THE ALBEDO OF THE PLANET EARTH AND OF CLOUDS

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ABSTRACT

The albedo of the whole earth is calculated to be 35 per cent, largely on the basis of Danjon's visual lunar measurements. The calculations also give a value of about 0.50 for the average albedo of clouds, which is in better agreement with measurements than the currently accepted value.

1. Introduction

The most commonly quoted value for the albedo of the earth is that resulting from Aldrich's [5] assumption that the average reflection for clouds alone is 0.78 of the energy incident on them; his calculation of the albedo, A, for the whole earth is 43 per cent of the total solar energy, Q, which reaches the earth.

The albedo of the earth may be expressed as the sum of three terms or

$$A = A_e + A_a + A_c \quad (1)$$

where

$$A_e = \frac{\text{energy reflected to space by earth's surface}}{Q} \times 100,$$

and A_a and A_c are the percentages of energy similarly reflected (or scattered) to space by the earth's atmosphere and by average clouds, respectively.

For A_e and A_a, Aldrich used the computations of Abbot and Fowle [2] and subdivided $A = 43$ per cent into $A_e = 2.3$ per cent, $A_a = 6$ per cent, and $A_c = 34.7$ per cent. In view of the very large contribution by clouds, and because it is almost certain [20; 21][1] that the average reflection by clouds alone must be considerably less than 0.78 of the energy incident on them, A_c must be less than 34.7 per cent and therefore, A must be less than 43 per cent, especially if the values quoted for A_e and A_a are (as will be shown later) approximately correct.

Another estimate of the albedo of the whole earth is obtained from photometric measurements of the relative intensity of the light on the dark and bright sides of the moon. The light side is illuminated by direct sunlight, while the dark side is illuminated by sunlight which has been reflected from the earth to the moon. Danjon [10] calculated, on the basis of numerous lunar measurements over a period of about 9 years, that the average *visual* albedo, A_v, of the earth is 39 per cent of the visible solar energy, Q_v, which is incident on the whole earth. Since nearly half the solar energy lies in the infrared, beyond the region Danjon measured, and since the albedo of the earth decreases with increasing wave length of the incident light (at least from blue to red light) [10], the albedo of the whole earth might be smaller than 39 per cent. In what follows an attempt will be made to determine the average albedo, A, of the whole earth for *total* solar radiation.

The visual albedo may be expressed as the sum of three terms,

$$A_v = A_{ev} + A_{av} + A_{cv} = 39 \text{ per cent}, \quad (2)$$

where

$$A_{ev} = \frac{\text{visible energy reflected to space by earth's surface}}{Q_v} \times 100,$$

and A_{av} and A_{cv} are the percentages of visible energy similarly reflected by the atmosphere and by average clouds, respectively.

In order to obtain A, the following rough outline will be followed. After estimates of A_e and A_a have been obtained, they will be subdivided into three broad spectral components, namely, into the ultraviolet, visible, and infrared components. From these subdivisions, A_{ev} and A_{av} will be obtained. After substituting these values of A_{ev} and A_{av} into equation (2), A_{cv} can be determined. Finally, A_c can be estimated with the aid of A_{cv}, and hence, A can be calculated from equation (1).

2. The extraterrestrial solar energy

In order to investigate the spectral reflections by the earth's reflecting agents, it is necessary to examine the spectral distribution of the extraterrestrial solar radiation. The extraterrestrial solar energy may be divided into the three broad spectral regions, comprising the energy approximately in the wave-length regions, 0–0.40μ (ultraviolet), 0.40–0.74μ (visible), and >0.74μ (infrared), and these comprise about 9, 45, and 46 per cent, respectively, of the total incoming energy. These percentages were determined from

[1] Additional data have been obtained from recent airplane measurements. The results will appear in another publication.

a graph of wave length, λ, plotted against relative intensities, $I_{0\lambda}$, of solar radiation, as measured by a V-2 rocket [15] (for the ultraviolet radiation up to 0.34μ) and by the Smithsonian Institution for the remainder of the spectrum [3; 1].

Absorption by ozone.—The absorption by ozone and oxygen would prevent energy from being scattered to space, but this would have a pronounced effect only in the ultraviolet. The amount of energy absorbed by ozone (neglecting scattering above the ozone "layer") is given by:

$$I_{0\lambda} - I_{d\lambda} = (1 - 10^{-a_\lambda d})I_{0\lambda},$$

where $I_{d\lambda}$ is the energy transmitted through the ozone in a small wave-length interval, a_λ the decimal absorption coefficient for ozone [12], and d the path through the ozone in cm reduced to 0C and 760 mm pressure.

After the quantity $(1 - 10^{-a_\lambda d})$ was plotted as a function of λ for $d = 0.3$ cm, the average value for each 0.01μ wave-length interval from 0.22μ to 0.36μ was multiplied by the corresponding relative area $I_{0\lambda}\Delta\lambda$, obtained from the solar spectral distribution curve. To the sum of these products, was added the energy below 0.22μ, which was considered to be completely absorbed by oxygen. This final sum, divided by the total area under the solar spectral curve was the percentage, G, of the total extraterrestrial radiation absorbed by ozone for $d = 0.3$ cm. This procedure was repeated for $d = 1.0$ and 3.0 cm. Assuming 0.3 cm of ozone in the zenith everywhere, 0.3 cm, 1.0 cm, and 3.0 cm correspond approximately to airmass 1, 3.3, and 10, respectively; G_m (per cent absorption at airmass m) is given as a function of m in fig. 1.

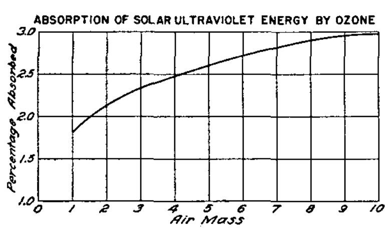

FIG. 1. Absorption of ultraviolet radiation by atmospheric ozone (per cent of total solar radiation). It is assumed that 0.3 cm is the total ozone path for 0° zenith distance (airmass = 1); latitudinal variation of total ozone is neglected.

To find the percentage of energy absorbed by ozone over the entire earth, it is necessary to account for the variation of airmass over the earth. As seen from the sun, the earth represents a unit circular area, which may be divided into narrow concentric rings of area, ΔS (expressed as a fraction of the entire circular area), and over each ring the average airmass may be considered to be constant. Hence it is easily seen that the percentage absorption over any ring is $G_m\Delta S$. This product was computed with the aid of fig. 1 and values of m and ΔS given by Abbot and Fowle [2]. Summing over the whole of the earth's projected area, we find that 2.1 per cent of the incoming solar energy is absorbed by ozone and oxygen. It will be noted that 2.1 per cent is less than the 4–6 per cent commonly assumed [9]; this is probably due to the assumption of 6000K black-body extraterrestrial radiation in previous investigations [18].

Since $0.09Q$ reached the outer atmosphere in the ultraviolet, below the ozone "layer" solar energy reaches the atmosphere in the ratio 7:45:46, approximately, for the three spectral regions.

3. Reflection by the earth's surface

According to Abbot and Fowle, the amount of energy reflected to space by the cloudless portions of the earth's surface is 2.3 per cent of Q or $A_e = 2.3$ per cent. For the present we shall adopt their value. The value of 2.3 per cent is a small portion of the reflected radiation, but it is necessary to divide it into the three broad spectral regions.

Since the amounts of visible and infrared solar energy which reach the earth's surface are of about the same order of magnitude, while the amount of ultraviolet energy is much smaller, and since some portions of the earth's surface reflect energy relatively more in the visible, while others reflect relatively more in the infrared, a fair approximation to the reflection by the earth's surface can be obtained by dividing the 2.3 per cent into 0.1, 1.1 and 1.1 per cent for the ultraviolet, visible and infrared energies, respectively (see table 1). These numbers are small, and apportioning them differently would not change the final result significantly.

TABLE 1. Reflection of sunlight to space (per cent), case 1.

	Ultra-violet	Visible Q_V	Visible Q	Infrared	Total
Earth	0.1	2.4	1.1	1.1	2.3
Clouds	1.8	25.1	11.3	10.2	23.3
Atmosphere	2.6	11.5	5.2	1.3	9.1
Totals	4.5	39.0	17.6	12.6	34.7
Albedos	50		39	27	35

4. Reflection by the atmosphere

Another reflecting agent is the atmosphere itself. The reflecting particles may be divided into three groups, namely, air molecules, water vapor, and dust.

Air molecules.—For air molecules, Fowle [11] gives the percentage of energy scattered from the direct solar beam as a function of airmass; his data for Washington, D. C. (near sea level), are plotted in fig. 2. After dividing the earth into concentric rings and integrating, as in the case for ozone absorption, we find that the total energy scattered by air alone over the whole earth is 15 per cent of Q.

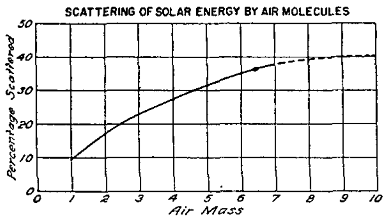

Fig. 2. Scattering of solar radiation by air molecules (per cent of total solar radiation). Dashed lines are extrapolated.

Water vapor.—Fowle also gives the percentage of energy scattered by various amounts of precipitable water vapor, w, (up to 2.0 cm) above Mt. Wilson. Ångström [6] doubts that this scattering is due to water vapor and attributes it instead to dust which is present simultaneously with water vapor, although he considers that above Mt. Wilson there should be very little "mineral dust." It would, therefore, be reasonable to associate the scattering agent with water vapor, large amounts of water vapor being accompanied directly by large amounts of scattering. Fowle's data have been extrapolated graphically from $w = 2$, to $w = 4.3$ cm on the assumption that for a given airmass, the scattering function was of the form $1 - e^{-kw}$ (which would be correct for monochromatic radiation), where k is a constant. The data were regrouped and plotted in fig. 3.

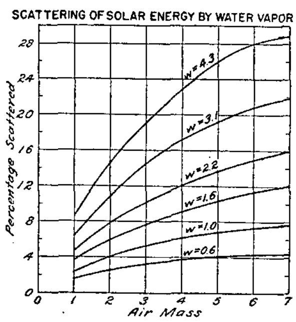

Fig. 3. Scattering of solar radiation by atmospheric water vapor (per cent of total solar radiation). Curves for $w > 2$ are drawn from extrapolated data.

To apply fig. 3, water-vapor data are needed. Abbot and Fowle [2] estimated the precipitable water vapor in various latitude belts from the surface vapor pressure and their values were adopted. They also divided the projected area of the earth as viewed from the sun into concentric rings, and further subdivided these by projecting upon them the latitude circles as they would appear at the equinox; they give the fractional areas, the airmass and the precipitable water vapor of each of these smaller units. Combining their calculations with the data shown in fig. 3, the percentage of Q which is scattered by water vapor in each small area is readily calculated; and after summing the areas over the whole earth, it is found that 10 per cent of Q is scattered by water vapor.

Dust.—The remaining scattering agent in the cloudless atmosphere is dust, but data concerning the depletion of solar radiation by dust are very meagre. Klein [17] showed that the depletion over ocean areas is usually small, while over land it is about 10 per cent, so that the depletion by dust is about 5 per cent for the whole earth; of this amount, a portion will be absorbed.

For particles which are very small (diameter less than 0.1 wave-length, approximately) Rayleigh scattering prevails, in which the forward and backward scattering are equal [13]. As the particles become large, the forward scattering exceeds the backward scattering for the most part.

Since the amounts of energy which are scattered in upward and downward directions are dependent on both the size and nature of the scattering particles [13], we consider two extreme cases for upward scattering:

Case 1 assumes—(*a*) that of the 15 per cent scattered by air itself, half (or 8 per cent) is scattered back to space; (*b*) that water-vapor scattering particles are small, so that of the 10 per cent scattered by water vapor half (or 5 per cent) is scattered back; and (*c*) that 1 per cent is scattered back by dust. That is, a total of $8 + 5 + 1 = 14$ per cent of Q, is assumed scattered back to space if there are no clouds.

Case 2 assumes—(*a*) that upward scattering occurs only by the air itself, and (*b*) that it amounts to 8 per cent of Q. In this case, the particles of water and dust are considered to be large enough so that only forward scattering results from these particles.

Case 1

Since the average cloudiness over the earth, neglecting latitude and longitude variations, is 0.54 (Brooks [8]), 0.14×0.46, or 6.4 per cent of Q is scattered back to space by the unclouded portions of the atmosphere. To this must be added the energy scattered by the air above clouds. Abbot and Fowle estimate that 6 per cent of Q is depleted by atmospheric scattering or nonselective absorption at the level of Mt. Wilson, which they take as the top of some low clouds. For clouds whose tops are higher, such depletion will be smaller in amount. If we assume that the average of such depletion at the level of the tops of all clouds is 5 per cent, and that nonselective absorption is negligible (no dust above clouds), the entire 5 per cent will be scattered back to space. Since this mechanism operates only over clouds, the amount scattered to space by the atmosphere above clouds will be $0.05 \times 0.54 = 2.7$ per cent of Q. The total energy returned to space by the atmosphere is then $6.4 + 2.7$, or 9.1 per cent of Q.

Spectral distribution of scattered radiation.—Here again, scattered radiation must be divided according to the three broad bands. From the assumptions for case 1, we see that the radiation scattered upward should have nearly the same spectral distribution as the radiation scattered downward (skylight). Kimball [16] gives the relative spectral distribution for skylight falling on a horizontal surface when the sun's zenith distance is 25 degrees for the wave lengths 0.395μ to 0.76μ. Extrapolating his data on the assumption that the skylight intensity is zero at 0.29μ and at 1.5μ, and reaches a maximum at 0.39μ (at somewhat larger λ, according to Albrecht [4]), the relative amounts of energy in the ultraviolet, visible and infrared are found by multiplying the average intensity for each region, by the wave-length interval. The average relative intensities in each region are in the ratio 100:60:6, and the relative amounts of energy are in the ratio 10:20:5. Since these energies make up 9.1 per cent of Q, the amounts in each spectral region are 2.6, 5.2, and 1.3 per cent of Q, respectively.[2]

Calculation of A_{ev} and A_{av}.—In the visible spectrum, table 1 shows that 1.1 and 5.2 per cent of Q are reflected to space by the earth's surface and by the atmosphere. In order to relate these to Danjon's measurements, it will be necessary to convert these reflections to percentages of the total incoming *visible* energy, Q_v, *i.e.*, to find A_{ev} and A_{av}. Since the visible energy directed toward the earth is 45 per cent of Q, the numbers expressed as a per cent of Q must be divided by 0.45 in order to express them as a per cent of Q_v. After that is done, it is found that $A_{ev} = 2.4$ per cent, and $A_{av} = 11.5$ per cent.

5. Reflection by clouds

Since Danjon gives 39 per cent as the visual albedo of the whole earth, it follows from equation (2) that $A_{cv} = 25.1$ per cent. After converting this to per cent of Q, it is found that 11.3 per cent of Q is reflected to space by clouds in the visible portion of the spectrum. To estimate the percentage of energy reflected by clouds in the infrared, use is made of Hewson's [14] work. In fig. 4 is given the distribution of reflectivity as a function of wave length for several types of clouds. Those referring to a cloud thickness of 200 m were obtained by combining two of Hewson's graphs; the curve for 1220 m, which approximates the reflectivity for an altostratus cloud, was computed from Hewson's equations. No attempt is made here to use the magnitude of the reflectivity; only the relative reflectivity, comparing the visible with the infrared, is needed. It will be noted that up to about 1.3μ, the reflectivity is almost independent of wave length, but that for longer wave lengths it decreases. For each of

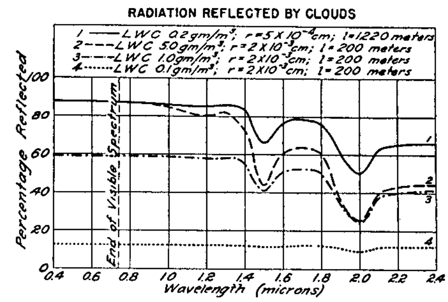

FIG. 4. Reflection of solar radiation by clouds with designated liquid-water content (LWC), drop-size radius (r), and vertical thickness (l). Reflection expressed in per cent of solar radiation incident on cloud.

the curves, taking account of the incoming energy distribution, the reflectivity for the entire infrared region is about 0.9 of that in the visible region. Using this relation, the reflection of the infrared energy by clouds is $11.3 \times 0.9 = 10.2$ per cent of Q, since the amounts of incoming energy reaching the clouds are nearly the same for both the visible and infrared radiation.

The absorption coefficient of water from 0.3μ to 0.4μ [12] is close to that in the visible spectrum, so that the reflectivity by clouds should be much the same in the visible and in the ultraviolet regions. Since the ratio of the energy which reaches the cloud level in the ultraviolet and in the visible will be somewhat less than 7:45 (ultraviolet energy is scattered more below the ozone layer) the amount of ultraviolet energy which is reflected by clouds is at most $11.3 \times 7/45 = 1.8$ per cent of Q.

6. Albedo of the whole earth

The sum of the reflections by clouds for the three spectral regions is 23.3 per cent, and hence from equation (1) the albedo for the whole earth is the sum of 2.3, 23.3, and 9.1 or 34.7 per cent. A summary of all these calculations appears in table 1 for the whole earth.

7. Albedo of clouds

Fowle and Abbot estimated that 85 per cent of Q reaches the Mt. Wilson level from sun and cloudless sky. They also estimated that 90 per cent of Q reached the clouds whose tops were above Mt. Wilson. If we assume that 88 per cent of Q reaches the tops of clouds on the average, and that the average cloudiness is 0.54, we find that the amount of energy received at the clouds is 0.54×0.88 or 48 per cent of Q. Since 23.3 per cent of Q is reflected by clouds, the average reflection by clouds over the whole earth is 23.3/48 or 0.49 of the energy incident upon them.

[2] The average zenith distance for the whole earth is somewhat larger than 25 degrees, but the calculation would not be significantly changed by using spectral sky radiation distribution appropriate to the larger zenith distance.

Case 2

Now consider that of the atmospheric elements only air itself reflects solar radiation back to space, and that the amount of scattered energy is 8 per cent of Q for cloudless conditions. This scattering is effective 46 per cent of the time (cloudiness 0.54); therefore 3.7 per cent of Q is scattered back. To this must be added the radiation which is scattered back above the clouds or 2.7 per cent of Q, making a total of 6.4 per cent scattered back by the air, which is very close to the 6 per cent assumed by Abbot and Fowle. For this case, the spectral distribution would follow Rayleigh's law, or the amount of scattered energy would be a function of the inverse fourth power of wave length. From a plot of the Rayleigh transmission "factors" [19], it is seen that the percentages of incident radiation which is scattered in the three spectral regions are roughly in the ratio 45:10:1; but since the incident energy is in the ratio 7:45:46 the amounts of energy scattered should be in the ratio of the respective products or about 3.1:4.5:0.5. Since the total amount of energy scattered upward is 6.4 per cent of Q, the amounts of energy scattered upward in each of the regions are 2.4, 3.6, 0.4, per cent, respectively. Following now the same procedure as for case 1, we obtain the results as shown in table 2.

Table 2. Reflection of sunlight to space (per cent), case 2.

	Ultra-violet	Visible Q_v	Visible Q	Infrared	Total
Earth	0.1	2.4	1.1	1.1	2.3
Clouds	2.0	28.6	12.9	11.6	26.5
Atmosphere	2.4	8.0	3.6	0.4	6.4
Totals	4.5	39.0	17.6	13.1	35.2
Albedos	50		39	29	35

Here again the albedo is about 35 per cent, while the average reflection by clouds alone is $26.5 \div 48.0 = 0.55$.

8. Discussion of results

It is interesting to compare the albedo in the ultraviolet and the infrared with Danjon's measurements. In the ultraviolet radiation, 4.5 per cent of Q is reflected. Since 9 per cent of Q was incident on the earth, the albedo of the whole earth in ultraviolet radiation is 50 per cent. Similarly the infrared albedo is about 28 per cent. Danjon gave for wave length 0.435μ an albedo of 59 per cent, and for 0.606μ (Penndorf [22]), 29 per cent. The lower value calculated here for the ultraviolet is undoubtedly due in part to the absorption by ozone. For the infrared, instead of the equality between the calculation and Danjon's observation, one might have expected that the calculated value would be lower because of the absorption of the infrared radiation by clouds, and smaller atmospheric scattering.

Effect of surface reflection.—It is instructive to examine the effect of the reflection by the earth's surface on the computed values of the earth's albedo and on the reflection by clouds. Earlier we had adopted the value $0.023Q$; but using Ångström's [7] measurements of the albedo of a water surface as a function of zenith distance of the sun, and integrating over the entire earth, assuming it to be entirely covered with water, we find that 8.9 per cent of the energy incident on the water surface is reflected. And considering that 0.7 (neglecting geographic distribution) of the earth's surface is covered by water, that the average cloudiness over water is 0.58 [8], and that $0.69Q$ [2] would reach the earth's surface if there were no clouds, it is easy to compute that $0.018\,Q$ is reflected by the earth's water surface.

For the remainder of the earth, about 1/5 of the total land surface lies between latitude 45 degrees and the Poles, and is almost entirely in the northern hemisphere. Consider the situation on March 21; if we assume that the land mass north of 45 degrees is snow-covered with an albedo of 60 per cent, and that the remaining 4/5 of the land surface has an albedo of 8 per cent, and consider that $0.69Q$ reaches the cloudless earth surface, that the cloudiness over the land is 0.51, and that the total land mass comprises 0.3 of the entire earth's surface, we find that $0.019Q$ is reflected to space by the land surface. This gives a total of $1.8 + 1.9 = 3.7$ per cent of Q as the reflection by the earth's surface.

The numbers chosen here are probably too high, so that it cannot be expected that the reflection to space by the earth's surface would be as high as 3.7 per cent. However, to use an upper limit, if we replace the earlier value of 2.3 by 3.7 per cent and substitute in tables 1 and 2, we find that the reflection by clouds is 0.47 of the energy incident on them for case 1, and 0.52 for case 2; the albedo of the entire earth remains close to 35 per cent. If, as an opposite extreme, the contribution by the earth's surface is taken as zero, then the albedo of the planet still remains about 35 per cent, but the reflection by clouds increases to 0.52 for case 1 and to 0.60 for case 2. This again is an extreme condition, so that the average reflection by cloud must be between the limits 0.47 and 0.60 of the energy incident on them, and should be close to 0.50. Table 3 gives a summary of these cloud reflections. It should be pointed out that although the average

Table 3. Average albedo of clouds.

Albedo of earth's surface (per cent)	Case 1	Case 2
0	0.52	0.60
2.3	0.49	0.55
3.7	0.47	0.52

albedo of clouds over the whole earth cannot be calculated at present from direct measurements, cloud albedo measurements [20; 21] indicate that 50 per cent *could* be the average cloud albedo for the whole earth, while 78 per cent is definitely too high.

9. Conclusions

Several other factors should be pointed out. Since Danjon's measurements were made in France, the Pacific Ocean area would not contribute to his measurements. Secondly, the latitudinal variation of cloudiness and of land and water surface might affect the calculations somewhat. This would also be true of the fact that the projected area of clouds as seen from the sun would not be exactly the same as the cloudiness reported by an observer on the earth's surface in regions of high airmass.

However, neither the assumptions made nor the factors neglected would all have effects in the same direction, and to a certain extent would balance each other. In conclusion, for the 9 years (1926–1934) of Danjon's measurements it seems that the earth's albedo was about 35 per cent, and that the reflection by clouds averaged over space and time was about 0.50 of the solar energy incident upon them.

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