distilled water. Luckiesh makes it clear that 90 per cent of the light returning from the sea as viewed normally, is due to light diffused within it. The foregoing estimate refers to direct overhead observation. In an oblique direction, the molecular scattering would give rise to a greater luminosity, as a more extensive surface layer of water would come into operation, and, indeed Luckiesh has noticed that the brightness increases more than twice when the sea-surface is viewed at an angle of 45°.

Besides the molecular scattering, there is also the specular reflection to be taken into account, which would give rise to a reflection factor of about 3 per cent.

On the whole, we may put 8 per cent to be the fraction coming back from the ocean waters. As regards land areas, Luckiesh has obtained the following reflection factors for some typical surfaces: fields, 7.2 per cent; barren lands, 12.0 per cent; woods, 4.3 per cent. A snow-covered surface is known to reflect about 75 per cent of the incident light, but almost the whole of the snow-covered areas of the earth are near the poles, where only a small fraction of the sun's energy is received and where, moreover, a large part of the incident light would have been scattered by the atmosphere before reaching the earth. We may take, without much error, 12 per cent to be the average reflecting power of the land areas of the earth. Thus, the percentage of light scattered from the earth's surface in the visual region would come to be nearly $0.80(\frac{3}{4}\times 8+\frac{1}{4}\times 12)$, i.e., 7.2. Of this, allowing 30 per cent for loss on transmission through the atmosphere and remembering that only 48 per cent of the earth's surface is unclouded, we get 2.5 per cent to be the contribution of the surface of the earth to the visual albedo.

As regards the photographic albedo, the scattered light from the sea would contribute much more. An examination of Table III would show the enormous concentration of energy in the violet end of the spectrum. In the near ultra-violet, the light scattered from the sea is likely to be even stronger, since the absorption coefficient of water gets smaller and smaller as we go to the region of shorter wave-lengths. But against this, it has to be said that the presence of motes would tend to increase the absorption. We have previously estimated the photographic albedo of the sky above Mount Wilson to be 0.19, and, from Table II, it is evident that we shall not be far wrong if we take the fraction of the incident energy scattered by the sea to be 0.30. With the usual allowance for the loss of energy of the incident and reflected rays on transmission through the atmosphere and the fact that a portion of the earth's surface is clouded, we get the photographic albedo due to the sea to be nearly 6 per cent. The land areas would contribute practically nothing to the photographic albedo except the snowy regions near the poles, whose effect may come to about 1 per cent. Thus, the aggregate photographic albedo due to the surface of the earth would come to nearly 7 per cent.

SUMMARY

TABLE IV

	Visual	Photographic
	Per Cent	Per Cent
Light scattered from the gases of the atmosphere above the dust level......	7.5	17
Light reflected from the clouds.........	31.6	29.0
Light scattered from the lower atmosphere...........................	4.5	4.5
Light reflected from the surface of the earth including the oceans..........	2.5	7.0
Total..........................	46	57.5

The visual and photographic albedoes obtained above agree very well with the astronomical value 0.45 and 0.6. Considering the uncertainties in the estimation of the earth's albedo factors and the difficulties of photometric measurement of the earth-shine on the moon, the agreement is actually better than could have been anticipated.

In conclusion, I have great pleasure in expressing my thanks to Professor C. V. Raman for his suggestion of the problem and interest in the progress of the work.

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