Reports

Lunar Surface: Composition Inferred from Optical Properties

Abstract. *The optical characteristics (intensity, polarization, spectrum, and albedo) of the moon surface are compared with those of rock and meteorite powders. The only materials whose optical properties match those of the lunar surface are basic rocks containing lattice iron but little or no free iron, and then only after irradiation of these rocks by a simulated solar wind. Optical properties of chondritic meteorite powders differ from those of the moon in significant respects. The lunar crust is probably not chondritic, but is similar in composition to terrestrial iron-rich basalts. These results are independent of those from the Surveyor V alpha-scattering experiment and, in addition, provide a basis for extrapolating the Surveyor V analysis to other areas of the moon. The Surveyor V experiment has thus confirmed the value of earth-based optical techniques for the study of the structure and composition of the surfaces of other planets.*

Only a limited amount of information is available concerning the chemical composition of the surface of the moon. The moon is commonly assumed to consist of silicate materials, from analogies with the earth and meteorites and from considerations of the abundances of the elements. Within this restriction opinions vary widely. The "classical" theory of lunar composition is that the highlands consist mainly of acidic material, while the maria are basic, in supposed analogy with the continent-ocean basin division of the earth's crust. O'Keefe and Cameron (*1*) have suggested that the maria have the composition of tektites and hence are intermediate or acidic. At the opposite extreme is the theory of Urey (*2*), who has suggested that the moon is a relatively undifferentiated, ultrabasic object with a composition similar to that of the average of chondritic meteorites. According to Urey's hypothesis, the outer layers have large-scale lateral variations in composition corresponding to the different varieties of chondritic meteorites. Specifically, Urey has suggested that the maria consist of carbonaceous chondritic material.

A gamma-ray spectrometer aboard the Soviet lunar orbiter Luna 10 detected a radioactivity level for the moon which is characteristic of basic or ultrabasic materials and which is too low for the lunar crust to be acidic (*3*). However, since over 95 percent of the counting rate was attributable to cosmic ray-induced activity, the Luna 10 results should be accepted with some degree of caution.

After this paper was submitted for publication, the results of the Surveyor V analyzer were released (*4*). The composition of mare material at the landing site was found to be similar to that of terrestrial basalt. While these results are of great scientific and historical interest, the extremely limited area actually analyzed should be kept in mind. One might imagine, for example, an earth probe sent by hypothetical inhabitants of the moon landing at White Sands National Monument, from which the selenite scientists might be led to infer that the crust of the earth consists of hydrous calcium sulfate. However, remote-sensing methods can be used to study the entire visible surface of the moon, and thus, in addition to giving independent data, are able to provide a basis for the extrapolation of this composition to other regions of the moon. Hence, remote-sensing techniques remain of fundamental importance in planetary exploration. I now report briefly on one of these remote methods, the optical, and describe the deductions concerning the chemical composition of the upper layers of the moon, deductions which follow from the optical properties of the lunar surface and from recent laboratory investigations.

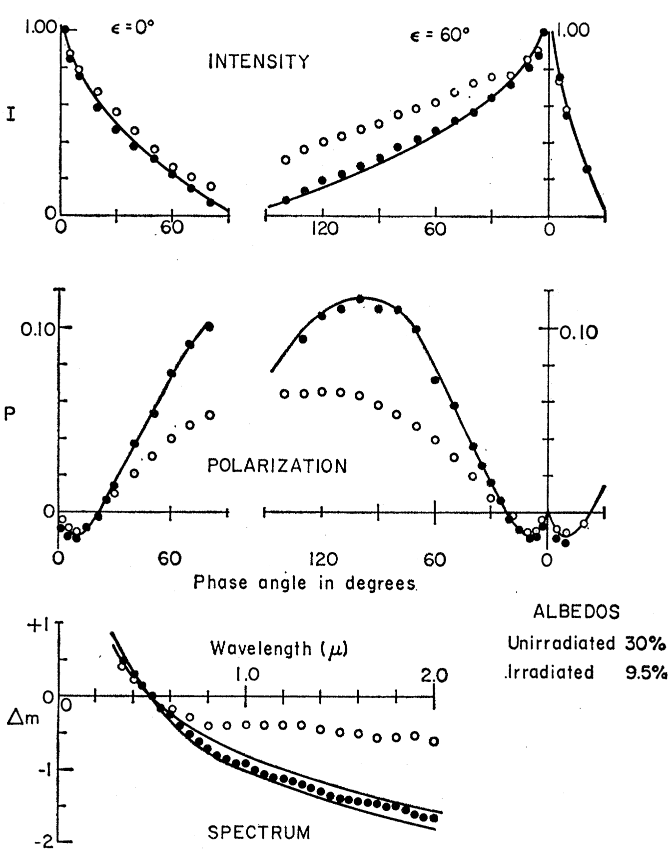
The lunar optical characteristics have four basic features: variation of intensity with phase angle, low albedo, variation of polarization with phase angle, and spectrum. These features are illustrated by the solid lines in Fig. 1 which have been abstracted from the observations of a number of persons (*5, 6*).

The brightness of any area on the lunar surface rises to a sharp maximum when the sun is directly behind the observer, irrespective of the location of the area on the lunar disk; this phenomenon is known as backscatter. The albedo or reflectivity of all areas on the moon is low, varying between about 5 and 18 percent relative to the brightness of a perfectly reflecting, diffusing screen placed at the same distance as the moon. Near full moon the sunlight reflected from the lunar surface is only slightly polarized. The plane of polarization lies in the plane formed by the direction of the incident and reflected rays (the light is then said to be negatively polarized). For all areas, the negative polarization goes through a maximum of about 1 percent at a phase angle around 10°, and the polarization falls to zero at about 23.5°. At larger phase angles the plane of polarization is perpendicular to the incident-reflected ray plane (positive polarization) and goes to a maximum at about 110°. The height of the positive maximum varies from 5 to 18 percent, depending on location, the darker areas generally having the larger polarization. The color of moonlight is distinctly redder than sunlight. The bottom curve of Fig. 1 shows the spectrum of the moon relative to that of the sun on a magnitude difference scale which has been arbitrarily normalized to zero at 5000 Å. Between 3500 Å and 2.2 μ the magnitude difference (Δm) spectrum of the moon decreases monotonically by nearly 2.5 magnitudes, corresponding to an increase in the reflectivity with wavelength by a factor of 10. Only small variations in all of these optical properties occur from region to region.

The Surveyor photographs have shown that the outermost layers of the lunar surface consist of very finely pulverized material, thus confirming the deductions made previously from the moon's thermal (*7*) and optical (*6, 8*) properties. Because of the ubiquity of these optical characteristics, there is little doubt that nearly the entire lunar surface is covered with at least a thin layer of fine powder. Hence it is clear that in attempting to duplicate these optical properties only fine powder need be considered—a fortunate circumstance which considerably limits the range of surfaces to be investigated. Accordingly, the materials which were investigated were prepared as follows. A sample of the material was ground with a diamondite mortar and pestle until all of it passed a 20-μ sieve. The powder was poured onto a frosted-glass microscope slide, and its surface was made rough by raking with the point of a needle. The intensity and polarization were then measured with a photometric apparatus for angles of observation of 0° and 60° from the normal and at frequent angles of incidence down to 80° on either side of normal. The light source was an incandescent lamp, and the detector an EMI 9592B photomultiplier tube. The spectrum of the material was obtained relative to an MgO-smoke standard; a Carey Model 14 spectrophotometer with an integrating sphere attachment was used. The powder was then irradiated by a beam of 2.0 kev hydrogen ions at a current density of about 0.5 ma/cm^2, to a dose of 40 coul/cm^2 (*9*) in order to simulate the effects of the solar wind hitting the lunar surface (*10*). The optical properties were then measured again.

The following materials (*11*) were investigated as described: Approximately 30 igneous rocks, including acidic, intermediate, basic, and ultrabasic rocks; approximately 20 igneous rock-forming minerals; eight chondrites, two achondrites, and three tektites. Briefly, the results can be summarized as follows. No unirradiated powder matched the result from the moon in all significant aspects. The open circles of Fig. 1, which give the optical data for olivine basalt powder, are quite typical of the properties of all the powders except the chondrites. The albedos of the rock powders are too high, typically of the order of 30 to 50 percent; their intensities are too high at large phase angles; their positive polarization peaks are too low, of the order of 3 to 6 percent; and their spectra are too flat in the infrared. The unirradiated chondrites had a large enough polarization, but still failed in having spectra whose Δm did not decrease with wavelength as rapidly as the moon's and in being too bright at large phase angles. The optical data for Colby, a typical olivine-hypersthene chondrite, are given in Fig. 2.

For all the powders, the proton irradiation caused a decrease in albedo, an increase in polarization, sharpening of the backscatter peak, and reddening of the spectrum; that is, the bombardment caused the optical properties of the powder to become similar to those of the moon surface (*9, 12*). However, after proton irradiation the properties of chondrites again failed to match those of the moon surface. Their albedos were now too low; both the positive and negative branches of their polarization curves were too large; and their Δm values did not decrease sufficiently rapidly in the infrared. Of



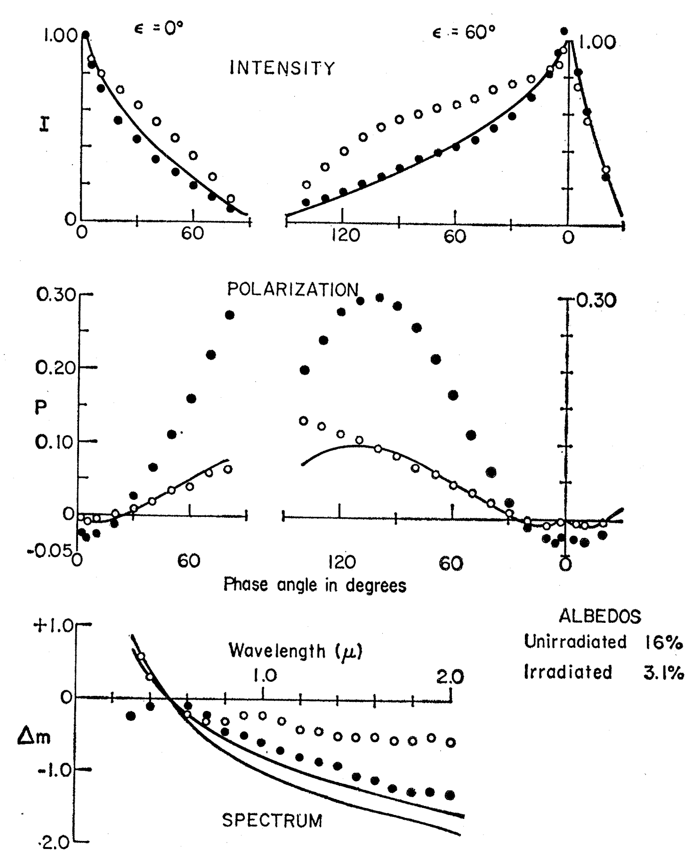


Fig. 1 (left). Optical properties of olivine basalt powder and the moon. (Top) Intensity plotted against phase angle for two angles of observation ϵ; (center) polarization plotted against phase angle; (bottom) reflection spectra (in magnitudes, normalized to $m = 0$ at 0.50 μ). Open circles, unirradiated; filled circles, irradiated; solid line, moon. Fig. 2 (right). Optical properties of chondritic meteorite powder (Colby, an olivine-hypersthene chondrite). Labeling of curves as in Fig. 1.

Table 1. Optical characteristics of selected powders. U, unirradiated; I, irradiated; A, normal albedo at 0.55 μ relative to MgO; P_-, maximum of the negative part of the polarization curve; P_+, maximum of the positive part of the polarization curve; U − G, difference (in magnitudes) between the reflectivities at 0.37 and 0.5 μ; I − G, difference (in magnitudes) between the reflectivities at 2.00 and 0.50 μ.

Material	Treatment	A (%)	P_- (%)	P_+ (%)	U − G (m)	I − G (m)
Murray	U	6.9	2.1	31	+0.35	−0.88
Murray	I	2.6	2.7	48	−0.12	−1.00
Holbrook	U	17.2	0.7	9	+0.20	−0.60
Holbrook	I	4.1	2.1	27	−0.22	−1.77
Colby	U	17.1	0.8	11	+0.48	−0.57
Colby	I	3.1	2.8	30	−0.52	−1.30
Bruderheim	U	15.9	0.9	12	+0.22	−0.50
Bruderheim	I	5.2	2.2	31	−0.18	+1.88
Plainview	U	14.1	1.0	8	+0.50	−0.60
Plainview	I	3.5	3.1	34	−0.16	−1.75
Bonita Springs	U	12.0	1.0	13	+0.53	−0.86
Bonita Springs	I	3.3	3.7	38	−0.08	−1.55
Forest City	U	15.8	0.8	9	+0.48	−0.72
Forest City	I	4.1	2.1	25	−0.14	−1.64
Indarch	U	7.8	1.1	19	+0.16	−0.76
Indarch	I	3.1	5.3	37	−0.12	−0.98
Basalt	I	9.6	0.9	13	+0.50	−1.68
Basalt +5% (Fe/FeS)	I	6.7	1.5	20	+0.13	−1.70
Basalt +15% (Fe/FeS)	I	4.2	3.0	33	−0.08	−1.45
Moon		5–18	0.9–1.3	5–17	+0.45–+0.85	−1.70*

* Range of I − G not well established for moon in view of paucity of measurements.

special interest, is the pronounced peak at 5000 Å in Δm of Colby (Fig. 2). This peak was found in the spectra of all the irradiated chondrite powders, but it is completely lacking in the lunar spectra (Table 1).

The irradiated igneous rock powders provide a closer match to the moon surface than the chondrites do. Since an important difference in composition between igneous rocks and chondrites is the presence of metallic iron and FeS in the latter (averaging 15 percent Fe/Ni and 6 percent FeS by weight), it was suspected that the metallic iron might be the cause of the differences between the chondrites and the rocks (and, by inference, the moon surface). Consequently, varying amounts of 10-μ carbonyl-iron powder were added to 400f olivine basalt powder, and the mixture was irradiated. The supposition was found to be correct. Adding as small an amount as 5 percent (by weight) of metallic Fe to the rock powder caused the albedo to decrease, the positive and negative polarization peaks to increase, and the ultraviolet Δm spectrum to decrease with decreasing wavelength below 5000 Å instead of increasing (Table 1).

After irradiation, the optical properties of other powders were more like those of the moon than the chondrites were. Several varieties of powdered rock matched the lunar optical properties exactly within experimental and observational error. Typical of these irradiated powders is olivine basalt (Fig. 1, solid circles). Those materials possessing an acceptable fit included several types of basalts, a dunite, an achondrite (Sioux County), and the tektites. However, none of the granitic powders matched the moon in detail. The chief discrepancies were higher albedos, typically around 20 percent, and greater (by a factor of 2 or more) reflected intensities at large phase angles. In addition, several of the intermediate, basaltic, and ultrabasaltic rocks, and also the other achrondrite (Norton County), departed from the lunar optical properties in a manner similar to the granites.

A possible explanation for the varying behavior of the basic powders appeared during the investigation of proton-irradiated, rock-forming minerals. As expected, the acidic minerals, such as quartz and orthoclase, did not show optical properties like those of the moon. Iron-bearing minerals such as hypersthene and hedenbergite had optical properties which were similar to those of the moon. However, iron-free minerals such as enstatite and diopside, in which all of the Fe is replaced by Mg were different. Similarly, Norton County meteorite, which is an enstatite achondrite and contains virtually no iron, did not match the moon, but Sioux County meteorite, which is an eucrite and is rich in lattice iron, did duplicate the moon. Tektites are usually considered to be of acidic or intermediate material; however, they are somewhat lower in aluminum and alkali oxides and richer in iron oxide than granites, and, in optical properties, they are like the moon.

Because of the complex composition of rocks, and because elemental analyses are not available for many of the rocks investigated, it is not yet possible to exclude other elements as having an important influence on the optical properties of a rock powder. However, the above results indicate that two important factors in determining whether the optical characteristics of an irradiated powder duplicate those of the moon is the presence of lattice iron and the absence of free iron.

If the majority of the lunar craters are interpreted as impact features, then the lunar surface has been well stirred by meteorite impacts to depths which probably exceed several meters in the maria and a kilometer in the highlands. Thus the composition of the uppermost layer, which is investigated by optical methods, is probably representative of the composition to a considerable depth in the lunar crust. The optical investigations described in this report indicate that the lunar surface contains little or no free iron. Hence, Urey's hypothesis (*2*) is not substantiated. This result also implies that the lunar crust is not the source of chondritic meteorites. If the moon is chondritic in composition, sufficient differentiation has occurred to remove the free iron from the surface regions. However, any differentiation appears not to have proceeded far enough to allow large areas of the surface to have a granitic composition, although this investigation cannot exclude tektites as being of lunar origin (see *3*). The terrestrial materials whose optical properties duplicate in detail those of the moon are intermediate, basic, and ultrabasic rocks containing appreciable quantities of iron in their lattices. It may be inferred that minerals similar to hypersthene, hedenbergite, and fayalite are abundant on the lunar surface. Thus my study does not confirm the suggestion of Kopal and Rackham (*13*) that large areas of the moon have a composition similar to enstatite achondrites.

A possible reason for the difference in optical characteristics of the lunar highlands and those of the maria (suggested by this investigation) is that the maria have somewhat more iron, since increasing the iron abundance decreases the albedo and makes the material bluer. The appearance of the moon suggests that the highland areas of the moon may be less differentiated than the maria, which are probably lava flows.

A higher iron content for the maria is consistent with this observation, since terrestrial experiments (*14*) have demonstrated that a basaltic melt differentiating under reducing conditions has a higher ratio of FeO to MgO than the parent material. Thus the highlands may be closer in composition to primordial lunar crustal material than the maria, which is the opposite of the situation on the earth. The lower iron content of the highlands is also consistent with the suggestion by Duke (*15*) that the maria have the composition of eucrite achondrites and the highlands of howardite achondrites, since the latter have somewhat lower iron abundances than the former.

Results from the Surveyor V α-scattering experiment have now become available (*4*) and indicate that the composition of the lunar surface near the southwestern edge of mare Tranquillitatis is similar to that of terrestrial basalts and also to basaltic achondrites. The resolution of the instrument was not sufficient to distinguish elements with atomic numbers between that of phosphorus and copper. My results suggest that iron is a major constituent of this group and that the mare material resembles terrestrial ferrobasalts. The optical properties of the moon imply that the composition determined by Surveyor V is representative of all the maria and, to a rough approximation, of the entire lunar surface.

Surveyor V also carried a magnet attached to one of its footpads. Some soil collected on the magnet, indicating the presence of a ferromagnetic mineral in the soil. From the amount of material clinging to the magnet the investigators estimated that there was less than 1 percent metallic Fe in the soil, a conclusion in agreement with my data (*4*).

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10. D. Nash [*J. Geophys. Res.* **72,** 3089 (1967)] has published studies indicating that some of the darkening (observed by me and others) induced by proton irradiation may have been due to contamination. However, among the evidence which may be adduced to indicate that the darkening effect is real and may be expected on the lunar surface are the following. (i) The amount of darkening is strongly dependent on the composition of the target material; some substances (pure Al_2O_3) actually lighten under bombardment rather than darken. (ii) Contaminants (such as hydrocarbon and pump-oil vapor) purposely introduced into the system during irradiation cause the target material to have optical properties that are quantitatively different from those of uncontaminated, irradiated material. (iii) Except for certain irradiated powders, no material which duplicates all the significant lunar optical properties has yet been discovered.
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Stone Meteorites: Time of Fall and Origin

Abstract. *The fact that twice as many chondritic meteorites are observed falling in the afternoon as in the morning is not believed to be primarily of social origin, but to be a dynamic effect. Monte Carlo calculations show that the observed afternoon excess is not compatible with a lunar or Apollo asteroidal origin. Compatibility appears to require a source having an aphelion near Jupiter, such as could be provided conceivably by the Hilda or Trojan families of asteroids, or by short-period comets.*

It has long been known that considerably more chondritic meteorites are observed falling in the afternoon and evening hours than in the morning (Fig. 1A). Although the statistical significance of the data is much poorer, this fact does not seem to be true for the achondrites as a whole (Fig. 1B). It is certain that the principal reason for the rarity of early-morning falls is that there are then fewer observers; to a lesser extent this is also true of evening falls. This social bias probably is not very effective during daylight hours; most falls of meteorites have been observed by farmers working in the fields, and should have been observed essentially equally well during the morning or afternoon. Nevertheless, even if the hours between 1800 and midnight and between midnight and 0600 hours are excluded, the proportion of daylight falls occurring in the afternoon is still .66; that is, there are nearly two afternoon falls for every morning fall. If the true probabilities of morning and afternoon falls were equal, the probability of this proportion occurring by chance is less than 10^{-4}. If the true proportion is .62 or .70, the probability of statistical fluctuations causing an observed proportion differing by as much as .04 is about 5 percent. Therefore the statistical uncertainty in the proportion may be taken to be $\pm$ .04. The corresponding proportion in the achondritic data is .50 $\pm$ .14.

It is commonly stated that this preponderance of afternoon falls for chondrites shows that the majority move in direct rather than retrograde orbits about Sun. While true, this is a considerable understatement of the implications of the data. Wood (*1*) showed that the observed time-of-fall