ICARUS 11, 332–337 (1969)

The Effect of Pulverization on the Albedo of Lunar Rocks

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Received July 15, 1969; revised October 21, 1969

Measures of the albedo under full-moon conditions have been made on two samples of very dark rocks, pulverized and sieved so as to obtain powders of different grain size. Below a size of 0.05 mm the albedo suddenly increases, obviously because the individual grains become transparent. By a rough calculation of the radiation transfer this is made understandable and a relation is found between the grain size and the absorption coefficient necessary to produce in combination an albedo of 0.10. If the Moon is covered by fine dust, its low albedo shows that the absorption coefficient must be very high, probably because of darkening by the solar wind.

In order to understand the albedo properties of the Moon, it is important to study the effect of the physical agents, acting on the lunar rocks. We know that pulverization increases the albedo (Hapke, 1965, 1966; Filice, 1967; Adams, 1967; Adams and Filice, 1967); that an uneven, roughened surface looks darker than a smooth one (Halajian, 1968); that by compaction the albedo increases if the grains are very small (Filice, 1967); and that the solar wind darkens the surface (Hapke, 1965, 1966; Shoemaker, 1966); but that irradiation by ultraviolet light bleaches the grains (Cohen and Hapke, 1968).

Laboratory Observations

We intend to investigate only one of these effects, namely the influence of pulverization, such as would occur, e.g., when meteoroids of all sizes impact on the lunar rocks. Similar studies have already been made by Hapke, Adams, and Filice. We investigate the albedo at full moon ("normal albedo"), because then the effects of the shadows have disappeared and the intrinsic properties of the material become apparent. On the other hand we avoid the special "opposition effect," which appears if the incident beam has a very small angular spread (<1°).

Two samples of very dark rocks were studied in the laboratory: (a) a dark basalt from the Rhön; (b) dark lapilli from the Eifel. They were ground and the powder of each sample was separated into several fractions by passing it through graded sieves; all fractions were washed, in order to remove adhering fine dust.

Already at first sight it was apparent that, proceeding from the coarse grains [>1 mm] to the finer ones [0.10–0.05 mm], the material taken as a whole first slightly darkened, but that the finest fraction [<0.05 mm] was strikingly brighter. The same effect occurred in both of our rock samples (Fig. 1).

In order to study the effect more quantitatively a simple photometric device was set up. A lamp, fed with a stabilized tension of 6 V, emits a horizontal beam of light which is reflected vertically down by a plane glass plate and illuminates the sample. The upwards reflected diffuse beam passes through the same glass plate; by a lens the vertical rays are focused on a silicon PIN photodiode, connected with a digital microammeter. A filter of a saturated solution of copper sulfate, thickness 1 cm, is inserted in order to eliminate the infrared.

Each measurement was preceded and followed by a measurement in which the sample was replaced by a piece of black

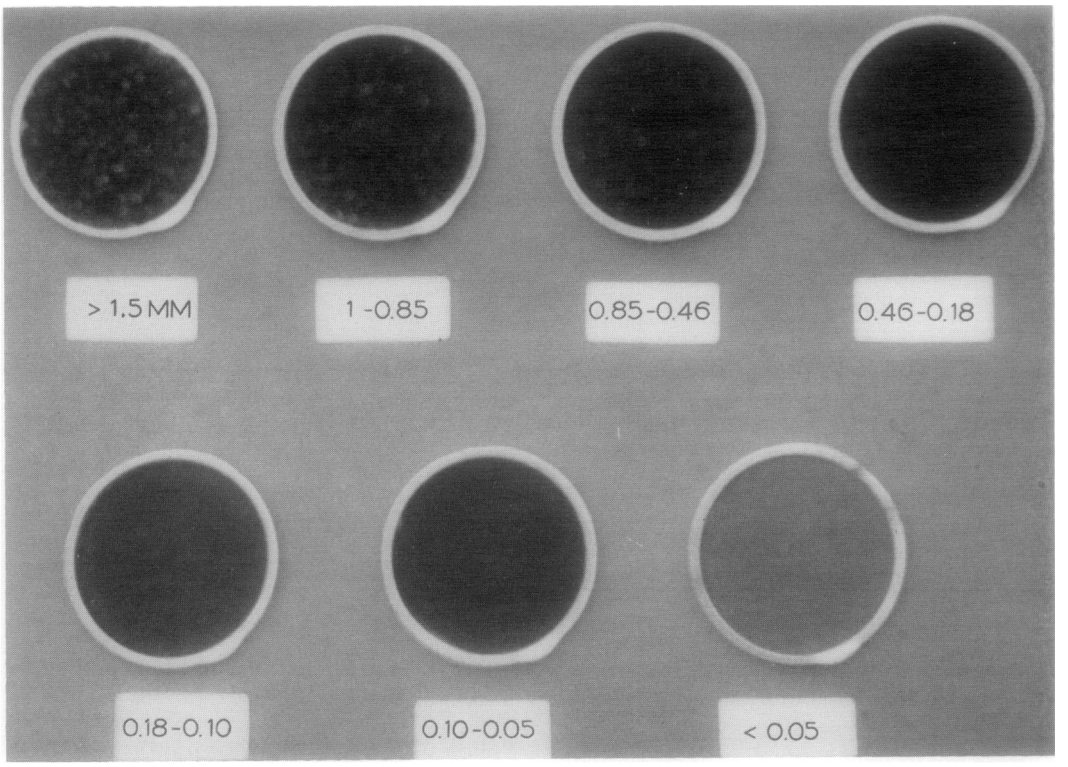

FIG. 1. Albedo of lapilli in different grades of grain size. The diameter of the recipients is 6 cm.

velvet and by a metal plate, covered with magnesium oxide; they were considered to correspond with the albedos 0 and 1.

Several series of measurements gave satisfactory agreement. The mean results are given in Table I. These measurements

TABLE I

ALBEDO OF PULVERIZED DARK ROCKS

Size (mm)	Reflected brightness (%) Basalt	Lapilli	Calculated brightness
>1.00	7.9	6.6	6
1.00–0.84	7.1	6.6	6
0.84–0.45	5.5	6.5	6
0.45–0.18	6.0	5.9	7
0.18–0.10	6.7	5.7	8
0.10–0.05	6.6	5.5	10
<0.05	19.4	13.6	17

confirm the visual appearance already described. They are essentially in agreement with the results obtained by the authors quoted above.

The phenomenon was so striking that some inhomogeneity of the material was suspected. It could have been that the lighter colored constituents were more friable than the darker ones, so that the material of the different fractions might differ not only in grain size, but also in optical properties. For this reason Röntgen spectra were taken, both of the finest (<0.05) fraction and of the 0.18–0.10 fraction. No difference appeared for either the basalt or for the lapilli. We conclude that the suspected separation did not occur; for each rock the material may be considered as differing only in grain size.

A moment's consideration convinces us that such an effect is to be expected. As long as the individual grains are practically opaque, the albedo is mainly determined by the surface reflection. When the individual grains become so small that light penetrates through them and is scattered back, not having suffered a too strong absorption on its way, the albedo will start increasing. Since the light has to pass back and forth

through a grain, we may expect that roughly $2Dk \simeq 1.6$, where D is the grain size at which the albedo begins to increase and k, the absorption coefficient of the bulk material.

Some mineralogical thin sections of very dark rocks were compared to a calibrated wedge and gave the following values for the absorption coefficient:

Basalt A	$k = 36$ per mm
Basalt B	$k = 3.2$ per mm
Dunite	$k = 15$ per mm

Assuming as an order of magnitude $k = 30$, $D = 0.03$ mm, we find $2kD = 1.8$, $\exp(-2kD) = 0.16$, which is of the expected order.

TABLE II

PHASE FUNCTION FOR SPHERICAL GRAINS ($n = 1.65$)

φ	Transparent	Opaque
0°	6.67	8.58
10°	5.80	5.30
20°	4.90	3.55
40°	2.65	1.72
60°	1.14	1.03
80°	0.40	0.72
100°	0.06	0.57
120°	0.06	0.53
140°	0.27	0.52
160°	0.70	0.52
180°	0.90	0.52

THEORY OF RADIATION TRANSFER

We shall now try to understand more quantitatively these results. The powder is schematically represented as a semiinfinite atmosphere with an absorption coefficient k and a scattering coefficient σ. From thin sections of three samples of such dark rocks we found absorption coefficients of 3, 15, and 36 per mm. The scattering is partly due to the intrinsic turbidity of the rock, partly to the irregular reflections and refractions at the boundaries of the grains. This last effect will be the most important when the size of the grains becomes very small. We assume that the grains will act on the average as if they were little beads with a diameter D and a refractive index 1.65, as commonly found for such minerals. Statistically speaking, every time a ray of light has progressed over a distance D, it disappears and has been split according to the characteristic rainbow phase function. This we approximate by assuming a scattering coefficient $\sigma = 1/D$, so that the intensity has decreased by a factor $e^{-\sigma D} = e^{-1}$ after a path length D; while the phase function $x(\varphi)$ is calculated according to the classical scheme which Wiener followed for waterdrops. The rainbow maximum is smoothed out over the neighboring directions and the function $x(\varphi)$ is normalized, so that $\int x(\varphi)d\omega = 4\pi$. This phase function is tabulated in Table II.

With this normalized indicatrix we compute the normal albedo ρ for different values of the parameter $\lambda = \sigma/(\sigma + k)$. For the angle of incidence i and the angle of observation r we first assume $i = r = 0$ and put $\eta = \cos i$, $\zeta = \cos r$. We apply Sobolev's (1963) "approximate method," by which the first order scattering is correctly accounted for, while the higher orders are only approximated; the albedo ρ is found.

This calculation takes into account the repeated reflections and refractions at the front side and at the back side of the grains according to Fresnel's formulas, but disregards diffraction.

Our model would be very imperfect, unless we take into consideration the surface irregularities of the powder, of which the surface elements have random inclinations. We have therefore to repeat the calculations of the albedo for different values of $\eta = \zeta$ and to average the results with the proper weight, thus deriving

$$\bar{\rho}(\lambda) = 3 \int_0^1 \rho(\eta,\lambda)\eta^2 d\eta,$$

which we call the *mean albedo*. The random distribution of the surface elements here assumed applies as well (on a microscopic scale) to the center as to the limb of the Moon, and is in agreement with the uniform brightness of the full moon.

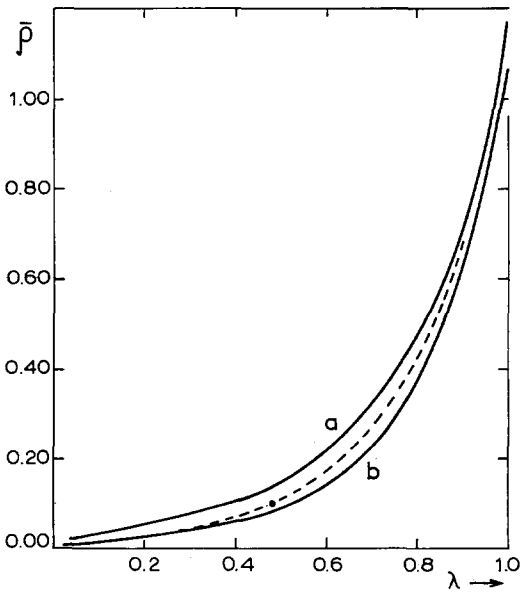

FIG. 2. Albedo $\bar{\rho}$, calculated for irregular layers of material, illuminated and observed in normal direction, as a function of $\lambda = \sigma/(k + \sigma)$. (a) With the phase function for transparent grains; (b) for opaque grains; dotted: probable actual curve. The point $\bar{\rho} = 0.10$ corresponds to a mean lunar albedo.

The results are represented in Fig. 2, curve a.

The phase function which we have chosen does not apply if the grains become very opaque, because then the reflections at the front side will have a preponderant influence. Let us calculate the form of the phase function also for this extreme case, again after Wiener (Table II); we normalize, apply the formulas for $\bar{\rho}(\lambda,\eta)$ and derive again the mean albedo $\bar{\rho}(\lambda)$. The results are found in Fig. 2, curve b.

The two curves a and b correspond, respectively, to the case of transparent grains and to the case of opaque grains. The real curve would show the gradual transition between the first and the second function, corresponding with a decreasing parameter $\lambda = \sigma/(\sigma + k)$; its probable shape is represented by the dotted curve.[1]

[1] A simplified formula for the albedo of powders or clouds, used by C. Sagan and J. B. Pollack (*J. Geophys. Res.* **72**, 469, 1967), gives rather similar research. By our more detailed method we obtain the *normal* albedo.

Application to the Laboratory Measurements and to the Moon

The scattering coefficient is put equal to $\sigma = C + (1/D)$ where C represents the intrinsic scattering coefficient; for even a bulk fragment of rock ($D \to \infty$) does show a measurable albedo. Thus

$$\lambda = \frac{C + (1/D)}{C + (1/D) + k}.$$

We fit the constants to the measurements, condensed in Table I, and obtain a rough agreement for the values $C = 15$, $k = 33$. Apparently our rocks are among the very darkest known. With these values and a mean $\bar{\rho}(\lambda)$ curve, we calculate the albedos, mentioned in the last column of Table I.

The general trend of the observed curves is rather well reproduced. The slight initial decrease in albedo is not explained by our theory; it is perhaps due to the appreciable divergency of the incident beam. A really satisfactory fit could hardly be expected: transfer theory as applied here is still imperfect, especially for such elongated indicatrices. Moreover we have used the same phase function for the intrinsic scattering as for the surface scattering. A more precise treatment could certainly be given.

Nevertheless, when applying these results to the lunar surface, it seems possible to draw some general conclusions: As a reasonable mean value of the lunar albedo we take 0.10. From our mean, dotted curve we read that this implies a value of $\sigma/(\sigma + k)$ of about 0.47. We shall assume that the intrinsic scattering coefficient C has the same value for the lunar rocks as for the terrestrial rocks which we investigated. In that case

$$15 + \frac{1}{D} = 0.47(15 + \frac{1}{D} + k),$$

or

$$k = 17 + \frac{1.13}{D}.$$

For each value of the grain size D we are now able to quote the bulk absorption coefficient k which would result in a normal albedo of 0.10 (Table III).

TABLE III

COMBINATIONS OF GRAIN SIZE D AND ABSORPTION COEFFICIENT k PRODUCING AN ALBEDO OF 0.10

D (mm)	k (mm^{-1})
∞	17
1	18
0.1	28
0.05	40
0.02	73
0.01	130
0.005	241

It appears that for grains above 0.09 mm the required values of the absorption coefficient should be such as they normally occur among very dark terrestrial rocks ($k = 30$); the albedos of 0.07 or 0.15 would require grains of 0.16 versus 0.05 mm.[2] Grains of 0.02 mm are excluded, unless the effect of the solar wind has enhanced their absorption. It looks plausible that the churning of the surface layer by micrometeorites would distribute this extra-absorption through the upper dust layer, so that our formulas would remain applicable. Several authors estimated that the grain size should be in the range of 0–10 μ; a value of 5 μ would require an absorption coefficient of 250.

It will be clear that we have in no way demonstrated that the Moon is covered by dust. We have only shown that it cannot be covered by fine-grained dust unless the bulk absorption coefficient is very high, so high that darkening by the solar wind has to be assumed. A more definite conclusion can only be reached by studying the polarimetric and other properties.

Apparently the solar wind and the pulverization act in opposite senses in modifying the albedo in the course of the millions of years. But they also interact: fine grains will be darkened more quickly than coarse grains. And the micrometeorites which churn up the surface layer will not only contribute to its pulverization, but they will also mix the surface material with the material below.

Various combinations of such effects have been suggested, by which it might be possible to understand the albedo differences between the continents, the maria, the crater rays, and the material ejected by the footpad of Surveyor 3, even if no differences in chemical constitution between these formations were assumed (Hapke, 1966; Shoemaker, 1966; Adams, 1967; Adams and Filice, 1967; Levin and Radlova, 1967). In this frame of mind, a very simple explanation would be the following: Assume that for moderately long periods the effect of the solar wind is the most important; the young ejecta of the crater rays darken rather quickly and disappear. After much longer periods, however, the pulverization reaches the critical point at which the material brightens up; the maria have not yet reached that stage, but the continentes, which are older, have.

There are, however, sound arguments which make it probable that this mechanism is not the only effect which plays a role and that real differences in composition exist.

[2] From the measurements of Table I we could have estimated directly grain sizes of 0.07 and >0.10 versus 0.04 mm. Our theory, however, provides the possibility to predict the albedo to be expected for other values of the absorption coefficient.

ACKNOWLEDGEMENT

It is a pleasure to thank Mr. H. Nieuwenhuijzen for setting up the apparatus used in the albedo measurement and for useful technical advice. Professor W. Vieuwenkamp and Miss J. Wevers were so kind as to prepare the pulverized samples.

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