PHOTOMETRIC AND OTHER LABORATORY STUDIES RELATING

TO THE LUNAR SURFACE

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PHOTOMETRIC PROPERTIES OF COMPLEX SURFACES

The remarkable manner in which the moon scatters light provides an important clue to the nature of the lunar surface materials. At the suggestion of T. Gold, and assisted by H. VanHorn, the author has been engaged in a study of the reflecting properties of a large variety of surfaces. The principle aim of these measurements is to obtain a qualitative understanding of the factors which govern the optical scattering characteristics of complex surfaces, and especially to understand the reason for the peculiar manner in which the moon reflects light. Such an understanding will greatly narrow the types of materials which may be thought of as composing the lunar surface.

The surface of the moon is characterized by several properties (1,2,3)[*] (see Figures 1 and 2): 1. The albedo is uniformly low, varying from about .05 to .18. 2. The surface strongly backscatters light, so that the intensity of sunlight reflected toward the earth from nearly all areas on the moon reaches a sharp maximum at full moon. 3. The polarization of sunlight reflected by the surface also exhibits an unusual behavior: the polarization is zero at full moon, but becomes negative for small phase angles, reaching a minimum of 1.2% at a phase angle of 11°; at about 23° the plane of polarization suddenly rotates, going through zero and becoming positive, and reaching a

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[*] Numbers in parentheses refer to similarly numbered references at the end of this paper.

broad maximum near 110° phase. (By convention, the polarization is positive if the plane of polarization is perpendicular to the plane containing the direction of illumination and the normal to the surface.) The maximum polarization is uniformly small, seldom exceeding 15%. Brighter formations on the moon generally polarize the light less strongly. 4. The manner in which both the polarization and brightness of a region vary during a lunation is almost exclusively a function of the lunar phase angle (i.e., of the angle between the source of illumination and the observor) and is very nearly independent of location on the *lunar* sphere or of the type of terrain. 5. The moon is essentially colorless, and reflection from its surface only slightly affects the spectrum of sunlight. Except for albedo there is little difference in appearance or color between the various types of terrain (Figure 3). Looked at close-up the lunar surface materials would appear grayish-brown.

These photometric properties are so grossly different from those of most of the common terrestrial materials *(Figures 4,5)* that it long ago became clear that the uppermost portions of the lunar surface could not be solid rock. In particular, the independence of the lunar reflection law on orientation of the surface implies a surface which is so rough on a scale large compared with a wavelength of visible light that the microrelief has little dependence on the local directions of vertical or horizontal. However, the fact

that the moon appears smooth to radar (4) indicates that the scale of this roughness is smaller than about 1 centimeter.

Previous investigations by other workers (summarized by Fessenkov (1)) of naturally-occurring materials, such as rocks, sands, lavas, volcanic ashes, and meteorites, showed that none of these substances possessed the correct reflecting properties. This result was not entirely surprising since the lunar surface has been exposed to a far different sort of "weathering" than terrestrial rocks. Bombardment by micrometeorites and solar radiation might be expected to alter the optical properties of minerals appreciably.

In view of the foregoing, the author decided to investigate the reflecting characteristics of a wide variety of surfaces in order to determine the properties which are essential for lunar-type scattering. Knowledge of these properties then forms the basis for deciding whether or not a given material is liable to be present in significant amounts on the moon.

The results of the measurements on the intensity of light reflected from various surfaces have been reported in detail (5), and may be summarized as follows. In order to backscatter light as strongly as the moon does, a material must not only have an extremely porous and open structure but the cavities in the surface must also be

<u>interconnected</u>. Materials whose backscatter peaks are as narrow as the moon's have fractional void volumes of the order of 90%. The scattering objects which comprise a lunar-like surface must be so dark as to absorb at least 75% of the light incident on them, and must be opaque, with rough microsurfaces.

Light can penetrate into such a surface freely from any direction and will partially illuminate objects under the surface. Light rays which are reflected directly back toward the source from the deeper objects can escape unattenuated along the path of incident radiation, but rays reflected from the deep objects into any other direction are partially blocked and absorbed. In this manner the brightness of the surface is greatly enhanced when viewed parallel to the direction of illumination. The reflecting objects cannot be translucent nor transparent nor have smooth, specularly-reflecting microsurfaces, or else the backscatter peak will be wider than the moon's. If the objects do not absorb light strongly, that is, if the albedo of the surface is too high, multiply-reflected rays will wash out the backscatter peak and the reflection law will tend toward that of a Lambert surface.

It has been found possible to treat the reflection process from a lunar-type surface mathematically. The author has derived theoretically an expression which accurately predicts the photometric behavior of the moon (6).

The single exception to the requirement for inter-connected cavities is provided by a surface consisting of large, dark, scoriaceous rock fragments jumbled together in a jagged pile so that the pits in the rock are pointed in random directions. Such a surface has a backscatter peak which is nearly as narrow as the moon's. However, such a material polarizes light far too strongly and thus must be rejected as being present on the lunar surface.

The results of polarimetric studies of various surfaces may be summarized as follows.[*] The maximum amount of polarization P_{max} of light reflected from a surface is inversely related to the albedo of the surface. This arises because light which is directly reflected from the surface of a substance tends to be positively polarized; but light which penetrates the surface of a translucent substance and is refracted and scattered from the interior tends to be negatively polarized, and this reduces the net positive polarization. As the opacity of a material is increased, the fraction of light which penetrates is reduced, the albedo is decreased, and P_{max} is increased. The moon is unusual in having a small P_{max} combined with a low albedo (Figure 6).

One way of obtaining a substance with polarization properties similar to the moon's is to mix a light, trans-lucent material having a low P_{max} with a dark, opaque one

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[*] The data reported in this portion of the paper are in part taken from the work of Lyot and Dollfus (2) and in part from unpublished work by the author.

of high P_{max}. Most volacanic ashes and pulverized
scoriaceous rocks consist of such a mixture, and it was
discovered by Lyot that certain volcanic ashes will
duplicate the lunar polarization curve (Figure 7).
However, due to the translucent particles the backscatter
peak of such powders is much wider than the moon's
(Figure 5b).

It is thus necessary to reduce P_{max} while constructing
the surface out of entirely opaque substances. The
intrinsically high P_{max} of a dark material can be
drastically decreased in three ways: .. by roughening
the microsurfaces, . by decreasing the particle size,
and by reducing the compaction of the surface.
Figure 8 shows this dependence of P_{max} on average
particle size and compaction for SiC abrasive powders.
The polarization decreases from almost 60% for particles
greater than about 50μ in diameter to about 15% for
particles with diameters smaller than 10μ. This
behavior is due to the increased effect of diffraction
around the edges of the particles as the size is
decreased. Reducing the compaction of the surface allows
more vertical surfaces to take part in the reflection
process; it is possible to lower P_{max} by a factor of
two in this manner.

Most rough surfaces display the general features of
the lunar polarization curve in that light reflected from

them is weakly negatively polarized when the source and detector are nearly aligned and is positively polarized for larger angular separations. However, the phase angle at which the plane of polarization rotates depends on the chemical composition of the material. Rough metallic surfaces, such as filings, lathe turnings, and whiskers invariably rotate polarization at phase angles of 40° or greater. Dielectric substances rotate the plane of polarization at phase angles of $15^{\circ} - 30^{\circ}$. It may be concluded that large quantities of free metal cannot be present on the lunar surface.

Thus, in order to match the lunar polarization law a surface must consist of extremely small, rough, opaque objects, arranged into a complex surface of low compaction.

CONCLUSIONS REGARDING THE NATURE OF THE LUNAR SURFACE MATERIALS

From the preceding discussion a number of important conclusions regarding the nature of the uppermost layers of the lunar surface can be drawn.

Since the sharp backscatter characteristics require interconnected cavities, the lunar surface cannot consist of solid rocks, even ones covered with pits and cracks, nor coarsely-pulverized rocks, nor pumaceous and scoriaceous rocks foams and slags. While volcanic foams

have low densities, their pores are separate so that
their surfaces consist of unconnected pits and do not
have the correct structure to backscatter light strongly.
Glassy spheroids and other transparent or translucent
objects can also be rejected as major constituents of
the lunar surface.

A number of materials are known to be able to form
the complex, dendritic structures of the sort required
for strong backscatter; among them are vegetation
(Figure 9), metallic and non-metallic whiskers, and dark,
finely-divided powders (Figure 10). Most of these substances can be
readily rejected as being present on the moon. Vegeta-
tion is unlikely. Large numbers of metallic whiskers
would cause the plane of polarization of moonlight to
rotate at a much larger phase angle. Dielectric whiskers
could conceivably be formed by the combined effects of
sputtering by the solar wind and condensation of material
vaporized by micrometeorites. Not enough is known con-
cerning accommodation coefficients and atomic surface
diffusion phenomena to state definitely whether or not
non-metallic whiskers could be present on the moon.
However, it seems unlikely that they would survive long
under micrometeorite bombardment. This last objections
also applies to the recent suggestion by Warren (private
communication) that the moon is covered with rock foam
or impactite glass which has been skeletonized by the

sputtering action of the solar wind.

Thus it must be concluded that the lunar surface is covered with a layer of pulverized rock powder. In order to lend credibility to this assertion it is necessary to describe some of the properties of finely-divided dielectrics.

Acting between any two surfaces in contact are adhesive forces which are generally of the Van der Waals type. Usually these surface-adhesive forces are so small in comparison with the other forces, such as electrical or gravitational, involved in a particular process that they do not materially affect the process. Thus if a coarsely-pulverized substance is stirred or poured the particles bounce and roll to the bottom of depressions to form a compact medium resembling a pile of gravel and which has a bulk density about one-half that of the solid material. However, this behavior is radically altered if the same material is finely-ground to such a small average particle size that these adhesive forces are stronger than the weight of the particles. If such particles are disturbed or deposited in such a way as to insure that they fall individually and impact the surface at a low velocity then a falling particle will adhere to the first object it strikes and will not roll into vacant depressions. In this manner an extremely underdense medium can be built up. Such dust clings tenaciously to any surface, even one held vertically.

When such a material is viewed under a stereo microscope, one sees fantastically complicated structures consisting of porous, open hills, out of which grow towers and branches, and interconnected with lacy bridges. These "fairy-castle" structures are in the category of structures which can sharply backscatter light. The photometric properties of finely-divided and sifted AgCl powder which has been darkened by exposure to ultra-violet light are shown in Figure 10.

In the terrestrial laboratory the upper size limit for formation of the fairy-castle structures appears to be about 15μ, but because of the reduced gravity and extreme cleanliness which obtains on the lunar surface, this critical diameter might be as much as 50μ on the moon.

Thus finely-divided rock dust in an extremely loose state of compaction meets every requirement for reproducing the lunar photometric laws, except that terrestrial rock powders are not sufficiently dark. It is hard to make rock particles as small as 10μ opaque; but the treatment that the exposed lunar surface has received is very different from that of terrestrial rocks. Quite probably the hydrogen ion bombardment of the solar wind is able to darken the rock powders sufficiently. Both Wehner (7) and the author (8) have bombarded insulators with ions of a few kilovolt energies and have succeeded in darkening insulating substances. This darkening is believed to be

due to the reduction of metal oxides to free metal by
the ions. However, more experimental work is necessary
before this matter can be regarded as settled. In
particular, coating the lunar particles with free metal
would cause the plane of polarization to rotate at
larger phase angles than is actually observed; so that
other darkening processes may be required to account for
the lunar photometric laws. At any rate, there is ample
evidence that a darkening agent is at work on the lunar
surface (9).

Various reasons may be thought of to explain why
rock dust would naturally form into such a loosely-
compacted state on the moon. If the electrostatic trans-
port mechanism proposed by Gold (10) is correct, rock dust
would be formed by these effects into   an underdense
medium. A more likely explanation (due to T. Gold,
private communication) is the action of micrometeoritic
bombardment. When a meteorite impacts a rocky material
much of the collision energy goes into pulverization of
the rock. Thus the action of meteoritic bombardment of
the primordial lunar surface material will be to produce
a layer of fine dust at least a few centimeters thick.
When a micrometeorite hits this layer of dust a few
particles will be thrown a large distance by the
disturbance, but vastly more particles will be moved
only short distances of the order of a few particle-

diameters. Thus the dust will be built into fairy-castle structures over geologic times.

In summary, it is concluded that the lunar surface is covered to an unknown depth by a layer of rock dust whose particles have an average size of the order of 10μ. The grains of rock have been darkended by exposure to solar radiation or some other agent and arranged by micrometeorite bombardment into a porous material with a bulk density only one-tenth that of solid rock.

DEPTH OF THE DUST LAYER

The photometric properties of the moon can furnish information concerning only the top millimeter of the lunar surface. However, recent analyses of the thermal component of the lunar radiation (11, 12) indicate that large areas of the moon are covered to depths of many meters by a substance which is ten times as underdense as rock. It is very reasonable to suspect that the underlying materials might be identical with those exposed at the surface.

If the subsurface layers are indeed dust, as Gold (10) has suggested, then the fairy-castle structures at depth must be capable of resisting the compaction due to the weight of overlying layers. In order to determine whether these structures have sufficient strength the following measurement was made. A sample of dunite (a

rock rich in olivine) was ground to an average particle size less than 10μ and baked in an argon atmosphere at $750^{\circ}C$ for 17 hours in order to remove all superficial layers of grease and water. The sample was cooled and then sifted into a cup, where it was compacted and the change in its density measured as a function of normal loading. At all times the sample remained in argon. This data was then integrated numerically, assuming hydrostatic equilibrium and lunar gravity, to give the density profile of a hypothetical lunar soil with the compaction properties of the dunite. This density profile is shown by the solid line in Figure 11.

A second sample of baked dunite was also sifted and placed in an atmosphere saturated with H_2O vapor for 21 hours. Its compressibility was then measured. The corresponding lunar density profile is shown by the dotted curve of Figure 11. The water vapor evidently caused a cementing action to occur which increased the bond strength between particles and thus increased the compaction resistance of the fairy-castles. On the moon the integrain bonds might be strengthened by cold vacuum-sintering or by the chemical action of water vapor outgassing from the lunar interior.

This data clearly shows that finely-divided powders are capable of maintaining themselves in an underdense

state to considerable depths on the moon. Thus, if the radio-thermal analyses are correct, the possibility of large areas of the lunar surface being covered with thick deposits of dust must be given serious consideration.

ACKNOWLEDGEMENTS

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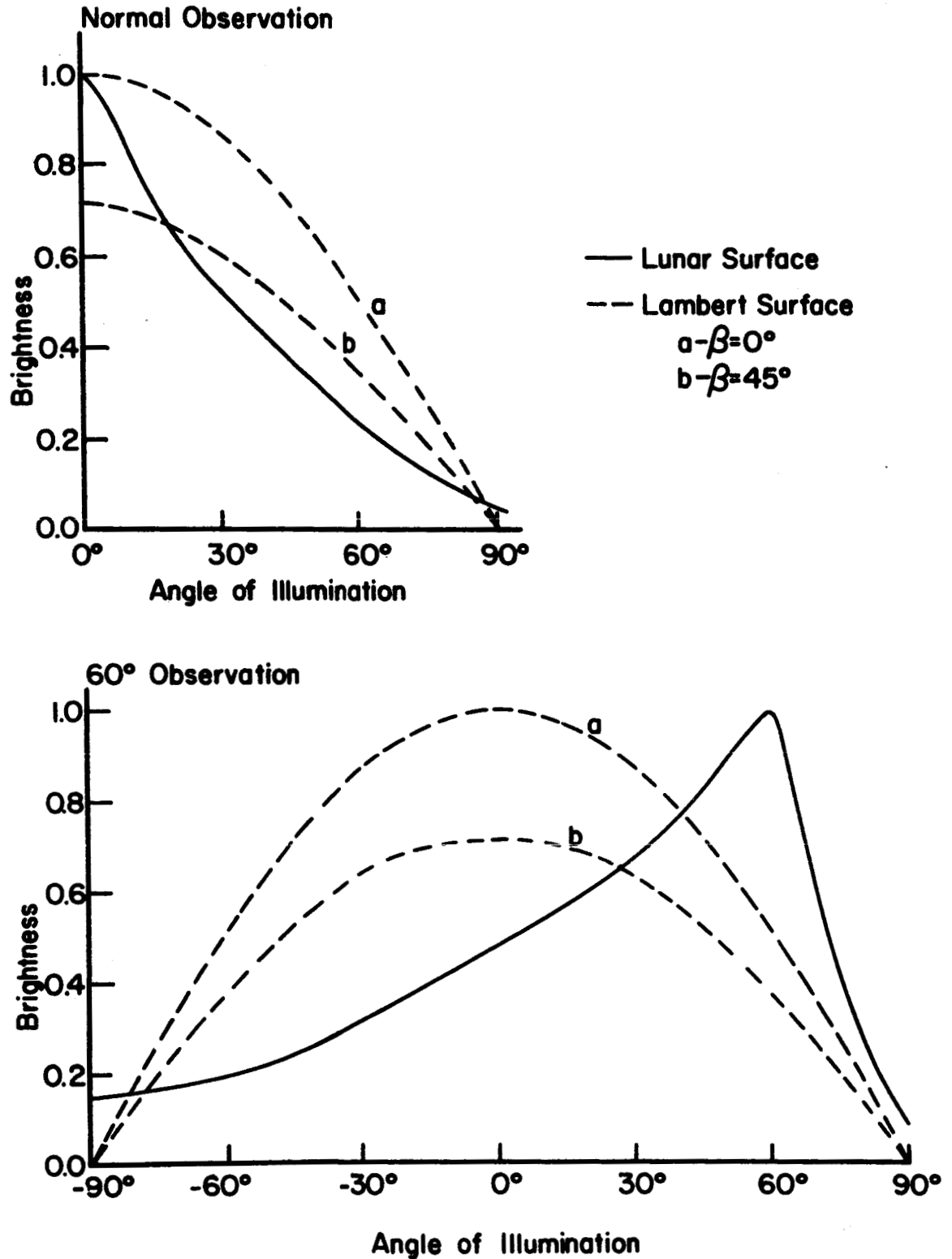
Figure 1.   Lunation curves for regions with selenographic
longitudes 0° and 60° (after Van Diggelen).   The
curves are very nearly independent of latitude.
If the lunar surface were a diffuse reflector,
lunation curves similar to the dashed lines
would be expected.
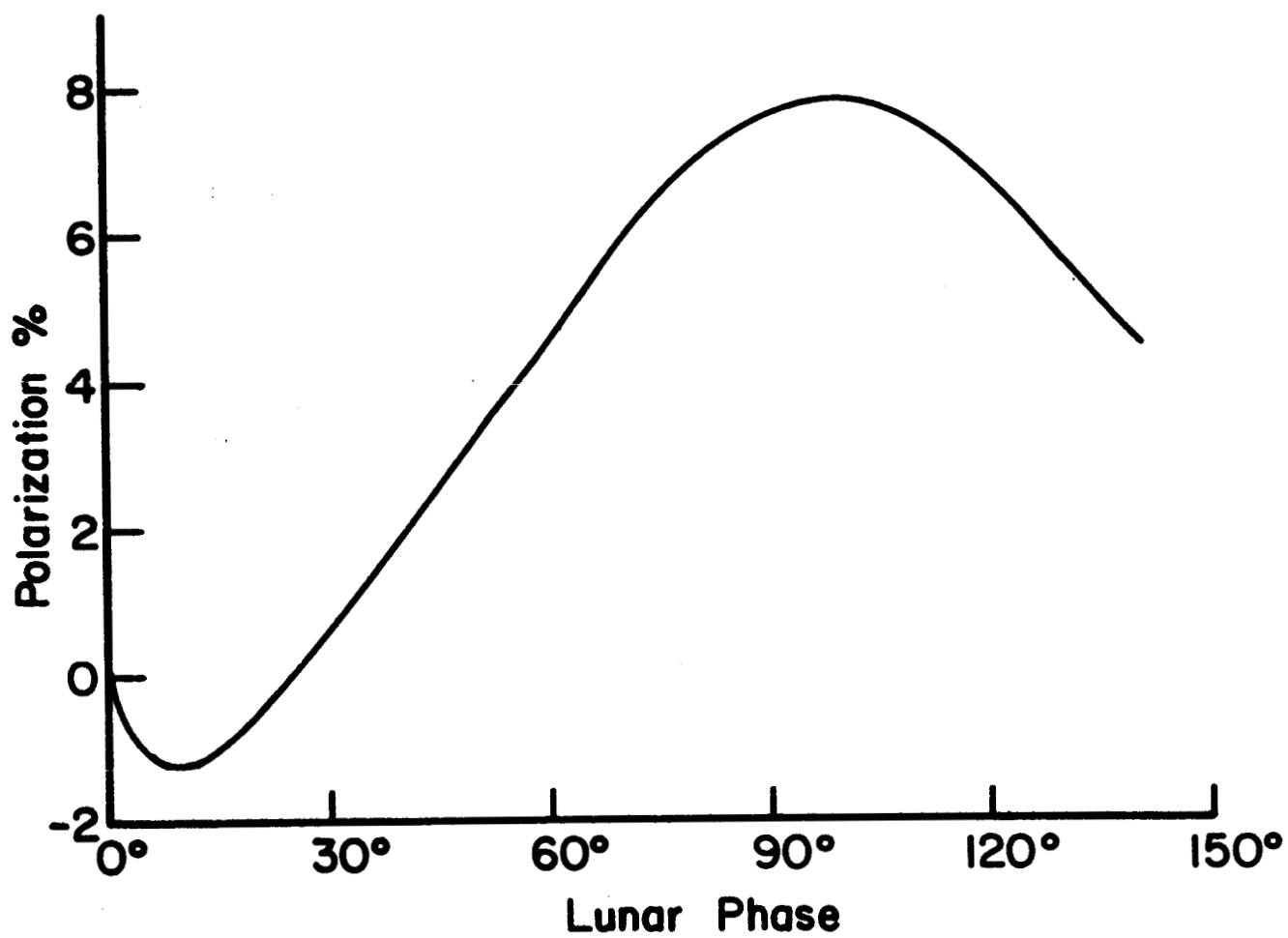
Figure 2.   Mean lunar polarization curve (after Lyot)
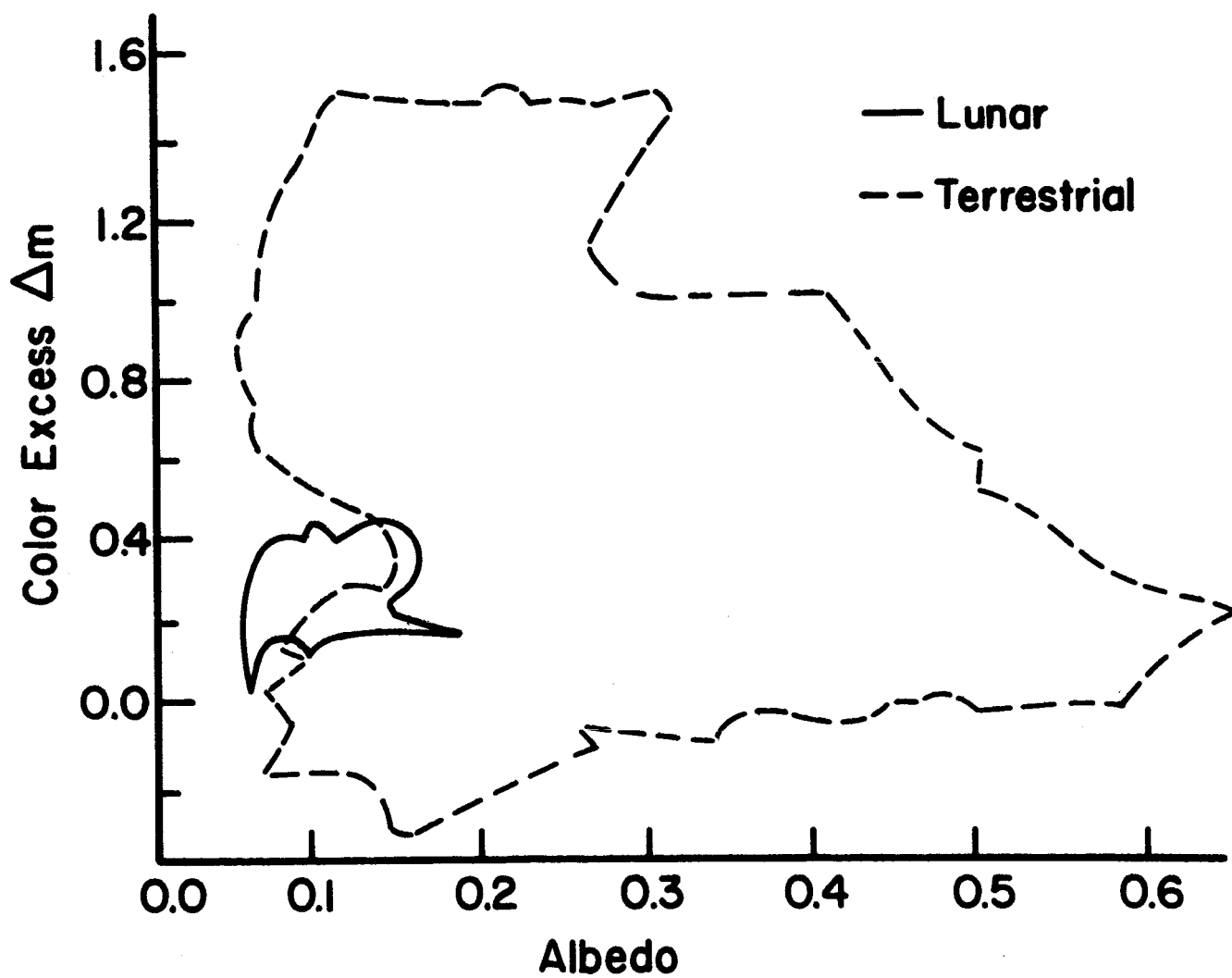
Figure 3. Color-brightness diagram for lunar and
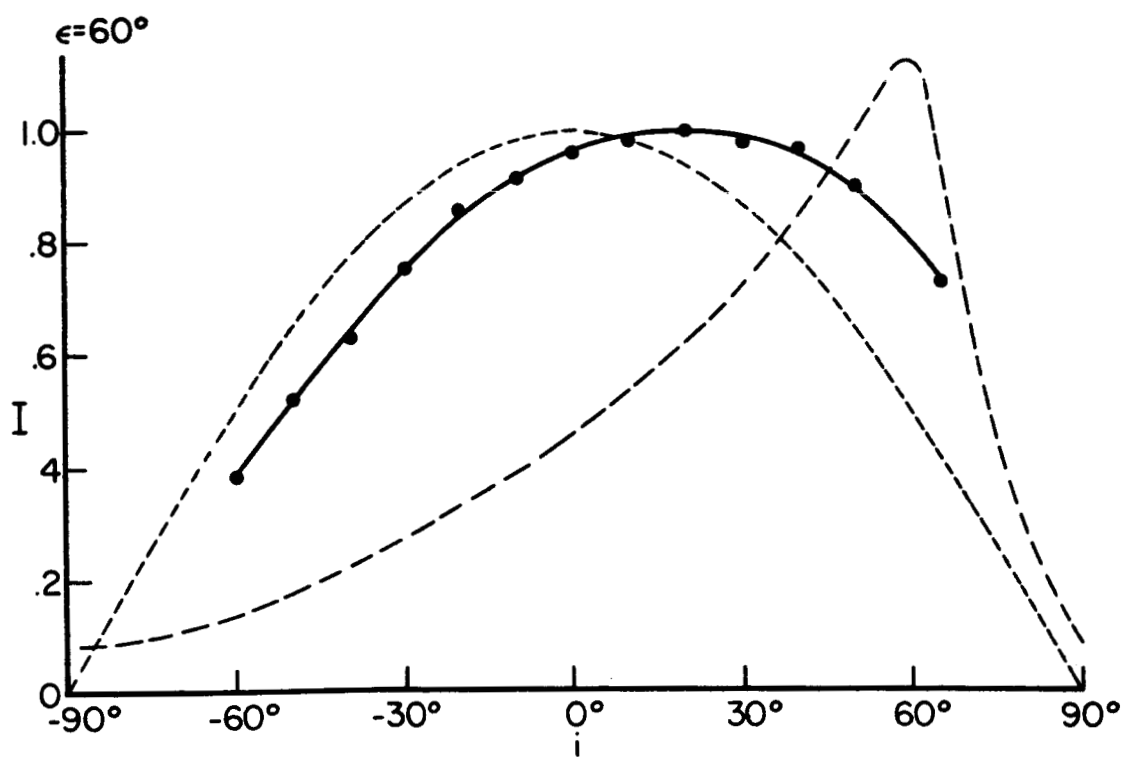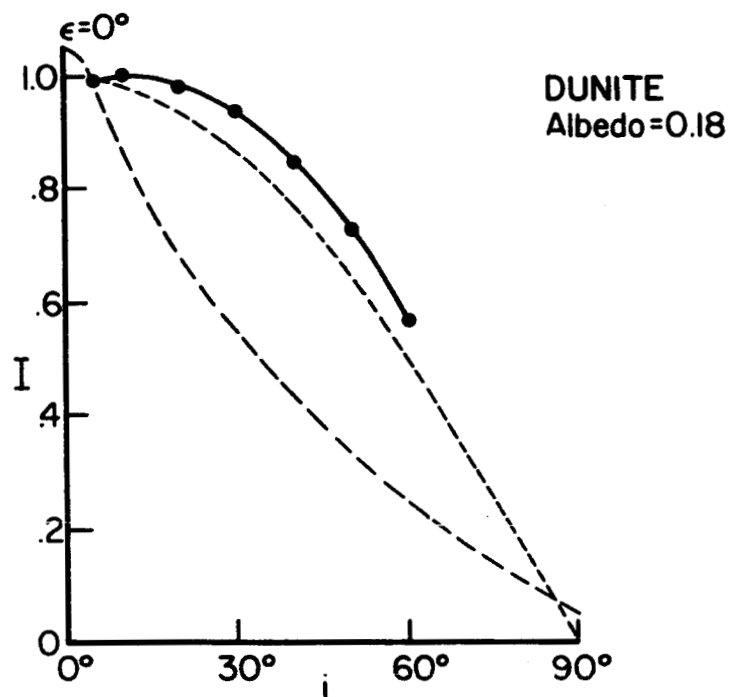terrestrial rocks (after Orlova)
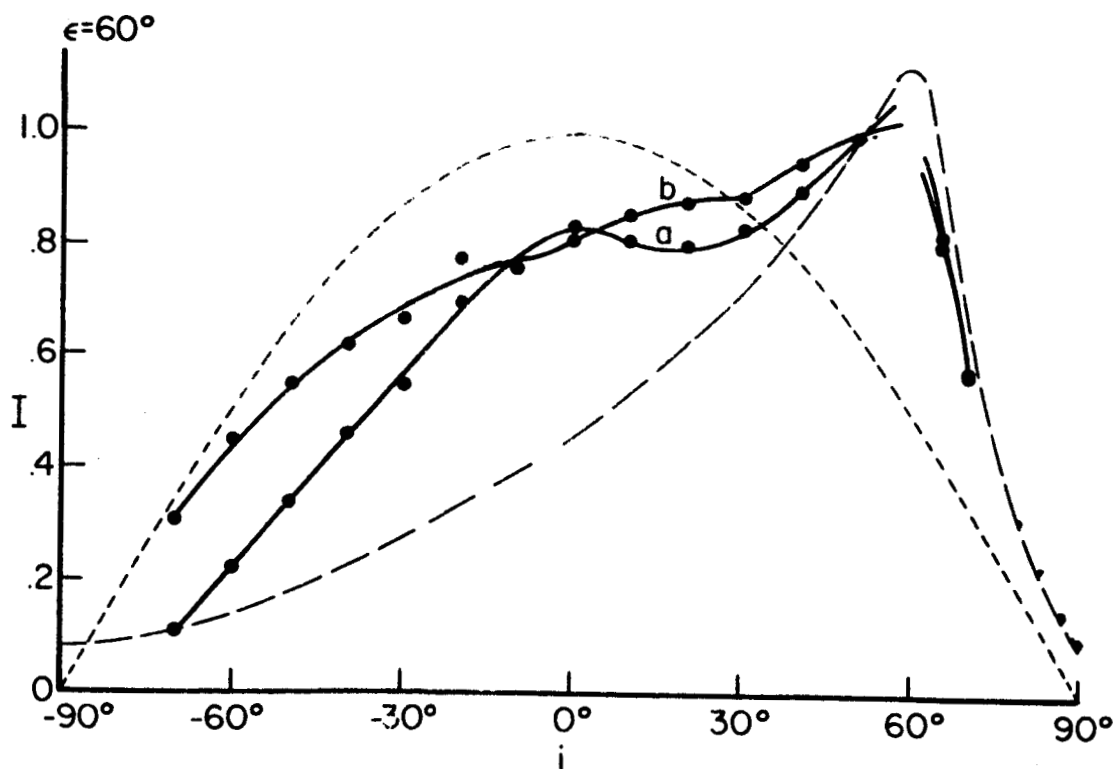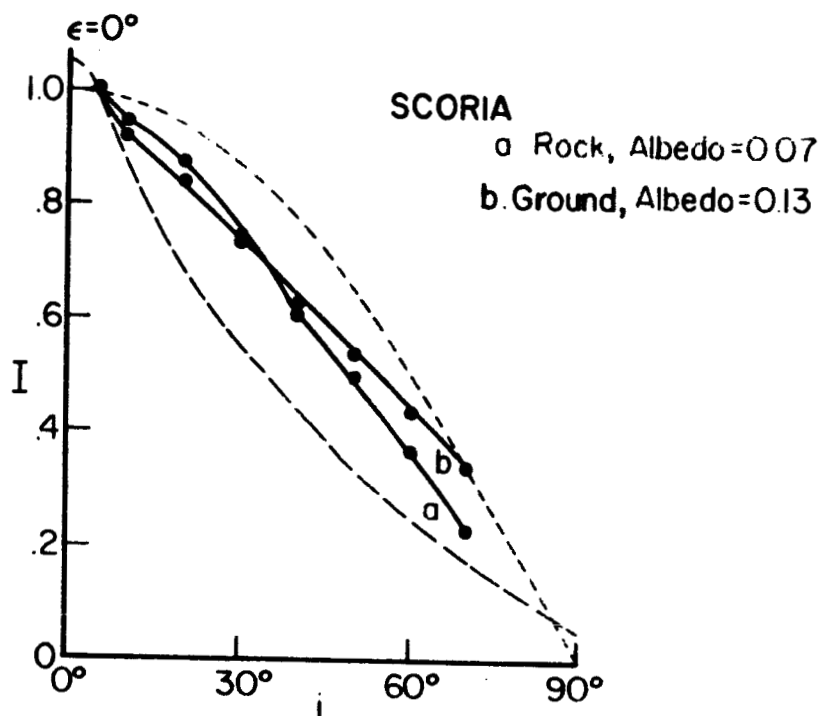
Figure 4.   Reflection curve for dunite rock

Figure 5. Reflection curves for solid and pulverized scoria
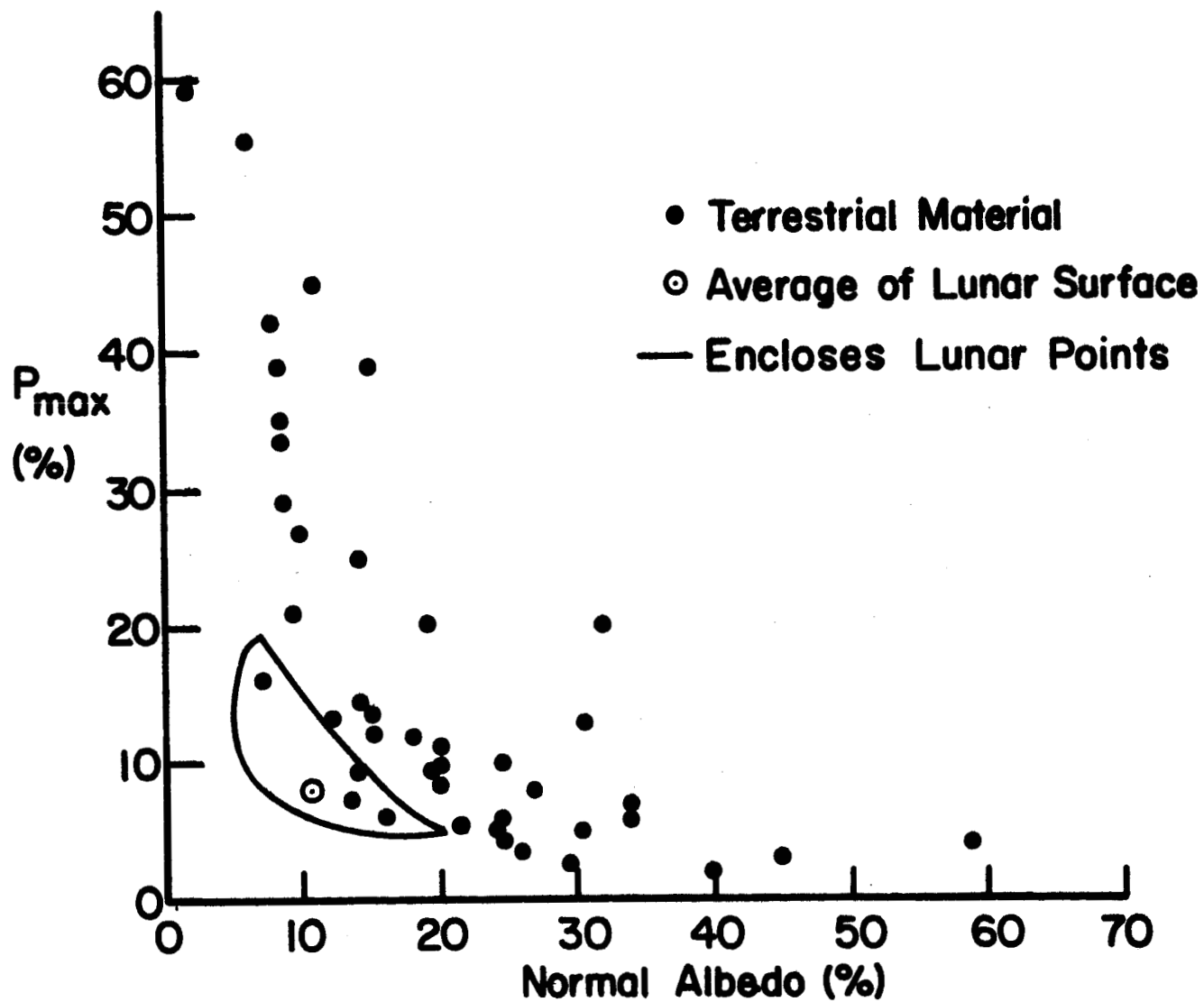
Figure 6. Polarization-brightness diagram for lunar
and terrestrial materials
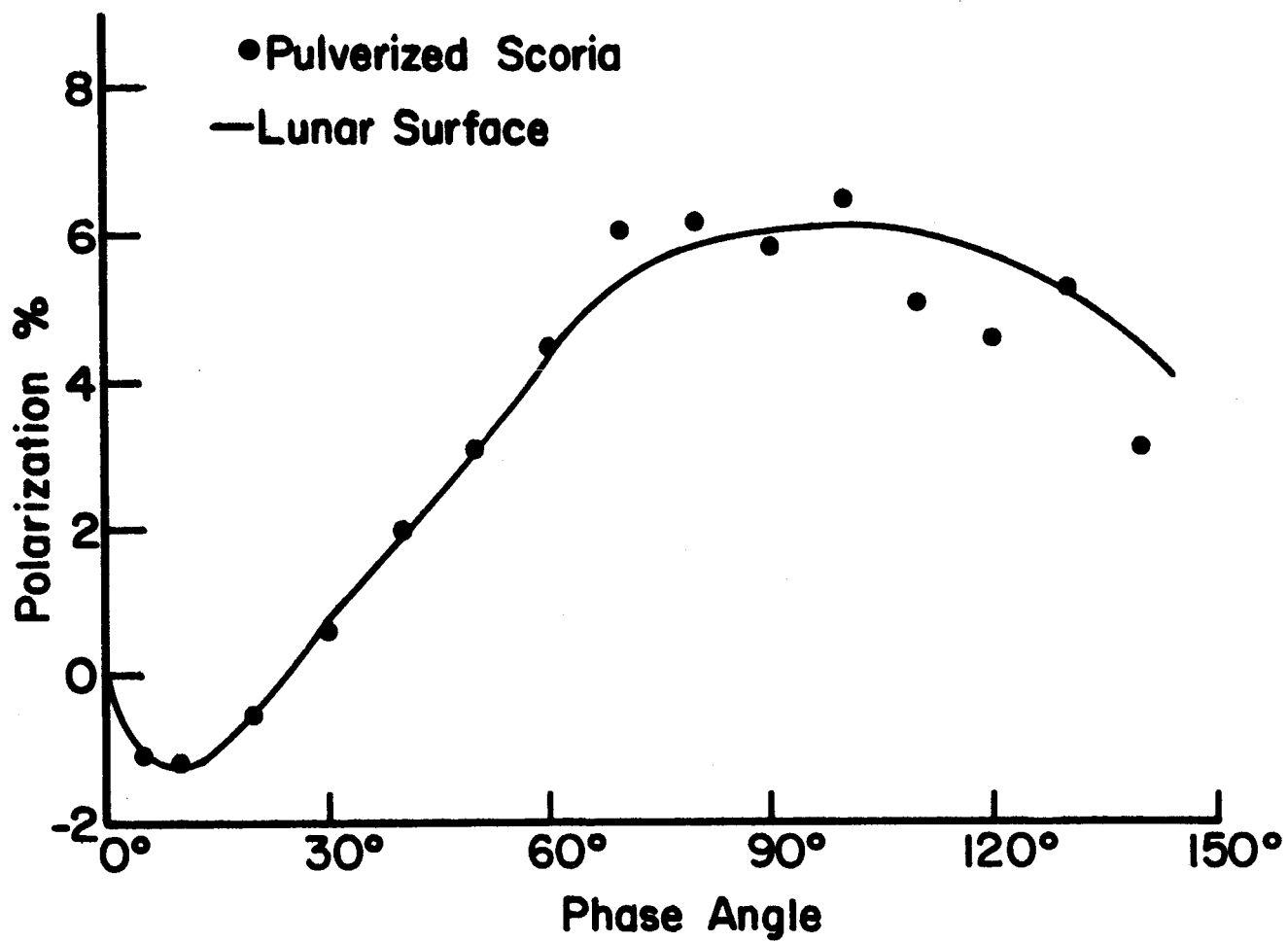
Figure 7. Polarization curve for pulverized scoria
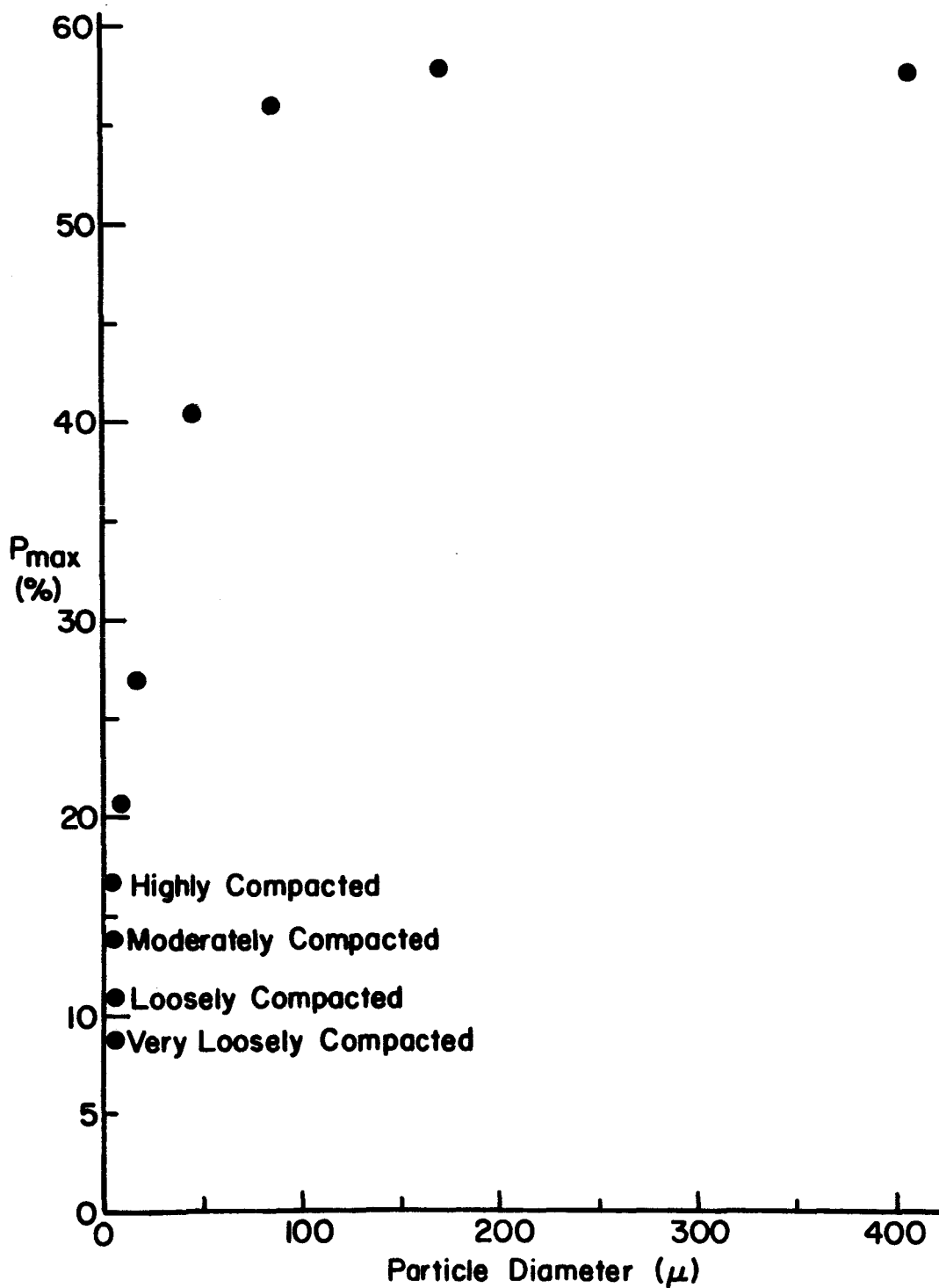
Figure 8. Variation of polarization with particle
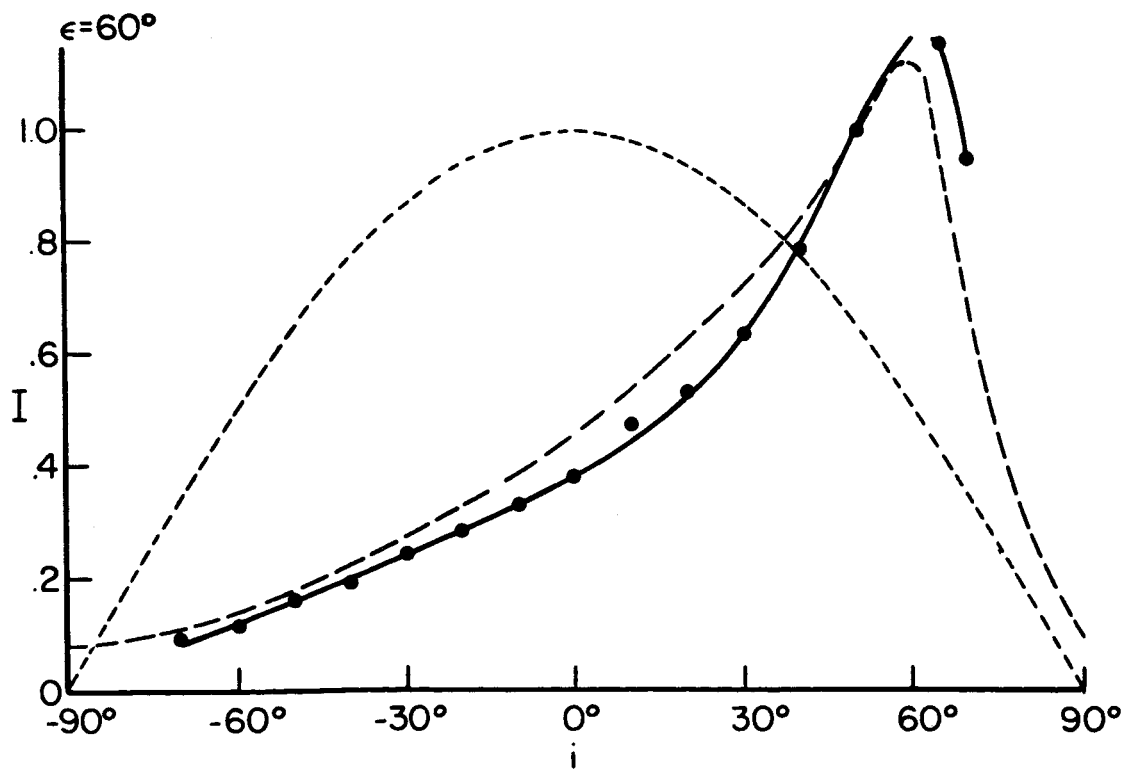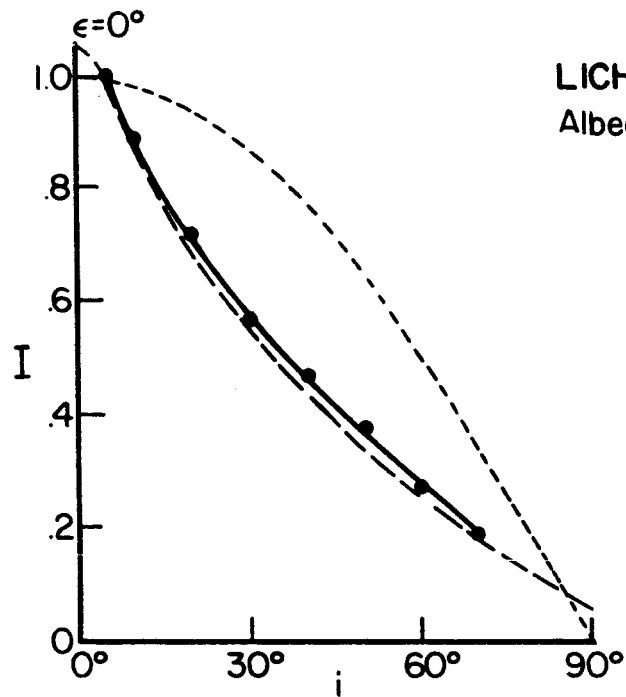size and compaction for SiC (Norton
Crystolon abrasive)
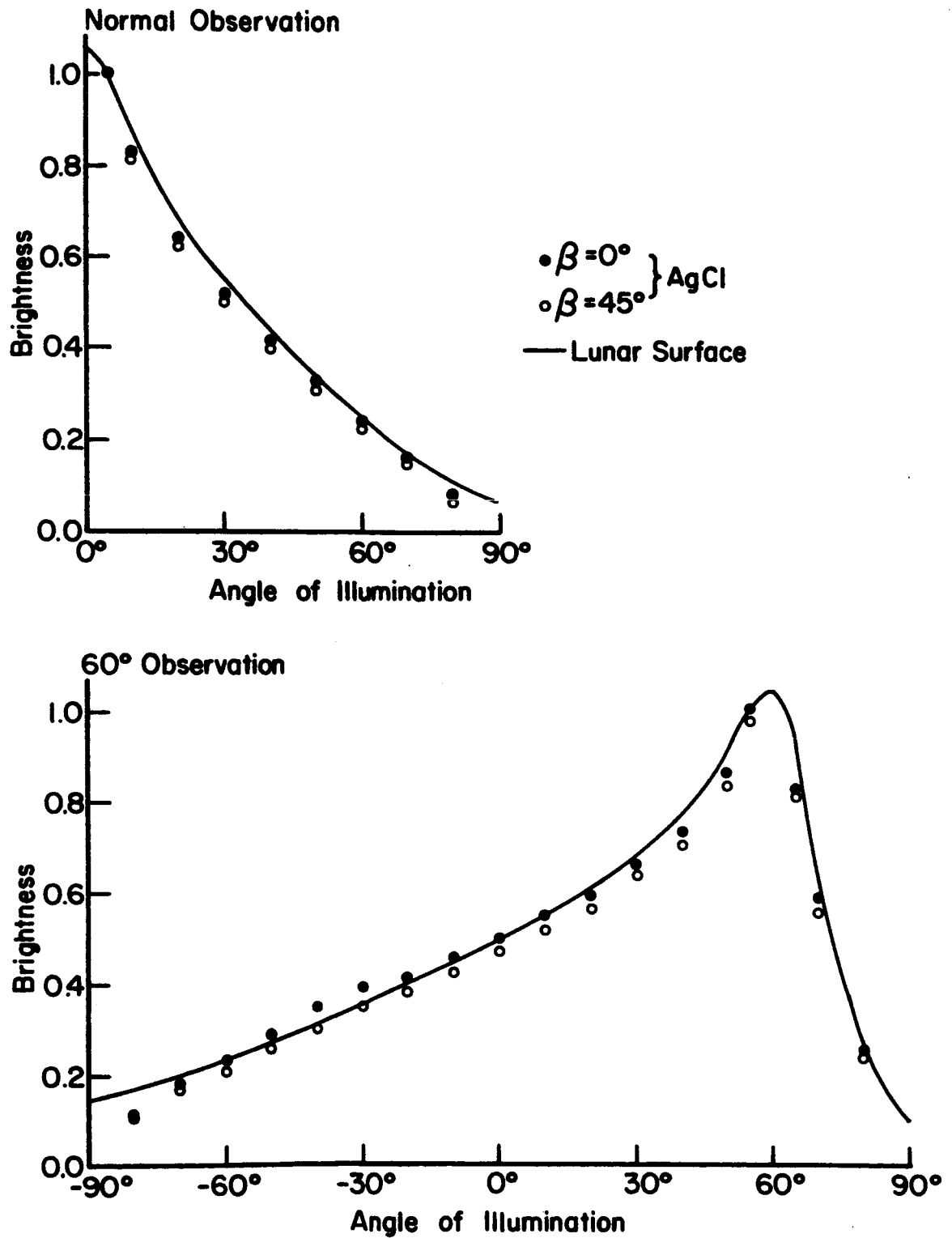
Figure 9. Reflection curve for lichen

Figure 10. Reflection curve for fairy-castle structures made of finely-divided, darkened AgCl. Like the moon, the curves are independent of selenographic latitude
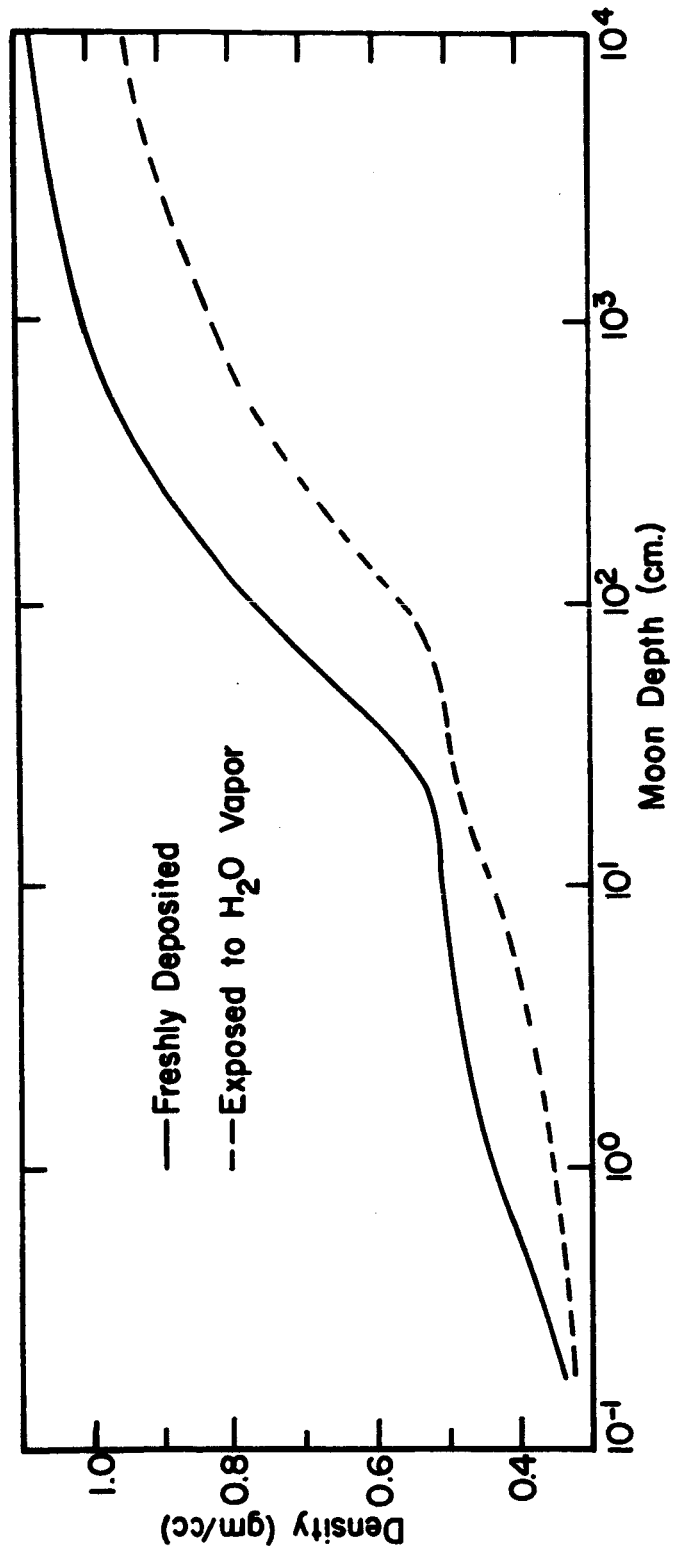
Figure 11. Density profile for hypothetical lunar
soil having the compaction properties
of dunite flour