Photometric Studies of Complex Surfaces, with Applications to the Moon

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Abstract. The reflection laws of a wide variety of surfaces have been measured. The factors that govern the optical scattering characteristics of complex surfaces are discussed, and the properties of surfaces that scatter light like the moon are specified. Surfaces of solid rocks, volcanic slags, or coarsely ground rock powders do not have the intricate structure necessary for backscattering light strongly, but finely pulverized dielectric particles can build extremely complex surfaces that can reproduce the lunar scattering law. It is concluded that the surface of the moon is covered with a layer of fine rock dust composed of particles of the order of 10-micron average diameter and that 90 per cent of the volume of the surface layer is voids.

INTRODUCTION

This paper reports the results of experiments in which the reflecting properties of complex surfaces were measured. The principal aim of these studies has been to obtain a qualitative understanding of the factors that govern the optical scattering characteristics of complex surfaces, and especially to understand the reason for the peculiar way in which the moon reflects light. Such an understanding will greatly restrict the types of materials that can be thought of as composing the lunar surface.

The surface of the moon is characterized by three distinctive photometric properties: the albedo is uniformly low, varying from 0.05 to 0.18; all areas on the moon reflect sunlight toward the earth in such a way that the intensity reaches a sharp maximum at or near full moon; the variation of brightness of a region is almost exclusively a function of the lunar phase angle (i.e., of the angle between the directions of illumination and of the observer) and is nearly independent of location on the lunar sphere or of the type of terrain. In contrast, most terrestrial surfaces scatter light more or less diffusively, in accordance with Lambert's law.

The second and third of the photometric properties were established by *Barabashev* [1922], *Markov* [1924], and *Öpik* [1924], and have been confirmed and extended by *Bennett* [1938], *Fedoretz* [1952], and *van Diggelen* [1959]. Fedoretz's measurements have provided the most extensive catalog of lunar photometric data now available. All these observations are reviewed by *Minnaert* [1961] and *Fessenkov* [1962].

Although the polarization of light reflected from the moon is not treated in this paper, it should be mentioned. The polarization has been studied by Lyot and Dollfus, and the measurements are reviewed by *Dollfus* [1962]. These workers found that the lunar surface polarizes the sunlight by only a small amount upon reflection, whereas most common terrestrial materials polarize light much more strongly. Small polarization is a characteristic of transparent materials and of objects whose size is not too much greater than a wavelength of light. Lyot, finding that volcanic ash reproduces the lunar polarization curve, concluded that the surface of the moon is covered with a layer of fine ash or dust.

Many hypotheses have been advanced to explain the unusual lunar optical scattering law. Although it is true that large backscatter could be produced by corner reflectors or transparent spheres of proper refractive index, such structures seem artificial and contrived when it is considered that they would have to cover the entire lunar surface, and in any event would not endure long under micrometeorite bombardment. The most reasonable explanation is that the peculiar photometric behavior can be attributed to the effects of shadows cast by an intricately structured material lying on the lunar surface. The structures into which this material is arranged must be large in comparison with a wavelength of visible light, since objects comparable with or smaller than a wavelength forward-scatter light markedly and a narrow backscatter peak would be impossible. An upper limit to the size of the structures can be inferred from radar reflection studies (summarized by *Evans* [1962]), which indicate that the moon is smooth on a scale of 10 to 100 cm. Thus it may be concluded that the surface of the moon is covered by an optically thick layer of extremely rough material with irregularities of size between 10 microns and 1 cm.

On the basis of measurements of the thermal radiation from the moon [*Petit and Nicholson,* 1930; *Wesselink,* 1948], most observers have concluded that the lunar surface is coated with dust; but it has been generally supposed that a dusty surface is not sufficiently rough to account for the optical properties and that structures of a larger size are required. It has been variously suggested that the surface is covered with cracks [*Barabashev,* 1922], rocks or domes [*Schönberg,* 1925], and cups or craters [*Bennett,* 1938; *van Diggelen,* 1959]. *Firsoff* [1959] holds to volcanic foam. *O'Keefe* [1957] suggests that the greater brilliance of the rays at full moon might be accounted for by glass beads similar to tektites. Gold (private communication, 1961) has maintained that under lunar conditions rock dust will build a surface sufficiently complex so that no other structures are needed.

Previous investigations of the photometric properties of surfaces have tended to concentrate on naturally occurring materials, such as rocks, sands, lavas, volcanic ashes, and meteorites [*Barabashev and Chekirda,* 1960; *Orlova,* 1952; *van Diggelen,* 1959]. None of these materials reproduced the lunar reflection law. This result is not entirely surprising, since the lunar surface has been exposed to a sort of weathering far different from what terrestrial rocks have been exposed to, as other investigators have been careful to point out. Bombardment by micrometeorites and solar corpuscular radiation might be expected to alter the optical properties of minerals appreciably.

In view of the foregoing, the present authors thought that an investigation restricted to rocks and minerals would prove unfruitful. Intsead, it was decided to measure the reflecting characteristics of a wide variety of materials in order to determine the surficial properties essential for lunar-type scattering.

The experiments revealed that the general features of the reflection law of a surface can be considered to be controlled by three parameters: the albedo, the optical scattering characteristics of the individual objects of which the surface is composed, and the type of structure in which the objects are arranged. Other factors, such as chemical composition, can be considered as affecting the scattering law indirectly through these parameters.

The manner in which the three parameters control the reflection law is discussed in detail in the body of this paper, and the photometric curves of a number of interesting surfaces are presented. An important finding of these experiments is that rock dust is capable of forming an extremely rough surface, confirming Gold's assumption. The general properties of a surface that can reflect light like the moon are specified, and the implications these experiments have for our knowledge of the nature of the lunar surface are discussed.

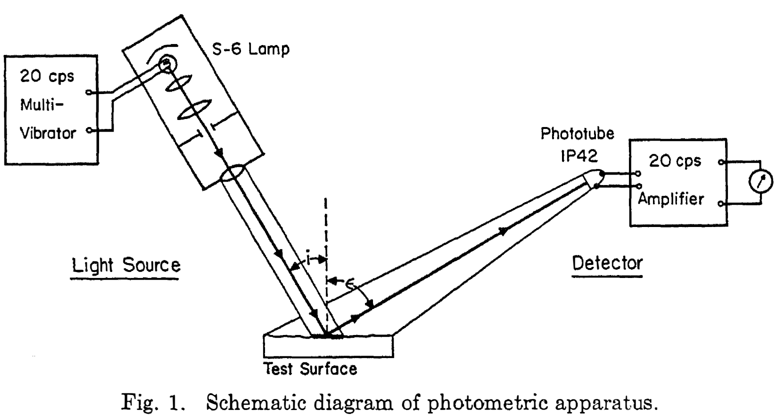

Fig. 1. Schematic diagram of photometric apparatus.

Optical Scattering from Complex Surfaces

The statements and conclusions in this section and in the following one have been arrived at from a study of more than 200 different surfaces, which have included the following: a variety of rocks and minerals, both in solid and powdered form; glass beads; metallic and nonmetallic whiskers; vegetation, such as grasses, lichens, and mosses; and artificial surfaces, such as wires suspended over a plate. In this section we will discuss qualitatively the effect certain properties of a surface have on the way in which the surface scatters light. The discussion will be primarily in the context of ray theory.

A plane surface separating a vacuum from a semi-infinite, uniform medium reflects light specularly, in accordance with the well-known Fresnel formulas. The reflection is due entirely to the change of electromagnetic constants at the interface. Slightly roughening the surface broadens the specular peak. This broadening is due both to the presence of minute areas oriented slightly differently from the main surface and to diffraction from the edges of the micro-

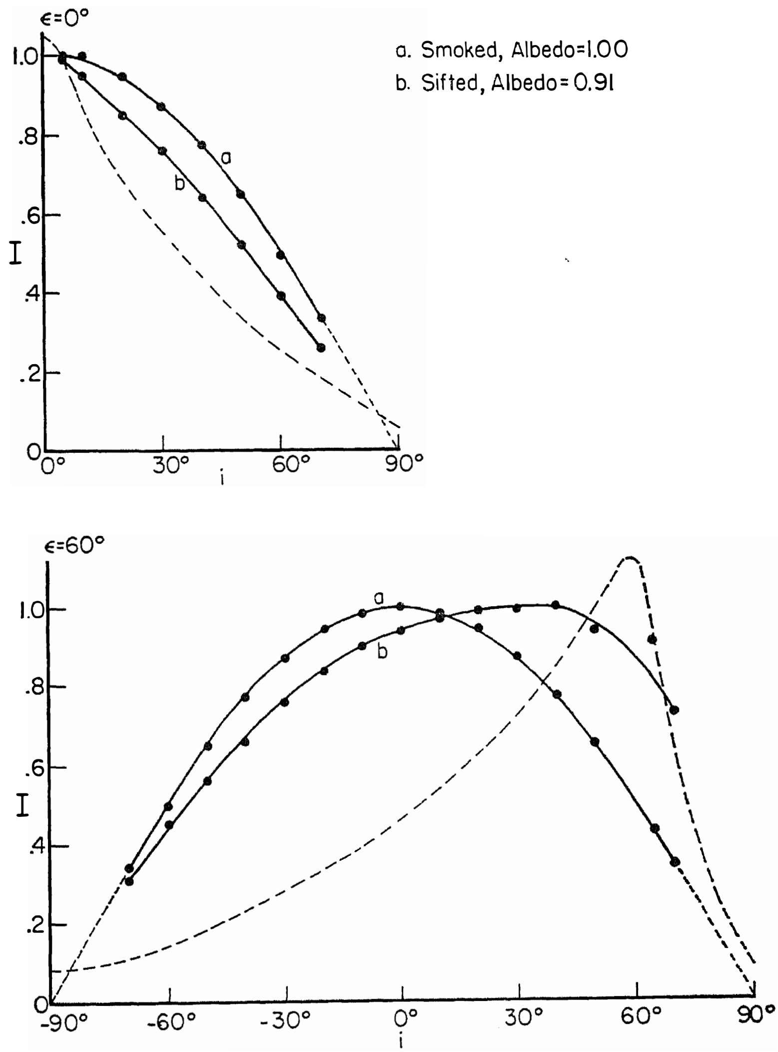

Fig. 2. Magnesium oxide.

surfaces. Increasing the intricacy of the surface beyond a mere roughening profoundly alters the reflection properties.

Consider a complex surface consisting of a large number of scattering objects, such as bits of rock, branches, or walls of cavities, of a size large in comparison with a wavelength, and arranged in some sort of intricate structure. The ensemble of scattering objects will be called the *macrostructure* of the surface; the average manner in which the individual surface elements scatter light will be referred to as the *microscattering properties* of the surface.

The most important characteristics of the surface for determining its reflecting properties are its albedo, its microscattering properties, and its macrostructure. We will discuss these characteristics and their effects. This discussion will then form the basis for deciding whether a given material is likely to be present in significant amounts on the moon.

When a bundle of rays of light encounters the surface of a scattering object, a portion is reflected and the remainder passes through the interface into the interior of the object. If the material is a metal or contains appreciable numbers of free electrons the refracted ray is completely absorbed. If the material is a dielectric

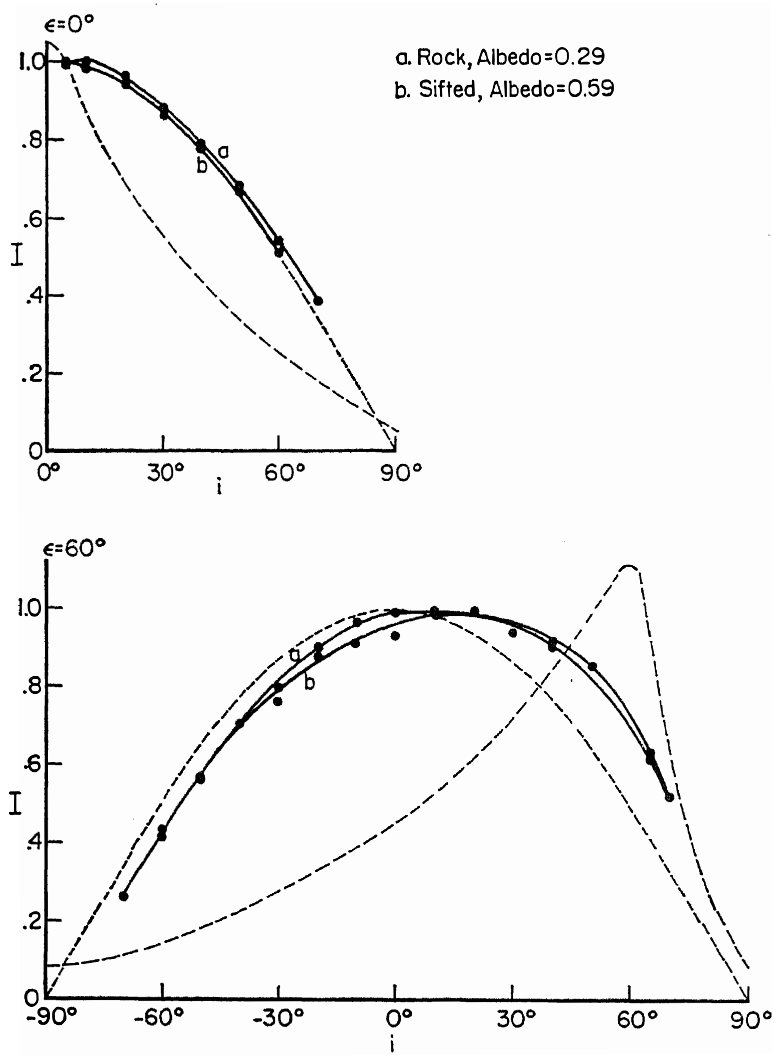

Fig. 3. Pumice.

the refracted ray may be scattered several times by imperfections, such as grain boundaries, within the object, but because most insulators do not have conduction and valence bands separated by optical frequencies, bulk absorption of the light will be small, although not zero. Since bulk absorption is proportional to the path length of a ray through an object, the amount of light absorbed will decrease with decreasing size of the object. It is evident that, if the scale of a complex surface made up of insulating objects is reduced while the geometry of the macrostructure is preserved, the surface will lighten.

The absorption that accompanies every reflection explains why the albedo of a surface is reduced when its macrostructure is roughened, for a typical ray of light must undergo more reflections to escape from a complex macrostructure. Since grinding up a substance into smaller particles generally produces a rougher macrostructure, the foregoing accounts for the well-known fact that metal powders tend to darken as they are more finely divided. Insulating powders, however, tend to lighten, because the darkening due to a rougher macrostructure is more than compensated by the decrease in bulk absorption as the grain size is reduced.

The macrostructure and microscattering prop-

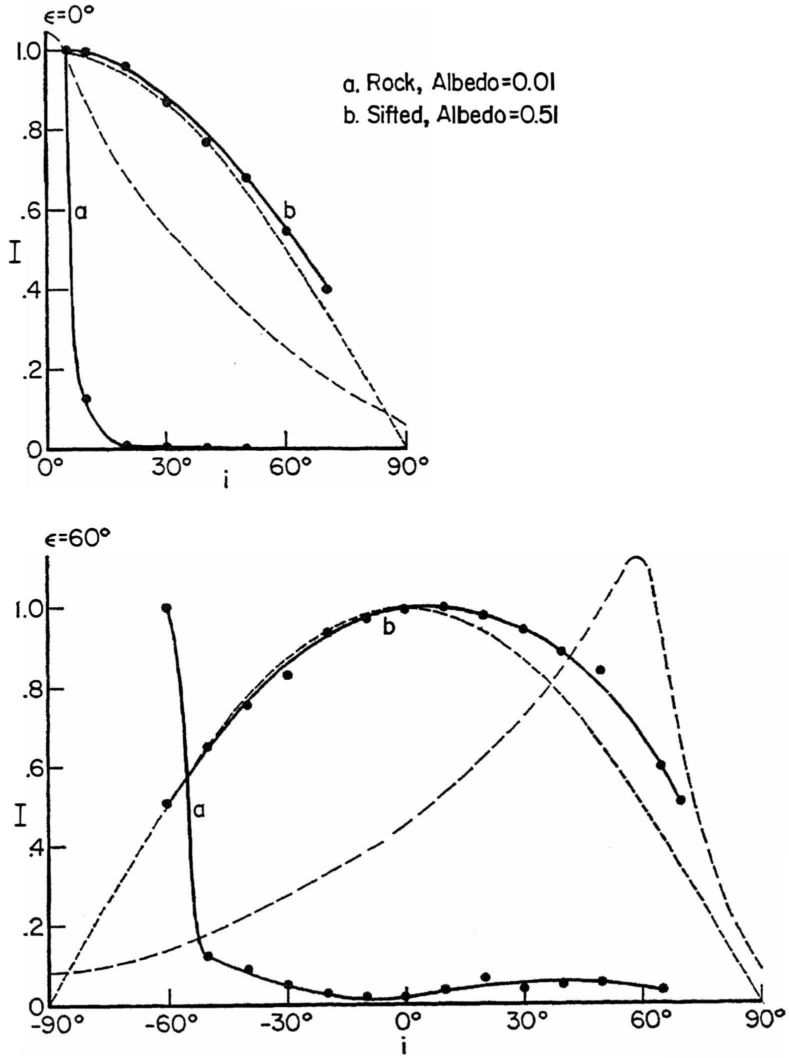

Fig. 4. Obsidian.

erties of a surface may each be divided into three broad classes. A macrostructure may be classified as *smooth*, *corrugated*, or *porous*. Typical of a smooth macrostructure is the surface of volcanic glass. The class of corrugated macrostructures includes the following: the rough surface of a fresh, unweathered rock; a surface perforated by cracks, pits, or craters; and the surface of a tightly compacted powder. Scoriaceous rocks and volcanic slags are extreme forms of this class. A porous macrostructure is one with many cavities, branches, and overhangs, but its distinguishing characteristic is that the voids in the surface are interconnected; the intricate structures formed by certain kinds of vegetation, like grasses, bushes, trees, and lichens, are good examples of porous macrostructures.

It is convenient to divide the microscattering properties into three general types: *forward-scatter, isotropic scatter,* and *backscatter.* Particles of size comparable with or less than a wavelength of light are in the first category; such particles forward-scatter because of diffraction. Transparent beads forward-scatter by refraction and focusing effects, and also to a lesser extent backscatter light by internal reflection. Approximately isotropic scattering is dis-

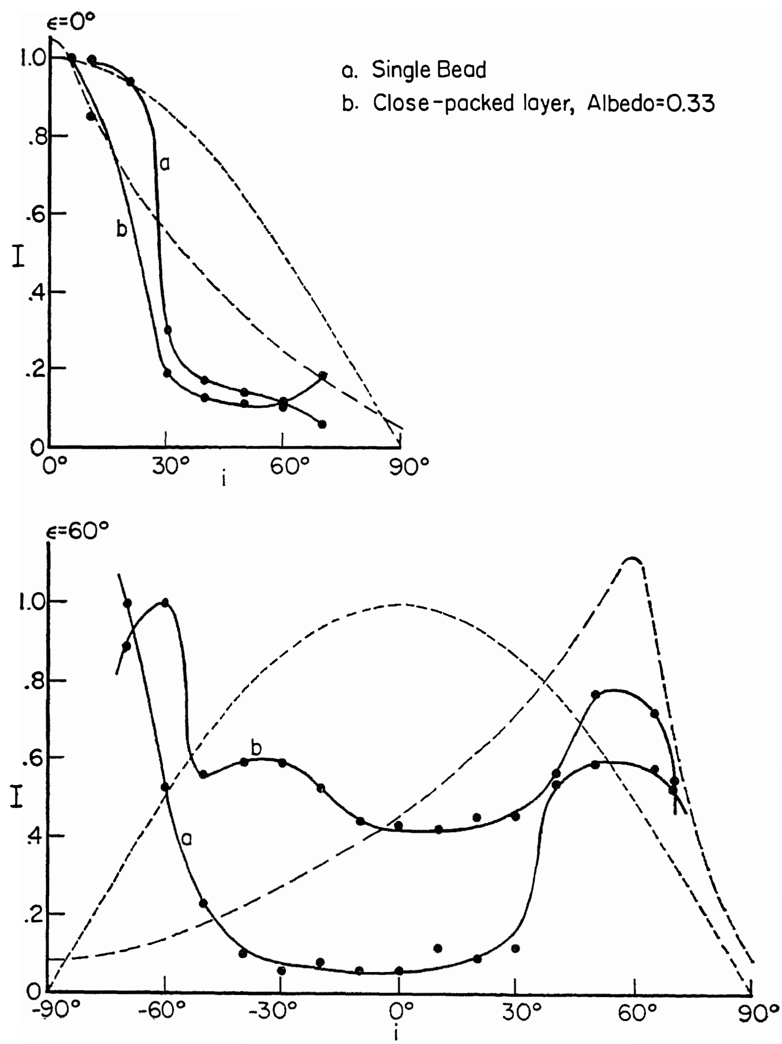

Fig. 5. Glass beads.

played by objects which are translucent but have many irregularities and inhomogeneities on their surfaces or in their interiors, since rays of light penetrating into such objects are (in the first approximation) equally likely to emerge in any direction. Small particles of rocks and other dielectrics usually fall into this category. Opaque objects with smooth surfaces oriented randomly also have an average microscattering law that is isotropic; examples are polished metal spheres and randomly oriented dark crystals whose surfaces are smooth cleavage planes. A broad backscatter type of microscattering law is exhibited by opaque objects with somewhat rough surfaces, such as a piece of rock several millimeters or more in size, for such an object appears brightest to an observer when the source of light is directly behind him so that he sees only the illuminated face, and is less bright if he views it at any other angle so that he also sees shadowed areas.

It should be clear that these classifications of surface properties are not sharply defined and that continuous gradations exist between the categories.

Surfaces of high albedo. Complex surfaces with high albedo reflect light diffusively for this reason: The brightness of a directly illuminated

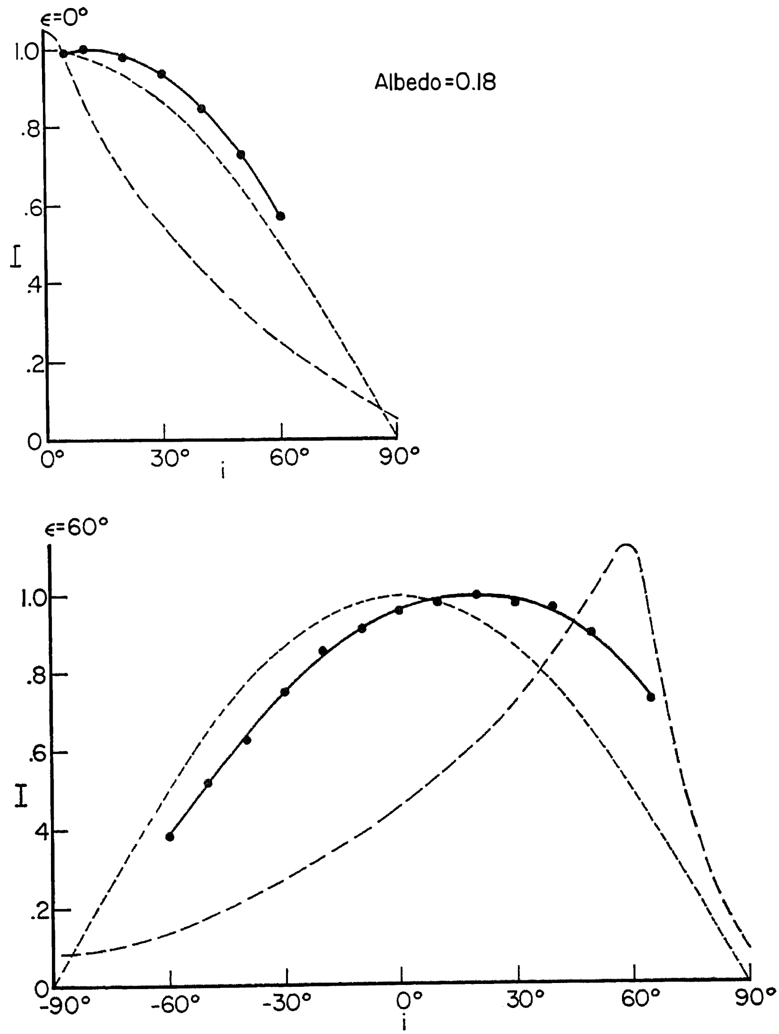

Fig. 6. Peridotite.

area depends on the first power of the albedo, but an area shielded from the source is still illuminated by multiply reflected rays and so its brightness depends on the second and higher powers of the albedo. If there is little absorption, rays of light scattered more than once contribute more to the brightness of the surface than singly scattered rays. A typical ray that escapes from a bright, intricate surface has undergone several reflections, so that its direction of motion has been nearly randomized. The direction into which such a ray leaves the surface is approximately independent of its initial direction and of the normal to the surface.

A surface for which the process of randomization by multiple scattering is complete is, by definition, a Lambert surface, since it appears equally bright from any direction. This tendency toward Lambert scattering exhibited by a bright surface is nearly independent of the microscattering properties and the macrostructure of the surface.

Surfaces of low albedo. When the albedo decreases below about 25 per cent, singly reflected

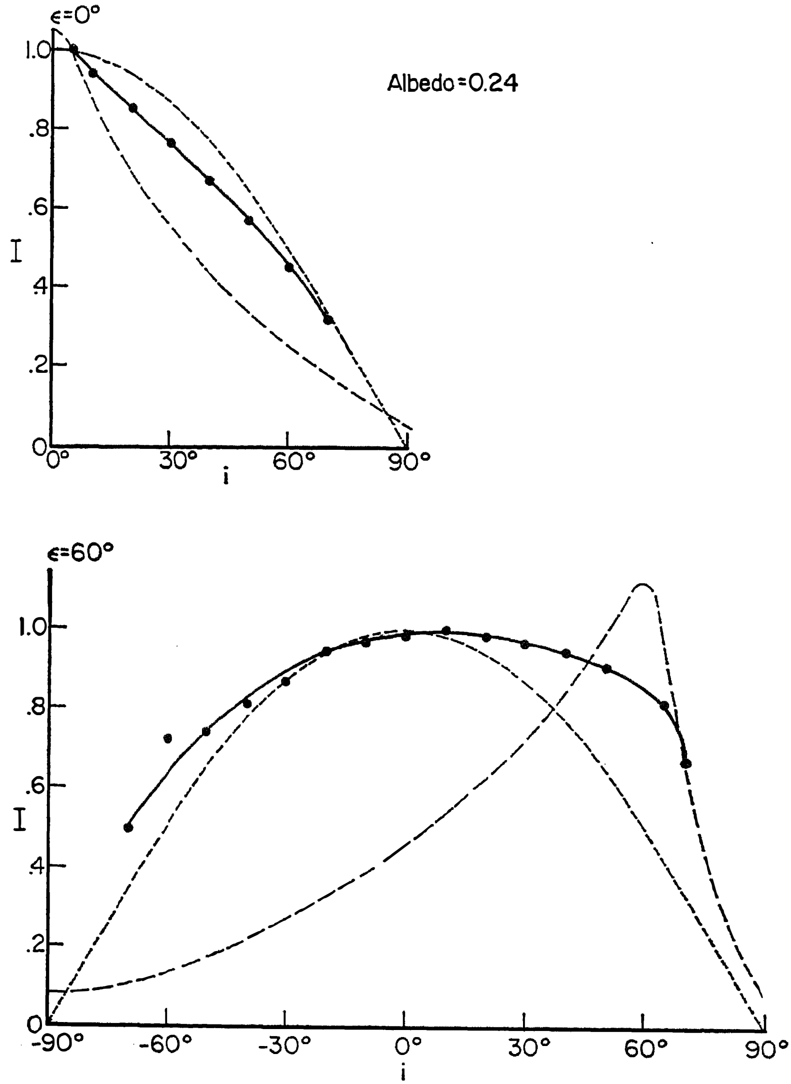

Fig. 7. Stainless-steel powder.

rays dominate over multiply reflected rays in determining the scattering characteristics of a surface. The photometric behavior is now controlled by the microscattering properties and the macrostructure.

A surface with a smooth macrostructure reflects light into a broad specular peak, as discussed at the beginning of this section.

The scattering law of a dark surface with a corrugated macrostructure is essentially the same as that of its microscattering elements. If the objects of which the surface is composed forward-scatter light the surface reflects light in a pseudospecular manner; the reflected intensity reaches a broad maximum on the opposite side of the normal to the surface from the direction of incident light, but the maximum does not necessarily occur when the angles of reflection and incidence are equal. If the surface consists of isotropic scatterers the photometric law approximates Lambert's law. A surface composed of backscattering objects has a reflection curve with a wide backscatter peak. For a deeply pitted surface this backscatter peak may become quite narrow when the direction of observation is aligned with the axes of the pits and the bottoms of the holes are illuminated, but it will remain broad when viewed from any other direc-

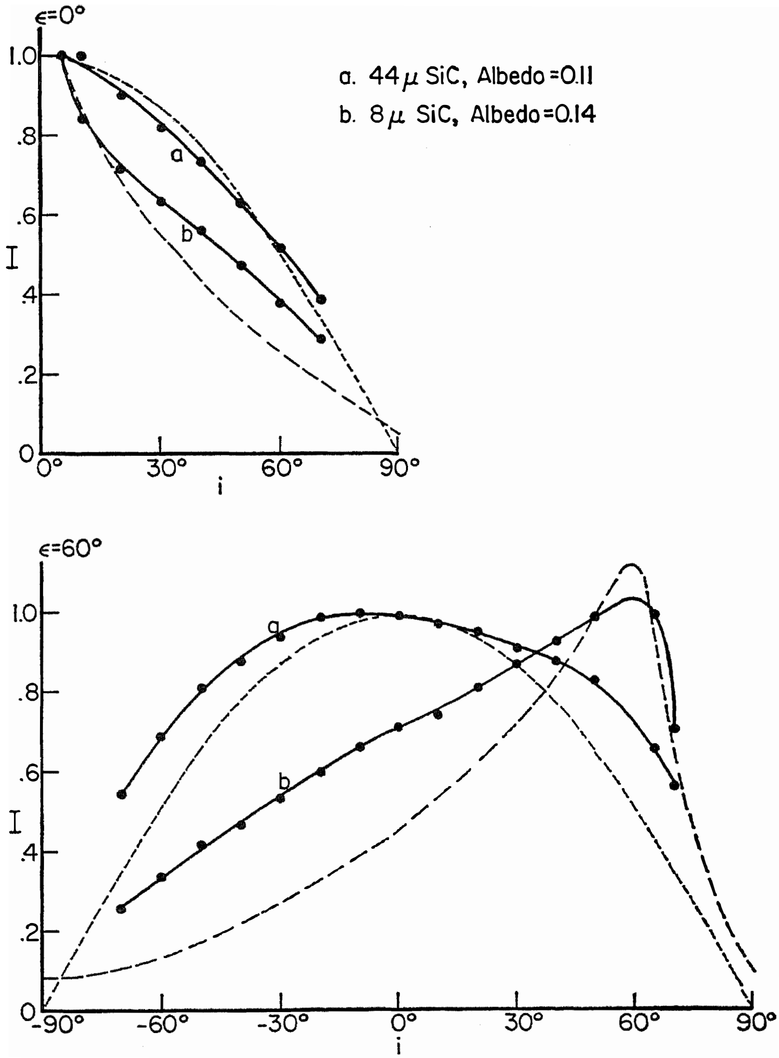

Fig. 8. Silicon carbide.

tion when the deep interiors of the pits cannot be seen.

A dark surface with a porous macrostructure backscatters light. This effect arises as follows. Light rays can penetrate into surfaces of high porosity with deep cavities and can illuminate particles or cavity walls far under the surface. When an observer looks parallel to the direction of incidence he sees the light reflected from these deep surfaces, but when he looks in any other direction the deeply reflected light is blocked and he sees only light from areas near the top of the macrostructure. Hence the reflected intensity is sharply enhanced when the direction of observation is nearly parallel to the direction of illumination. This is a minor effect for bright surfaces, where it is largely masked by multiply reflected rays, but dominates the reflection process for dark, porous surfaces. Since light can penetrate freely from any direction into a surface with a porous macrostructure, the surface backscatters light strongly regardless of the direction from which it is observed.

The reflection law of a surface of forward-scattering objects arranged in a porous macrostructure has both a broad pseudospecular peak and a backscatter peak. If the objects are isotropic scatterers the surface reflects light in a

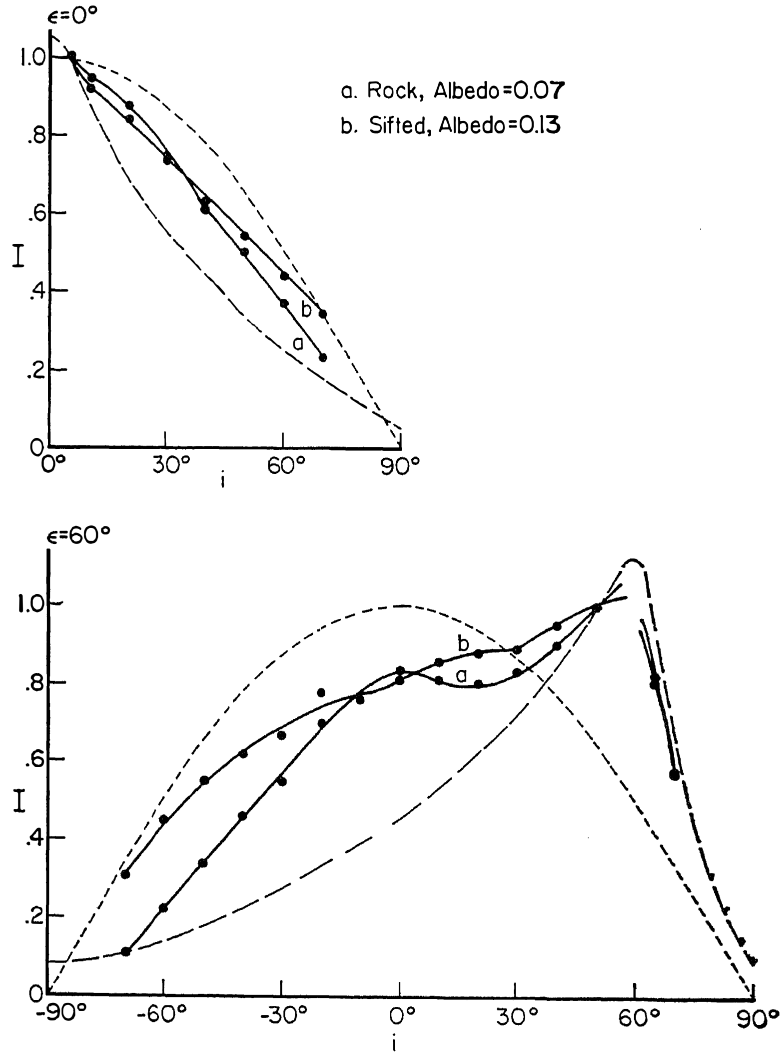

Fig. 9. Scoria.

broad backscatter peak, whereas if the microscatter properties are of the backscatter class the surface backscatters light sharply.

The width of the backscatter peak of a porous surface is also affected by the porosity of the macrostructure. The more porous and open the surface, the narrower the peak. Surfaces that backscatter light as sharply as the moon generally have fractional void volumes of the order of 90 per cent.

It has been found possible to treat these backscatter effects mathematically, and a detailed theory of optical scattering from dark, porous surfaces is presented by *Hapke* [1963].

EXPERIMENTAL SCATTERING CHARACTERISTICS OF SELECTED SURFACES

Apparatus and data reduction. The apparatus for investigating the light-reflecting properties of surfaces is based on a design by Kalmus [*Kalmus and Sanders,* 1950]. The photometer uses a modulated light source and an ac detector, thus permitting operation in a lighted room (see Figure 1). A multivibrator drives a 6-watt lamp, which produces a nearly sinusoidal 20-cps light signal. A system of lenses projects the light into a narrow beam about ½ inch wide at the surface being investigated. A vacuum phototube

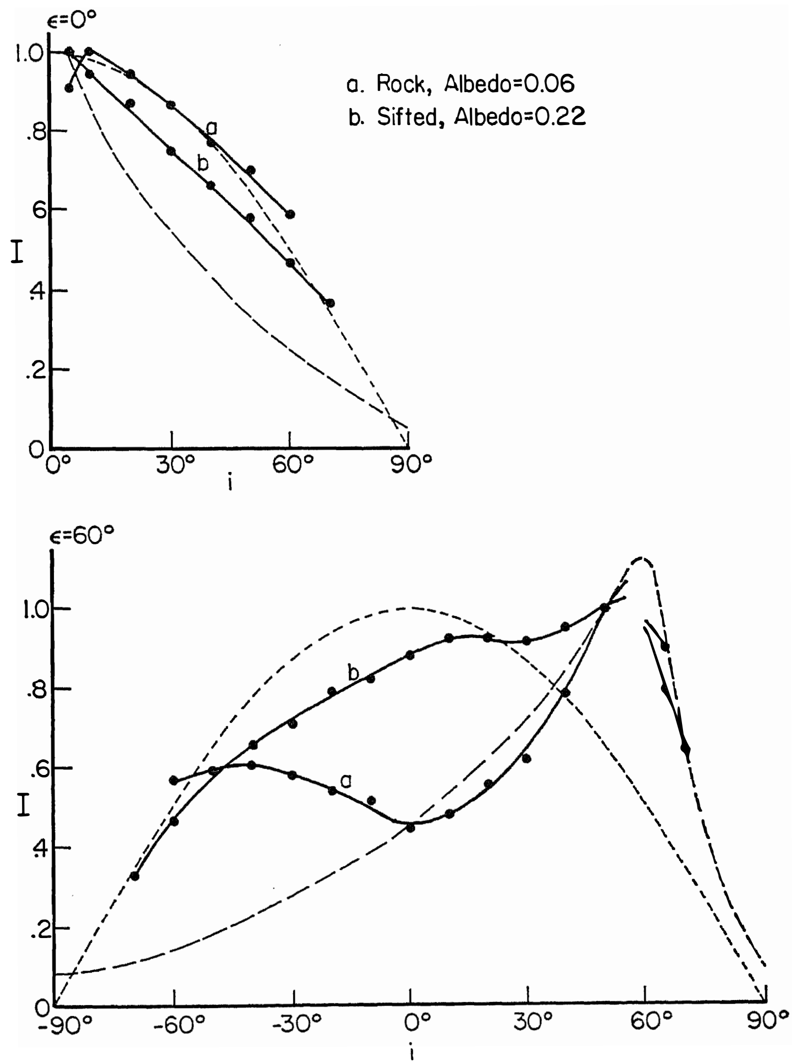

Fig. 10. Basalt.

observes the area on the surface containing the spot of light. The signal from the phototube is amplified by a narrow-bandwidth 20-cps amplifier, and the output appears as a deflection on a meter.

To convert the meter reading to a number proportional to the brightness of the surface, the output of the meter is multiplied by cos i/cos ϵ, where i and ϵ are, respectively, the angles the direction of incidence and the direction of observation make with the normal to the surface, and by a second factor that corrects for certain instrumental errors. The correction factor was determined by using a surface of known photometric properties. This standard surface is a glass plate covered with a thick layer of magnesium oxide smoke; it closely approximates a Lambert surface and has an albedo of nearly 1.00.

The reflecting properties of a surface were measured at two standard angles of observation, $\epsilon = 0°$ and $\epsilon = 60°$, while the angle of incidence i was varied. At all times the direction of incidence, the direction of observation, and the normal to the surface remained coplanar. The albedo of the surface was measured by fixing the

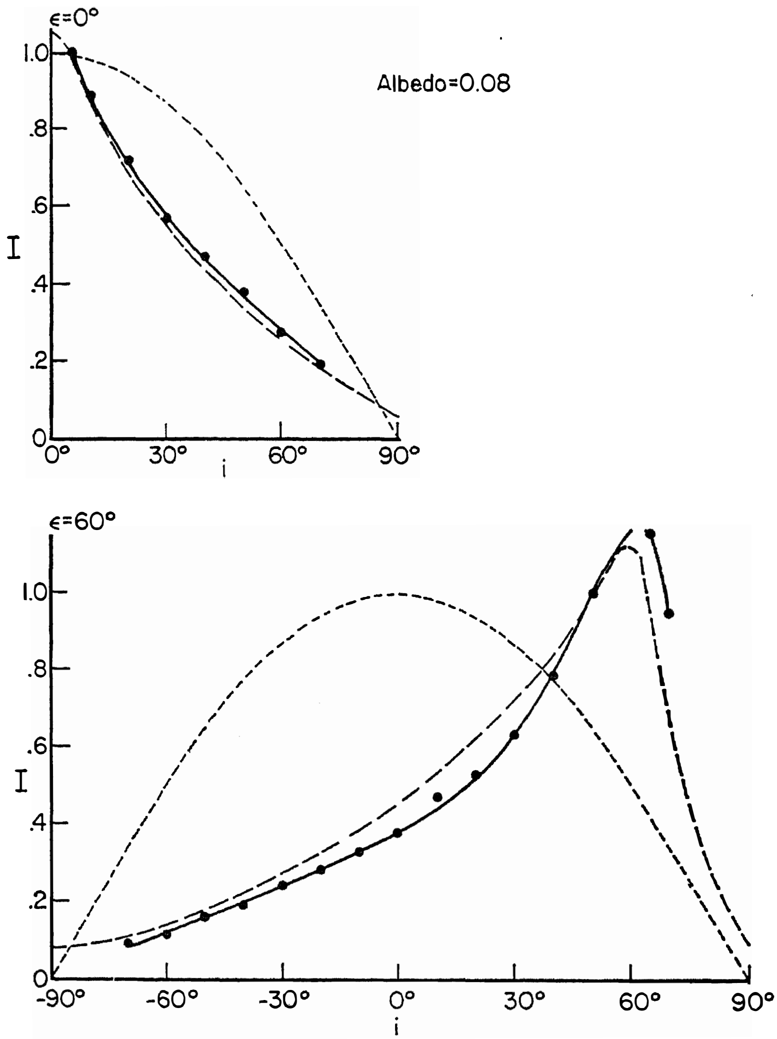

Fig. 11. Lichen.

angle of incidence at 0° and varying the angle of observation, and was calibrated absolutely by reference to the standard MgO surface.

Experimental results. The results of the photometric measurements on selected surfaces are shown in Figures 2 through 15. In these figures the circles and solid lines are the normalized experimental data. The measured albedo is also given. For comparison, on each figure are shown the normalized scattering functions of a Lambert surface (dotted line) and the lunar surface (dashed line). The mean lunar curves are those obtained by *van Diggelen* [1959, Figure 74] by averaging photometric measurements of selected crater floors. The surfaces whose scattering characteristics are shown in the figures were chosen to be presented here either because they are often mentioned as being possible constituents of the lunar surface or because they illustrate some of the statements made in the preceding section.

The Lambert-type reflection laws exhibited by bright surfaces are shown in Figures 2, 3, and 4. Figure 2*a* is a thick layer of colloidal-sized particles of MgO smoke deposited on a flat plate; Figure 2*b* is a layer of MgO powder sifted in air through a 200-mesh sieve onto a flat plate. The sifted surface, with the porous macrostructure,

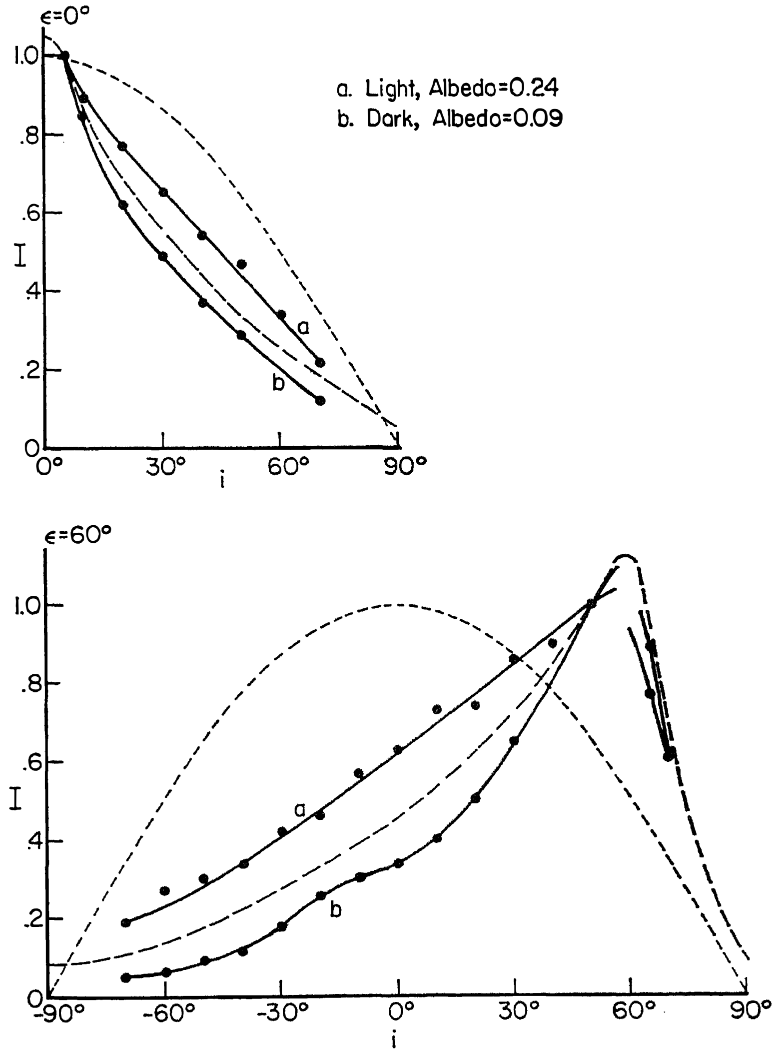

Fig. 12. Silver whiskers.

has the lower albedo and also a small amount of backscatter. Figure 3*a* is pumice rock; Figure 3*b* is the same material pulverized and sifted. Figure 4*b* is pulverized and sifted obsidian. Diffusive scattering is also displayed by most sands, snow and hoarfrost, glass wool, and nonmetallic whiskers.

The specular reflection law of obsidian rock, a dark smooth surface, is shown in Figure 4*a*.

Figure 5 shows the curves for glass beads. Figure 5*a* is a single glass bead 6 mm in diameter; Figure 5*b* is a layer of beads lying on a black surface. The strong forward-scatter and secondary backscatter peaks should be noted.

The scattering from fresh, unweathered peridotite (Figure 6) is typical of many rocks. The reflection is of the diffusive type because the surface consists of tiny, translucent mineral crystals, which are approximately isotropic scatterers. Lambert-type scattering is also displayed by compacted stainless-steel powder (Figure 7) and compacted, coarse silicon carbide abrasive powder (Figure 8*a*). Both these surfaces are composed of opaque particles with smooth surfaces.

Scoria is shown in Figure 9. The surface of the rock (Figures 9*a* and 16) is covered with deep pits and is classed as having an extremely rough, corrugated macrostructure. Since the surface consists of opaque, rough scattering areas ori-

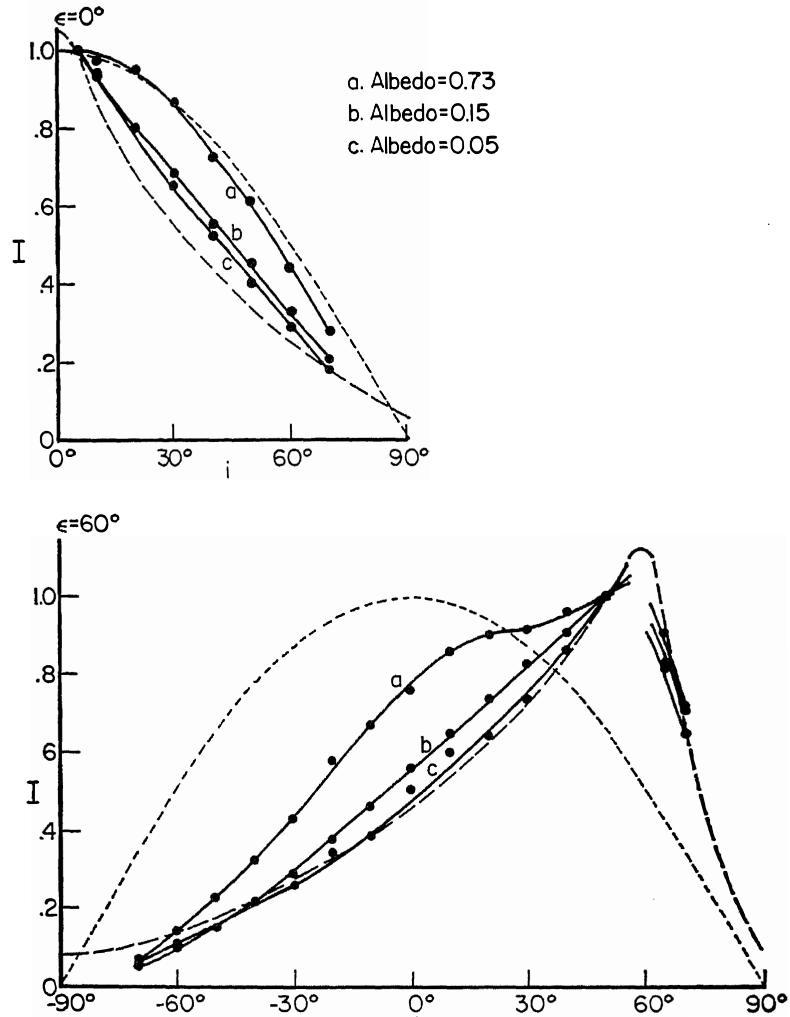

Fig. 13. Cellulose sponge.

ented in a variety of directions a broad backscatter type of reflection law is to be expected, and this is indeed observed. Pulverizing and sifting the scoria (Figure 9*b*) create a surface of translucent grains arranged in a porous macrostructure, and again a broad backscatter peak results.

The rough surface of black basalt rock (Figure 10*a*) is imbedded with tiny transparent grains which both forward-scatter and backscatter light, so that two peaks are observed in the reflection curve. As with scoria, pulverized and sifted basalt has a broad backscatter peak.

A number of different surfaces exhibiting sharp backscatter properties were investigated. They include lichen (Figures 11 and 17), grass, silver whiskers (Figure 12), a cellulose sponge (Figure 13), and finely divided dark powders sifted to form complex surfaces of low density, such as silver chloride (Figure 14), carbon (Figure 15), nickel sulfide, and cupric oxide. All these substances have the porous type of macrostructure, and no surface has been discovered that reproduces the lunar scattering function without having this macrostructure.

The lichen (Figure 11), which was discovered

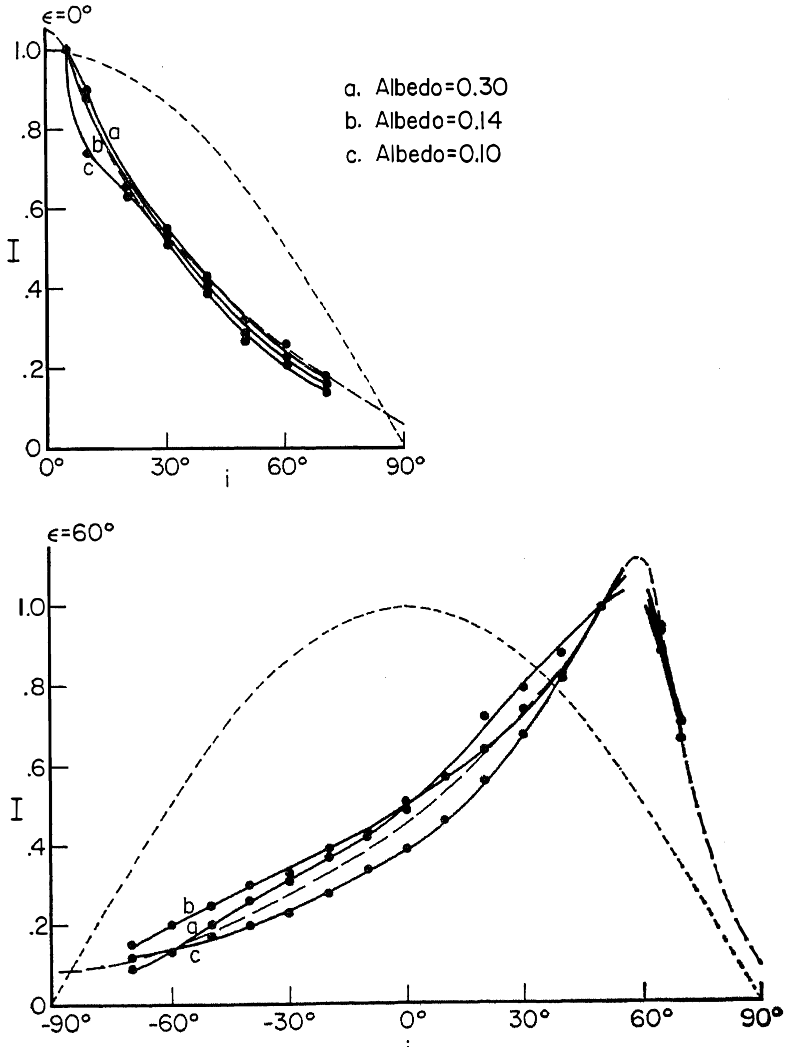

Fig. 14. Silver chloride.

by *van Diggelen* [1959] to scatter light like the moon, has a porous macrostructure and opaque, somewhat rough microsurfaces.

The silver whiskers were grown from silver sulfide in a hydrogen atmosphere at 350°C. The scattering function for metallic silver whiskers is given in Figure 12*a*. The whiskers were then placed in a sulfur atmosphere and darkened (Figure 12*b*). With multiple reflections thus eliminated the whiskers reproduced the lunar reflection law almost exactly. It is likely that metallic iron whiskers would duplicate the lunar curve without darkening, since the albedo of iron is about half that of silver.

The effect of reducing the albedo is also illustrated by the sponge and by AgCl. The sponge is made of artificial cellulose plastic. Superficially it has the appearance of a foam with a pitted surface resembling scoria. Closer examination, however, shows that the holes are interconnected so that the macrostructure is similar to that of the lichen, although the void volume is smaller. According to the manufacturer, the Nylonge Corporation, of Cleveland, Ohio, the sponge was made by forming a matrix of a viscous cellulose fluid mixed with a large number of organic crystals. After the fluid had set, the crystals were allowed to evaporate, leaving a mate-

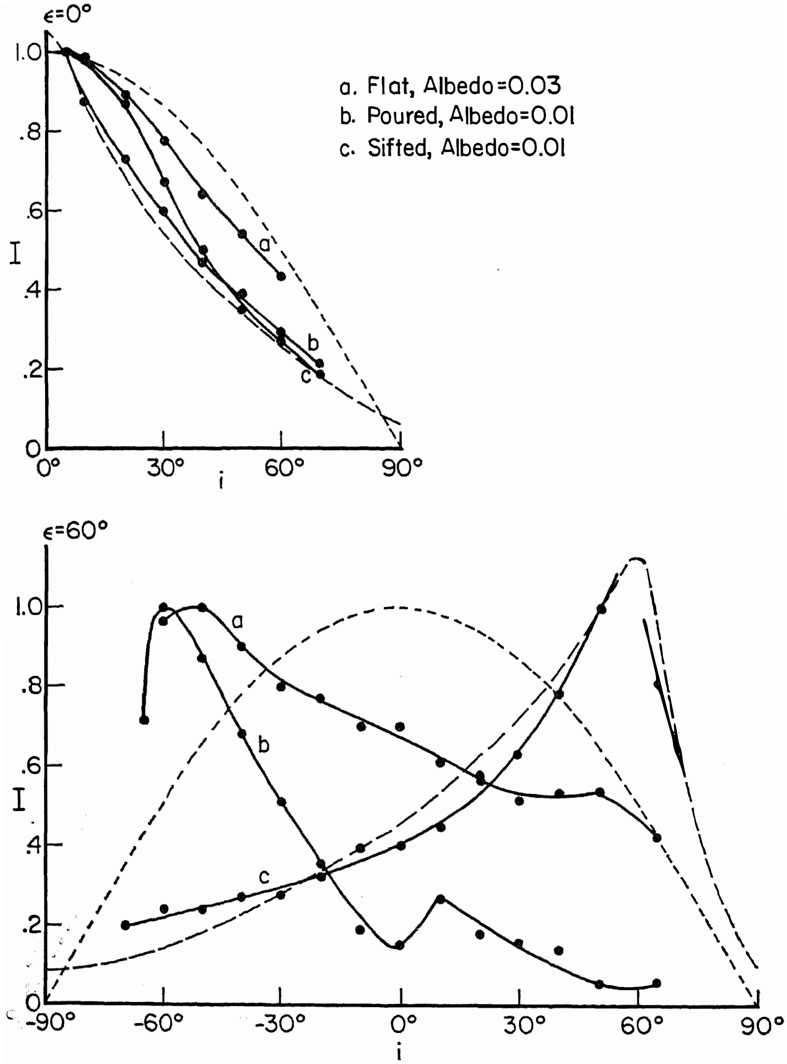

Fig. 15. Carbon (charcoal powder).

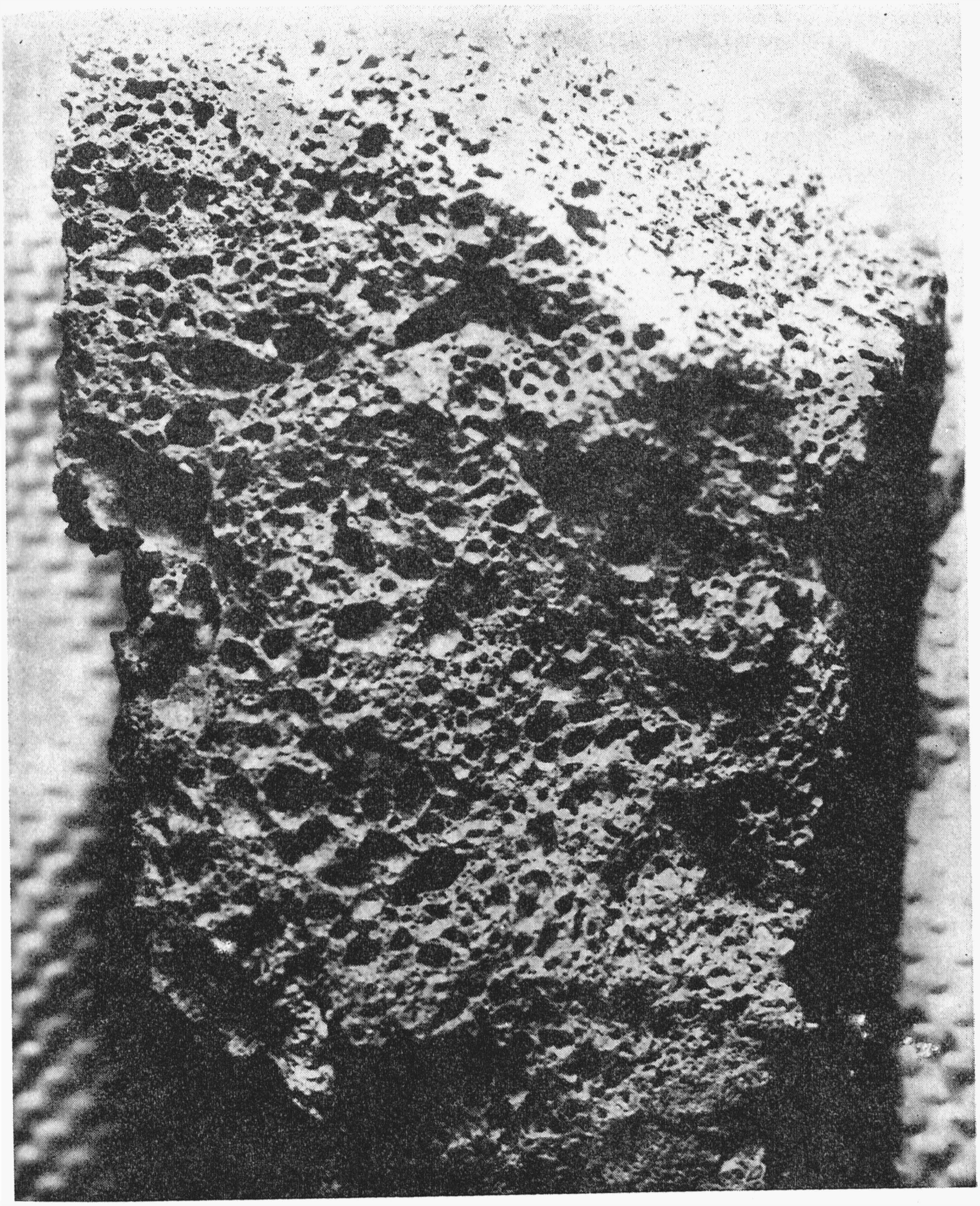

Fig. 16. Scoria.

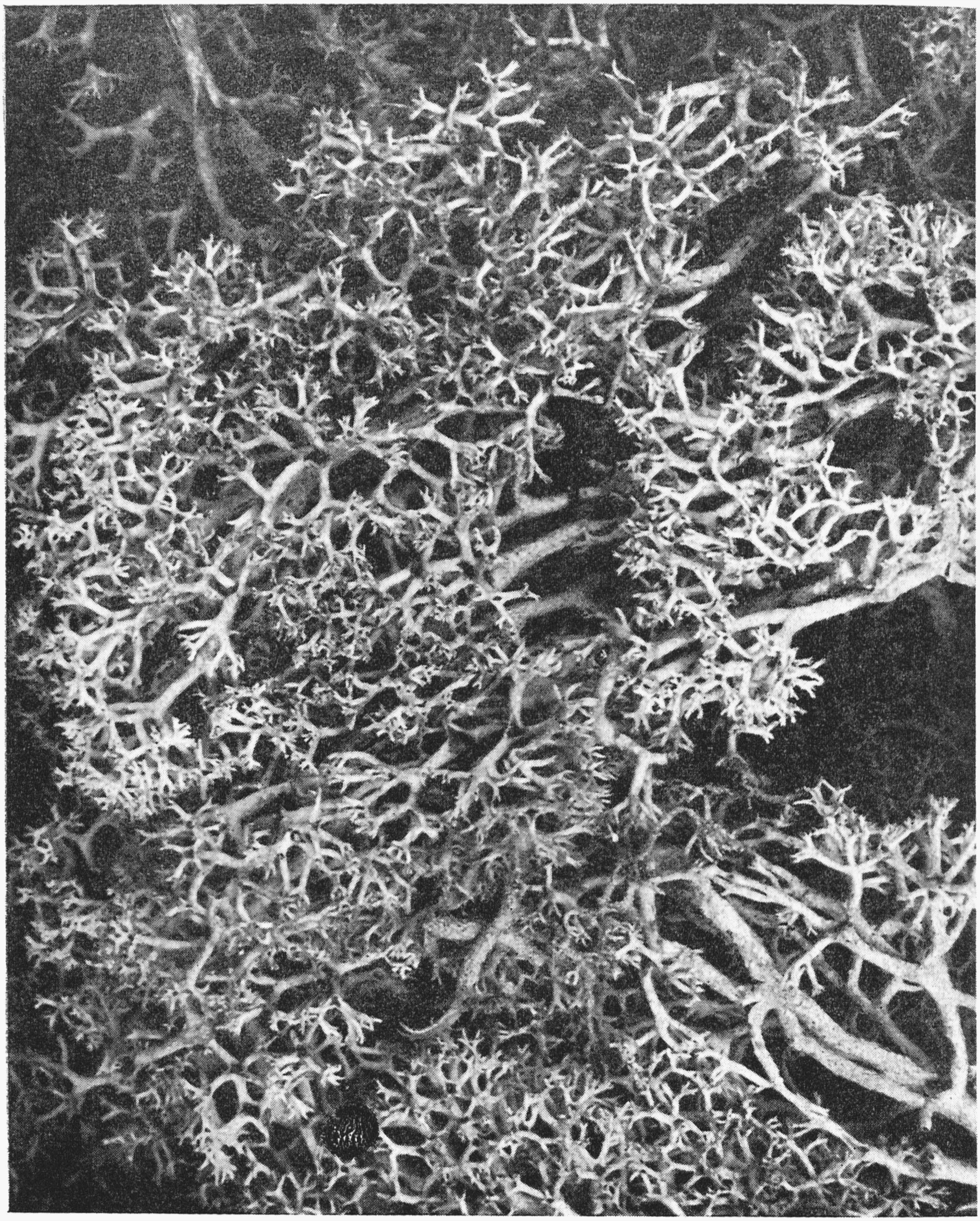

Fig. 17. Lichen.

rial with a porous macrostructure. The sponge was progressively darkened by soaking in various mixtures of black and white water-color paint. After each soaking the sponge was allowed to dry and its scattering curve was measured. As shown in Figure 13, decreasing the albedo results in an elimination of the diffusive component of the curve and a decrease in the width of the backscatter peak. The peak never becomes as narrow as that of the lichen because of the lower void volume and also because the microsurfaces are smooth.

A surface of special interest is powdered AgCl (Figure 14). A quantity of AgCl was prepared in darkness and sifted through a 200-mesh screen onto a flat plate. The scattering characteristics of this surface were measured under low ambient lighting conditions. The surface was then exposed to ultraviolet radiation and was uniformly darkened without disturbing the macrostructure. The darkening was caused by the photoproduction of colloidal-sized particles of free silver at the surface of the grains. Again, decreasing the albedo sharpens the backscatter peak.

To the naked eye the surface of the powder appeared smooth and featureless. Microscopic examination, however, revealed that the powder grains had clumped themselves into complex towers and bridges to form an open, porous macrostructure of the type necessary for sharp backscatter. This ability to form extremely intricate structures is not limited to AgCl but appears to be a property of all finely divided solids, particularly insulators.

If a dielectric, such as a piece of rock, is pulverized to a large average particle size and the powder is poured or sifted onto a plate the resulting macrostructure is not particularly complex; viewed under a microscope the surface resembles a pile of gravel. But if the particles are smaller than a certain critical size, and if they are deposited in such a way as to ensure that they fall individually and impact the surface at a low velocity (in the laboratory these conditions are most conveniently ensured by sifting the powder through a fine-mesh sieve in an atmosphere), then the grains will build up fantastically complicated structures. When such a surface is viewed under a stereoscopic microscope, porous open hills are seen, out of which grow towers and branches, many of them interconnected with lacy bridges. These 'fairy-castle' structures are fully as complex as the lichen and are certainly capable of sharply backscattering light (provided that the other requirements for strong backscatter previously cited are met).

Photomicrographs of large particles in 'gravel-pile' packing and small particles in fairy-castle packing are reproduced in Figures 18 and 19, respectively. The material in the photographs is ordinary commercial Portland cement powder; it is used here because the surface structures show up best in a photomicrograph and not because the structures are necessarily more complex than those formed by other materials. Both powders were deposited in air by being sifted through a standard 200-mesh sieve and allowed to fall onto a flat plate.

In the gravel-pile form of packing, each grain is supported by several of its nearest neighbors, but in the fairy-castle form many of the grains are supported by only one or two adjacent grains. Thus, the maximum grain size for which fairy-castle packing will occur is determined by the ratio of the weight of a grain to the intergrain forces. The most important intergrain force is probably surface adhesion, although electrostatic forces may also be important initially in forming the structures. For ordinary dielectric materials, such as pulverized rocks or commercial abrasives, deposited in air, the critical diameter appears to be about 15 microns. The appendix provides a further summary of what is known about this low-density form of packing.

The importance of the macrostructure to producing sharp backscatter is illustrated by powdered charcoal (Figure 15). The surface labeled 'flat' was prepared by pouring a quantity of Norit A powder into acetone and shaking the mixture vigorously; the suspension was then poured into a shallow dish and allowed to settle out, and the acetone to evaporate undisturbed. The resulting surface was quite smooth and scattered light into a broad specular peak (Figure 15*a*). That a complex macrostructure cannot be obtained merely by pouring a fine powder from a container onto a flat plate is shown in Figure 15*b* by the curve labeled 'poured,' which is also specular. When the same powder is sifted through a 200-mesh sieve onto a plate the surface has a porous macrostructure and backscatters light strongly (Figure 15*c*).

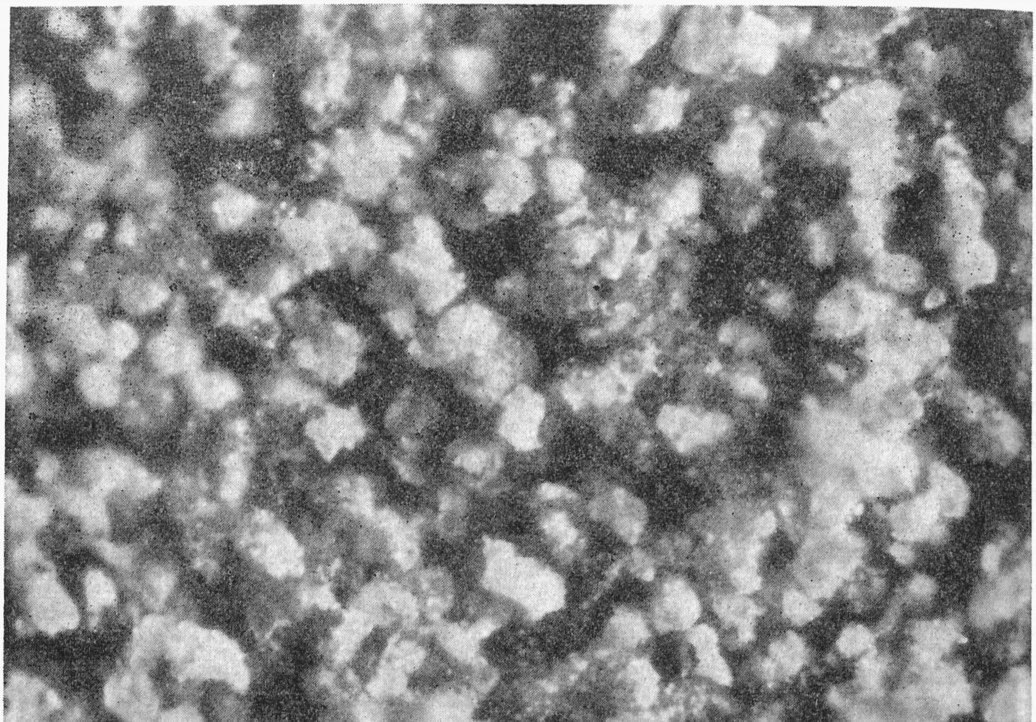

Fig. 18. Photograph of coarse powder showing gravel-pile packing. 52×.

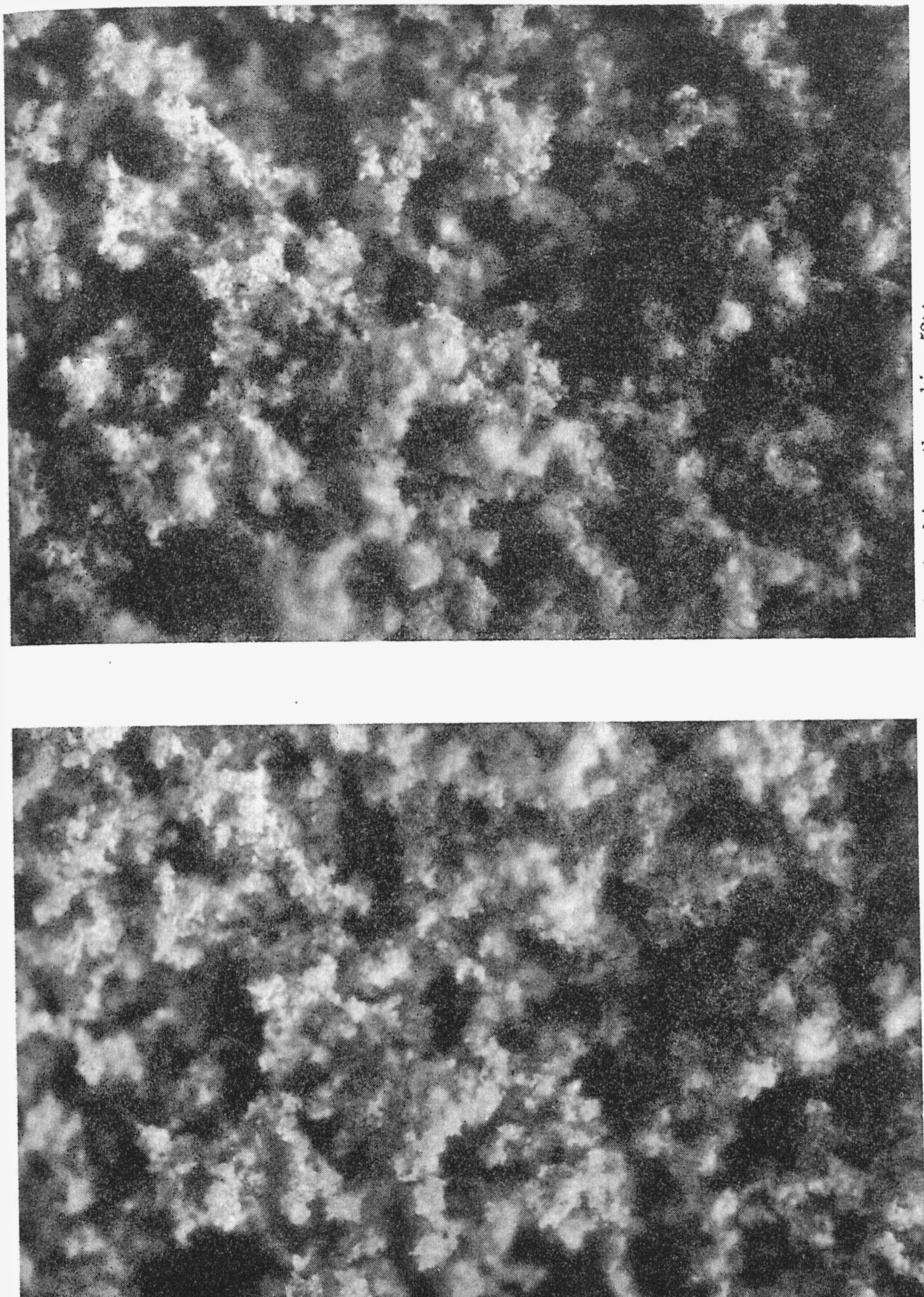

Fig. 19. Stereo pair photographs of fine powder showing fairy-castle packing. 52×.

The importance of fairy-castle packing to producing backscatter from dielectric powders is also illustrated by Figure 8. The silicon carbide is a commercial abrasive (Norton Crystolon). Figure 8*a* is the scattering curve for number 280 abrasive consisting of 44-micron-diameter grains in gravel-pile packing. Figure 8*b* is number 600 abrasive with 8-micron-diameter grains in fairy-castle packing. Both surfaces were prepared by sifting the powder through a 200-mesh sieve in air.

The sharpness of the backscatter peak of dark, open surfaces is determined not only by the porosity of the macrostructure but also by the average reflecting properties of the particles that make up the surface. A fairy-castle surface of translucent particles has a wider peak than one of opaque particles. The scoria (Figure 9*b*) and basalt (Figure 10*b*) powders were translucent and thus had broad backscatter peaks. The SiC (Figure 8) also contained an appreciable number of translucent particles. In addition, the albedos of the scoria and basalt powders were high enough so that multiply reflected light could contribute to the scattered intensity.

The results of this and the preceding section are summarized in Table 1. The moon's surface would belong with the bottom category of Table 1, having sharp backscatter and being dark.

Applications to the Moon

The optical scattering law of the lunar surface is characterized by a low albedo of the order of 10 per cent, and a sharp backscatter peak, which is independent of the orientation of the surface. All parts of the moon reflect light in this way. On the basis of the discussion of the preceding sections it is possible to specify with reasonable confidence certain features the uppermost layers of the lunar surface must have in order to scatter light as described.

No matter what the origin or nature of the lunar surface, the top layer must be extremely porous and open with *interconnected* cavities and a void volume of the order of 90 per cent. The scattering objects comprising the surface must absorb more than about 70 per cent of the light incident on them and must be opaque, with fairly rough surfaces.

The sharp backscatter characteristic of the lunar reflection law arises from the loose, open macrostructure as follows. Light can penetrate freely into such a surface from any direction and partially illuminate objects under the surface; rays reflected from the deeper objects back toward the source can escape freely along the path of the incident radiation, but rays reflected into any other direction are blocked. If the reflecting objects are translucent or transparent the backscatter peak will be wider than the moon's. If the objects do not absorb light strongly enough, that is, if the albedo of the surface is too high, multiply scattered rays will mask the backscatter peak and the reflection law will tend toward that of a Lambert surface.

The low albedo is a known characteristic of the moon. The requirement of high porosity implies that the thermal conductivity and the spe-

TABLE 1. Reflection Laws of Complex Surfaces

	Surface Characteristics			
Reflection Law	Albedo	Microscattering	Macrostructure	Examples
Sharp specular	Any		Smooth	Volcanic glass; sheet metal
Broad specular	Dark	Forward	Corrugated or porous	Layers of glass beads*
Lambert	Bright	Any	Corrugated or porous	Light powders; sand; pumice; hoarfrost; some vegetation
	Dark	Isotropic	Corrugated	Some dark compact powders; most rocks
Broad backscatter	Dark	Back	Corrugated	Some dark compact powders; scorias; slags
	Dark	Isotropic	Porous	Some dark uncompacted powders
Sharp backscatter	Dark	Back	Porous	Some dark uncompacted powders; some vegetation

* Also exhibits secondary backscatter peak.

cific heat of the lunar surface are much lower than for solid rocks, in agreement with inferences from infrared and radio-frequency measurements of the lunar thermal radiation (summarized in *Sinton* [1962]).

The need for interconnected cavities eliminates solid rocks, even a rock covered with cracks and pits, and also pumaceous and scoriaceous rock foams and slags, as comprising the uppermost layers of the lunar surface. The volcanic foams have low densities, but the pores are separate so that their surfaces consist of unconnected pits and do not have the correct macrostructure to backscatter light strongly. Although processes that could tear the bubble walls, such as the whipping of the lava as it is on the verge of solidifying, are conceivable, it is unlikely that they could occur over the whole moon, including the mountains and rays. Glassy spheroids and other transparent or translucent objects can also be rejected as major constituents of the lunar surface, because they would cause the backscatter peak to be too wide, even when arranged in an extremely porous macrostructure.

Among the materials known to be able to form the complex dendritic macrostructure of the required sort are vegetation, whiskers (both metallic and nonmetallic), certain types of artificial sponges, and finely divided powders. In addition, *Warren* [1963] has recently suggested a skeletal fuzz, which is presumably scoria or impactite glass, the walls of which have been partly eroded by the sputtering action of the solar wind. Sytinskaya and her associates in the USSR [*Sytinskaya*, 1959] have suggested that the lunar surface is covered with a porous substance that resembles foundry slag but is produced by meteoric bombardment, and hence is called 'meteoric slag.'

In deciding whether a given material is likely to be present in large amounts on the surface of the moon two considerations are relevant. The first is the observation that all parts of the lunar surface, irrespective of terrain, backscatter light strongly. Therefore the characteristic lunar soil must be able to form on any type of terrain. On this basis it is possible to reject materials that depend for their formation on the presence of a specific type of bedrock, such as scoria, or on some localized process.

The second consideration is our knowledge of the lunar environment, of which the most important features are lack of atmosphere, meteoritic bombardment, and solar radiation. Thus vegetation is unlikely to be present on the moon. (However, the photometric properties of vegetation may be relevant to the interpretation of observations of Mars.)

The predominant effect of particles impacting rocks at hypervelocities appears to be pulverization. Laboratory experiments and studies of terrestrial meteorite craters [*Shoemaker*, 1962; *Gault et al.*, 1963; *Dietz*, 1961] show that the energy of impact is divided primarily between vaporization and pulverization of the target material. Although some melting is observed it appears to be an extremely local phenomenon, and the amount of material melted in comparison with that pulverized can be completely neglected. Thus, irrespective of the nature of the original lunar rocks (i.e., whether of volcanic or meteoric origin), repeated meteoritic bombardment will reduce at least the upper few centimeters of the primordial lunar surface to a powdered state over geologic times. The production of foams or slags or materials of a similar sort is probably quite minor.

Hence it is likely that the structures responsible for the peculiar lunar optical properties must be built from a finely pulverized surface. Further, they must be of such a nature that the lunar environment can repair or rebuild them after an impact. Only two types of substances appear to have these properties: whiskers and finely divided powders.

Metallic whiskers can be rejected because their presence in numbers sufficient to account for the optical laws would cause the radar reflectivity of the moon to be higher than it is actually observed to be. Nonmetallic whiskers could conceivably be formed by the combined effects of sputtering by the solar wind and condensation of material vaporized by micrometeoric impacts. Not enough is known about accommodation coefficients or atomic surface diffusion phenomena to state definitely whether nonmetallic whiskers could occur on the moon. Since the volume of material pulverized by a micrometeorite impact probably greatly exceeds the volume vaporized, however, it seems doubtful that the growth rate of a whiskery surface would exceed the destruction rate.

Thus, discounting some substance completely unknown terrestrially, the available evidence strongly suggests that the lunar surface is covered with a layer of finely divided rock powder in an extremely loose state of compaction. Terrestrial rock powders that are ground up finely enough to build fairy castles (Figures 3*b*, 4*b*, 9*b*, 10*b*) are too translucent to reproduce the lunar photometric law. But the treatment the exposed lunar material has received has been very different from that of terrestrial rocks, and there are several reasons why lunar rock powders should be much darker. Repeated shocking of the silicate lattice by impacts and prolonged exposure to high-energy cosmic radiation will result in a highly disordered lattice, which will have a higher opacity and electrical conductivity than similar terrestrial minerals. Also the bombardment by the hydrogen ions in the solar wind could probably darken the rock powders sufficiently. *Hapke* [1962] has irradiated various minerals with 10-kev protons and obtained darkening, which was attributed to the reduction of metal oxides to free metal by the monatomic hydrogen. (This is reminiscent of the experiment with the AgCl powder.) *Wehner* [1962], who reports that ion bombardment darkens insulators with rough surfaces, attributes this effect to differences between sticking coefficients and sputtering yields of the atoms composing the insulators. More experimental work is necessary before this matter can be regarded as definitely settled. However, there is ample observational evidence that a darkening process is at work on the lunar surface [*Shoemaker*, 1962].

Various reasons may be advanced to explain why the rock dust on the moon would be naturally formed into the fairy-castle structures. Such structures would result if the electrostatic transport mechanism suggested by *Gold* [1955] is correct. A more likely explanation, also due to Gold (private communication, 1961), is that the micrometeorite impacts will themselves build the dust up into a loosely compacted state. When a micrometeorite hits the 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, over geologic times, a surface of solid rock or one of compacted powder could be built into fairy-castle structures.

Lunar rays are relatively new features, but their backscatter peak is sharper than that of the rest of the lunar surface, implying an even looser state of compaction. Apparently, however, they are pulverized debris flung out from the giant impacts, and hence should be more compacted. A possible explanation of why ray material may be even looser than other surfaces may be the following. A loosely compacted surface would be formed if the debris were a mixture of rock powder and pulverized ice. (The ice might come from a permafrost layer under the lunar surface or from the impacting body if it were of cometary material rich in frozen volatiles.) The ice would rapidly evaporate, leaving a porous surface consisting of bridges of rock. Such a process has been demonstrated in the laboratory (see the appendix) and also bears a certain similarity to the way the sponge was made.

As O'Keefe suggests, it is possible that a small number of glass beads may be scattered among the ray material. By half-burying glassy spheroids in the dark lunar soil the forward-scatter peak of the beads can be largely eliminated, and the beads would enhance the brightness of the rays at full moon but contribute little to the reflected intensity at other phase angles. The principal objection to large quantities of glassy spheroids in the rays is that it is difficult to conceive of a process that would neatly half-bury all the beads. It would be expected that any process which partially covered some beads would leave others buried insufficiently to block the forward-scattered radiation. Therefore the brightness of the rays of the limb should be enhanced near new moon as well as at zero phase, contrary to observations.

An upper limit to the size of the dust particles on the moon responsible for the reflection properties may be estimated. In the laboratory the critical diameter for transition from gravel-pile to fairy-castle packing is about 15 microns. However, no attempt was made to clean the powder. The adhesive forces between grains are proportional to the product of the area of real contact and the intermolecular surface forces. Both quantities are approximately independent of particle size, but the intermolecular surface forces depend on the cleanliness of the surface. Hence removing all adsorbed surface films might increase the adhesive forces by possibly an order of magnitude. Transferring the particles to the moon would decrease their weight by a factor of 6. Therefore, for clean rock dust on the moon the critical diameter may be increased by a factor of $(6 \times 10)^{1/3} = 4$, so that the upper limit to the lunar particles is estimated to be about 60 microns.

However, the small degree of polarization exhibited by light reflected from the surface of the moon argues for a significant fraction of the particles to be of a size not too far above the limits set by diffraction. Thus it is concluded that the average diameter of the particles comprising the uppermost layer of the lunar surface is of the order of 10 microns. These grains of rock probably have been darkened by exposure to solar corpuscular radiation, so that they are indeed darker now than any common terrestrial rock in powdered form, and have been arranged by micrometeorite bombardment into a loose, porous material with a bulk density of only 10 per cent that of solid rock. The depth of the dust layer is unknown.

Appendix

Properties of Dust in a State of Low Compaction

This appendix summarizes some of the properties of finely divided powders arranged in fairy-castle packing. Although this subject is not properly a part of the present paper, the widespread interest expressed in it justifies the publication of what is known about the low-density form of packing.

As is stated in the body of this paper, two conditions are necessary for the formation of the fairy-castle structures. The weight of the dust grains must be less than the attractive force between two adjacent grains, and the deceleration forces that occur when a grain impacts the surface must be small enough so as not to rupture the intergrain bonds. The first condition implies small grain sizes, of the order of 10^{-9} to 10^{-8} gram. The second requires a low impact velocity, which can be guaranteed either by depositing the surface in an atmosphere, so that the velocity of the particle never exceeds its terminal velocity, or by allowing the particle to fall from a low height in a vacuum. The maximum height for vacuum deposition in a terrestrial laboratory appears to be of the order of 1 mm, but, because of the reduced gravity and extreme cleanliness that obtain on the lunar surface, this height might be of the order of several centimeters on the moon.

The intergrain forces responsible for maintaining the fairy-castle structures are believed to be adhesive forces of the van der Waals type. However, since the grains are certainly charged, it is probable that long-range electrostatic forces act between grains during deposition and strongly influence their trajectories. Once a particle has touched another the short-range adhesive forces dominate and hold the network together.

The fairy-castle structures are surprisingly strong. They do not collapse when the container in which they are sitting is struck sharply. They have been stored for months in the laboratory under varying conditions of temperature and humidity. The structures are stable against evacuation of interstitial air and have been cycled repeatedly between atmospheric pressure and high vacuum with no apparent deterioration. They have also been baked at 750°C in a hydrogen atmosphere and in a vacuum.

Optically thick layers of fine dust easily adhere to surfaces held vertically and even upside down. Thus there is no validity to the objection frequently raised against a coating of dust on the moon that the dust could not cling to steep slopes.

Powder in this low compaction state has bulk densities of the order of 10 to 20 per cent of that of the solid material from which it is made. Relative densities appreciably smaller than this are unlikely because of the need for mutual support of the grains. Rocks pulverized and deposited in air can build up low-density layers greater than 1 cm thick before the bottom portions begin to compact. On the moon the corresponding thickness may be of the order of 60 cm for fresh, clean dust. If transport of fine dust does occur in some fashion on the moon, as *Gold* [1955] has postulated, low-density deposits of considerable thickness are sure to exist in the maria and crater floors, for the lower layers will have compressed only to the extent necessary to support the weight of the overlying dust.

A very porous layer of dust was also produced in a vacuum by the following method. A mixture of finely ground insulating powder and H_2O ice was cooled to low temperatures and immediately placed in an evacuated chamber. Within a few hours the ice sublimed away completely, leaving an underdense block of rock dust arranged in a porous macrostructure. For the most part the material outgassed quietly with no visible disturbance, but occasionally a more compacted portion of the surface was observed to explode like popcorn.

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