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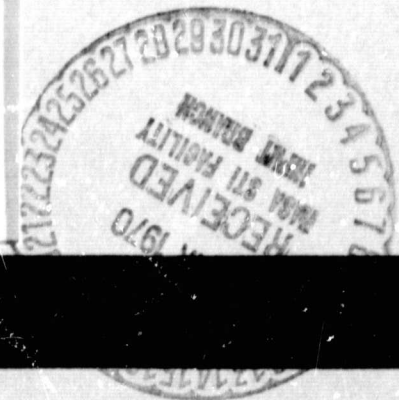
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ITHACA, N. Y.

**N70-20838**

(ACCESSION NUMBER)

20

(PAGES)

CR-108282

(NASA CR OR TMX OR AD NUMBER)

(THRU)

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(CODE)

30

(CATEGORY)

CENTER FOR RADIOPHYSICS AND SPACE RESEARCH
CORNELL UNIVERSITY
ITHACA, NEW YORK

January 1970

NAS9-8018

CRSR 364

MOON: OPTICAL PROPERTIES OF APOLLO 11 SAMPLES

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Submitted to SCIENCE.

ABSTRACT

Lunar powder samples returned by Apollo 11 are remarkably similar in their optical properties to those measured for a several km^2 area surrounding Tranquillity Base, suggesting a ubiquitous covering of the same material in the region. However, there are minor exceptions to the close match: the powder sample shows larger polarizations and a larger opposition effect than would be expected from previous observations. In the spectrum of the lunar rock samples, we detected a strong, broad absorption near 1μ and a weaker band $\gtrsim 1.8\mu$ which may be due to orthopyroxenes in the presence of other iron-bearing silicates. The 1μ band was absent in the powder sample (presumably because the particle sizes were too small), which suggests that the spectrophotometer may become a valuable tool in distinguishing between rocky and dusty areas on the Moon.

In recent years there has been considerable interest in extracting meaning from optical measurements of the Moon and planets. Several investigators have suggested that the spectrum, albedo, color, photometric phase function and polarimetric phase function can collectively yield diagnostic information about composition, particle size and their variation over the lunar or planetary disc. Most of these studies are performed by measuring the optical properties of terrestrial mineral samples until a reasonable match is found with Earth-based observations of the planet in question. For example, Hapke (1) has suggested a close match between the Moon and basalts irradiated by a simulated solar wind. Moreover, the presence of a weak absorption band near 1 micron in the lunar spectrum has been suggested (2); this band may originate from olivine or iron- and calcium-bearing clinopyroxene as major constituents on the Moon (3).

With the return of lunar samples from Tranquillity Base, it has become possible to study the optical properties of a piece of the Moon itself with the same thoroughness as a terrestrial sample. Such studies should add a new important dimension in the attempts at identifying the composition and particle sizes and their variations over the lunar surface. The purpose of this report is to present in detail the optical properties of some of the Tranquillity Base

samples and how these properties compare with the Moon as a whole (4).

For the photometric and polarimetric work, we used a photometer-polarimeter which has been described earlier (5), but with some minor modifications. The sample was illuminated by an incandescent lamp which can be moved along a ring at any desired angle of incidence, i . The detector was an EMI 9698QB phototube, and it was set at two angles of viewing, $\epsilon = 0^\circ$ (normal) and $\epsilon = 60^\circ$. We define the phase angle as that angle between the light source and detector formed at the sample. The detector aperture was reduced to a half cone angle of $\lesssim 1/2^\circ$ in order to improve resolution for nonlinear effects in the phase function (6). We made all measurements with one of three broad-band color filters; the effective wavelengths of the filter-phototube-light source combinations were 0.44μ , 0.56μ , and 0.65μ . To obtain the polarizations we measured the components of intensity orthogonal to and within the plane of vision by rotating a polaroid filter.

Reflectivity values were derived by measuring a freshly deposited smoked magnesium surface (MgO) at various intervals during the experiment. We assumed that unity reflectivity could be obtained from measuring MgO at $i = 10^\circ$ and $\epsilon = 0^\circ$ from past experience with the reflective properties of MgO (6). All values were corrected for a projection

factor, $\cos i$, in view of the fact that the light spot was larger than the area seen by the phototube.

We used a Cary 14 spectrophotometer with an integrating sphere coated with MgO to obtain the diffuse reflectance of the lunar samples as a function of wavelength (from 0.25 to 1.8μ).

Fine-grained material from the bulk sample (hereafter called powder) and rock chips were studied. All measurements of various powder samples repeated very well, with uncertainties of $\sim 0.2\%$ in reflectivity in both the photometric and spectrophotometric measurements, and $\sim 0.1\%$ in polarization. These dispersions are somewhat greater at larger phase angles and at infrared wavelengths in the spectrophotometry. The limiting factor for the lunar powder was the low signal-to-noise resulting from its low albedo rather than intrinsic variations from one part of the sample to another. On the other hand, intrinsic variations in the albedoes and phase functions of the rock samples were considerably larger, and resultant uncertainties large. In the spectrophotometry of the rock chips, it was necessary to measure two samples together (samples 10017.26 and 10017.28) because of their small size with respect to the slit length. Measurements taken over various portions of the two, rocks repeated very well.

Figure 1 shows the dependence of reflectivity on phase angle of the Apollo 11 samples at 0.56μ wavelength and at viewing angles $\epsilon = 0^\circ$ and 60° . For comparison, the solid lines indicate mean lunar values adopted by Hapke (1), and normalized in reflectivity to a normal albedo of 0.0996, as determined for the Apollo 11 site at the same wavelength by Apollo photography and Earth-based observations (7). It is immediately apparent that the normal albedo of our powder sample, estimated to be $0.102 \pm .002$ at 0.56μ , is very close to that derived for a several km^2 area of uniform albedo in the region of Tranquillity Base (7). This suggests that the finely divided material returned by the Apollo 11 astronauts is typical of material ubiquitously covering an area extending several kilometers from the landing site. Table 1 lists the normal albedoes of the returned lunar powder for the three colors.

We next consider the photometric function of the powder sample. At normal viewing ($\epsilon = 0^\circ$), there is a close match with mean lunar values and it is again tempting to conclude that the powder sample is typical of large regions — particularly the maria — over the lunar surface. However, Wildey and Pohn (7) pointed out major differences between the opposition effects of the Tranquillity Base area and other lunar regions: they reported a brightness increase of only 7% between phase angles of 1.5° and 0° ,

as compared to a value of 19% for other regions measured from Apollo orbiter photography (8). Our measurements on the Apollo 11 powder show the increase to be $12 \pm 1\%$, intermediate between the Tranquillity Base region and the Moon as a whole. Thus, our measurements provide some evidence that the photometric properties of the returned powder do not match precisely those averaged over the surrounding Moonscape. As more lunar samples are returned from more sites, it will be interesting to search for correlations between opposition effects and microstructure (e.g., particle size distribution, appearance through a microscope, etc.). Such comparisons should provide a definitive test of the hypothesis that the pronounced lunar opposition effect is due to shadowing within an intricate structure of fibers ("fairy castles") in the powder (9).

At a viewing angle of 60° and at phase angles greater than $\sim 15^\circ$, the phase function of the Apollo 11 lunar powder is more gradual than that observed for the Moon as a whole (Fig. 1). However, the comparison is difficult to interpret, since no observations have been made of Mare Tranquillitatis inclined 60° to the observed and the normalization of the Moon curve is arbitrary.

The rock chip sample in Figure 1 exhibits an appreciably higher albedo, and the phase functions tend to be erratic because of the various facets which come into and

out of view. Moreover, there are major differences between the rocks themselves (only one result is shown here), so it is difficult to draw conclusions about the photometric behavior of "typical" lunar rocks, unlike the case of the powder samples.

Figure 2 shows the photometric functions of the powder sample in three colors, where the normal albedoes in Table 1 are determined by slight extrapolation of the curves for $\epsilon = 0^\circ$. Also plotted on Fig. 2 is the color index $B-V = -2.5 \log(I_{0.44\mu}/I_{0.56\mu})$ for the powder sample at $\epsilon = 0^\circ$, where I represents the observed reflectivity at a given color and phase angle. Also plotted are $B-V$ values of Earth-based observations of Mare Tranquillitatis by Gehrels, Coffeen and Owings (8) and corrected for a solar $B-V$ of 0.63. The effective wavelengths of the photometric systems at the telescope and in the laboratory were close enough to make reasonable comparisons.

It is apparent that the color of the powder sample is very similar to that of Mare Tranquillitatis as observed from the Earth. In both cases, the soil is essentially gray with only a slight reddening at larger phase angles. However, an interesting effect occurs in the Apollo 11 sample: the powder also reddens toward zero phase, i.e. the opposition effect is greater in the red than in the blue. Although both reddening effects appear subtle as

seen through a photometer, it is more obvious to the eye and color film. For example, the Apollo 12 astronauts remarked that the lunar surface was gray during their first EVA and brown during their second EVA, when the incidence angle of sunlight became very large. Moreover, Apollo photography suggests a browner surface at zero phase than at a few degrees away.

The polarization-phase angle relation at 0.56μ (Fig. 3) shows a good match between the powder sample and the mean lunar curve at phase angles $\leq 40^\circ$. However, for larger phase angles, the sample exhibits much greater polarizations, approaching a maximum value of 23%. The apparent discrepancy is partially resolved when the results are compared with Earth-based observations of the lunar maria (10), where the maximum polarization is typically 15-17%. The Apollo 11 sample therefore exhibits slightly greater polarization than any values previously obtained of the Moon. To our knowledge, there exist no Earth-based or orbiter-based observations of polarization of the Tranquillity Base region, so it is presently impossible to determine whether our sample or the region is anomalous in polarization. The rock sample also shows large polarizations, but the negative branch was considerably smaller than either the powder sample or the Moon as a whole. This latter property is not surprising, since it is well known that the negative branch

becomes smaller for coarser and/or higher albedo material (11).

Figure 4 shows the polarization of the powder sample in 3 colors. The polarizations in the blue are generally larger than those at longer wavelengths; (at 90° phase angle) the value is typically 6 per cent polarization higher at 0.44μ than at 0.56μ . This is an excellent quantitative agreement with recent Earth-based observations (12) of the lunar maria (the lunar highlands show much smaller differences). The greater polarizations of the lunar maria in the blue has been interpreted as a decrease in translucency of the particles with decreasing wavelength (12).

We finally turn to the spectrophotometry of the samples (Fig. 5). The mean lunar curve shows the albedo increasing steadily toward longer wavelengths. The spectrum is essentially featureless, except for a suggestion of a shallow, very broad feature near 1μ (2). The powder sample behaves similarly, except that the 1μ feature is absent and there is a slight hint of an absorption $\geq 1.8\mu$.

The most provocative result is the presence of a strong band centered between 0.90 and 0.95μ in the rock sample, and another band $\geq 1.8\mu$. Adams (3) found that orthopyroxenes have a strong minimum at 0.90μ (due to Fe^{2+} in sixfold coordination) and one at 1.8 to 1.9μ (probably

caused by Fe^{2+} in a highly distorted octahedral state). On the other hand, basalts bearing olivine or clinopyroxene show a minimum between 1.00 and 1.05 μ and no feature at 1.8 μ . Adams stated, "If the lunar minimum is nearer 0.95 than 1.0 μ , the presence is indicated of some orthopyroxene in addition to olivine or clinopyroxene, or both." The preliminary modal analysis of the Apollo 11 rocks indicates a high concentration of clinopyroxene, $\sim 50\%$ (13). We suggest that samples 10017.26 and 10017.28 may also contain orthopyroxene.

The fact that the 1 micron band was absent in the powder but present in the rocks can be easily explained by the dominance of small particles ($\leq 10\mu$) in the powder (3,4). The strong 1- μ band in the rock raises some interesting questions: Is the soil covering Tranquillity Base — and perhaps covering most of the lunar surface — composed primarily of iron-bearing silicates, such as clinopyroxenes and orthopyroxenes? Do these minerals give rise to the alleged 1- μ band observed from Earth? Does the 1- μ band appear in all lunar rocks? If so, a spectrophotometer may become a valuable tool for distinguishing between rocky and dusty areas on the Moon. Perhaps the weak 1- μ feature suggested from Earth-based observations can be attributed to rocks (or large particles) covering small fractional areas of the lunar surface. These questions await further analysis of the returned Apollo samples (14).

TABLE 1: Normal Albedoes of the
lunar powder sample from Apollo 11.

	Blue	Green	Red
Filter Wavelength (μ)	0.44	0.56	0.65
Normal Albedo ($\pm .002$)	0.083	0.102	0.115

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14. This research was supported by the National Aeronautics and Space Administration under grant NAS9-8018.

FIGURE CAPTIONS

- Fig. 1. The reflectivity of Apollo 11 lunar samples versus phase angle at 0.56μ wavelength and viewing angles $\epsilon = 0^\circ$ and 60° .
- Fig. 2. The reflectivity of the Apollo 11 powder sample versus phase angle at 3 wavelengths and viewing angles $\epsilon = 0^\circ$ and 60° . (Top) Color index B-V of the powder sample versus phase angle at $\epsilon = 0^\circ$. Also plotted are B-V values derived from Earth-based observations by Gehrels et al (1964) (see text).
- Fig. 3. The polarization of Apollo 11 lunar samples versus phase angle at 0.56μ wavelength and viewing angles $\epsilon = 0^\circ$ and 60° .
- Fig. 4. The polarization of the Apollo 11 lunar sample versus phase angle at 3 wavelengths and viewing angles $\epsilon = 0^\circ$ and 60° .
- Fig. 5. Diffuse reflectance versus wavelength of the Apollo 11 lunar samples as obtained by a Cary 14 spectrophotometer. The Moon curve is derived from Earth-based observations by Wattson and Danielson (2) of Mare Tranquillitatis, and normalized arbitrarily in diffuse reflectance.

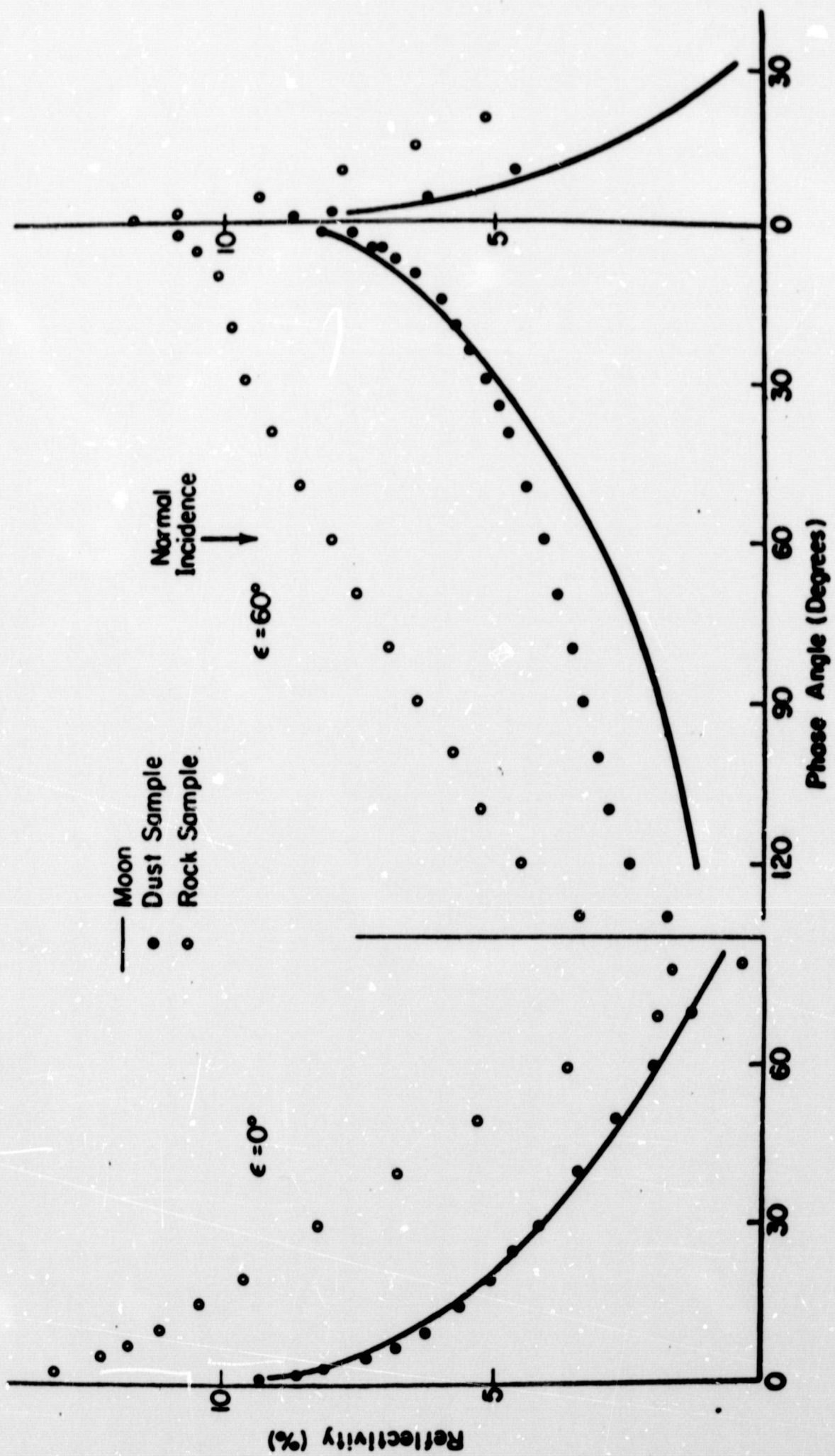


Figure 1.

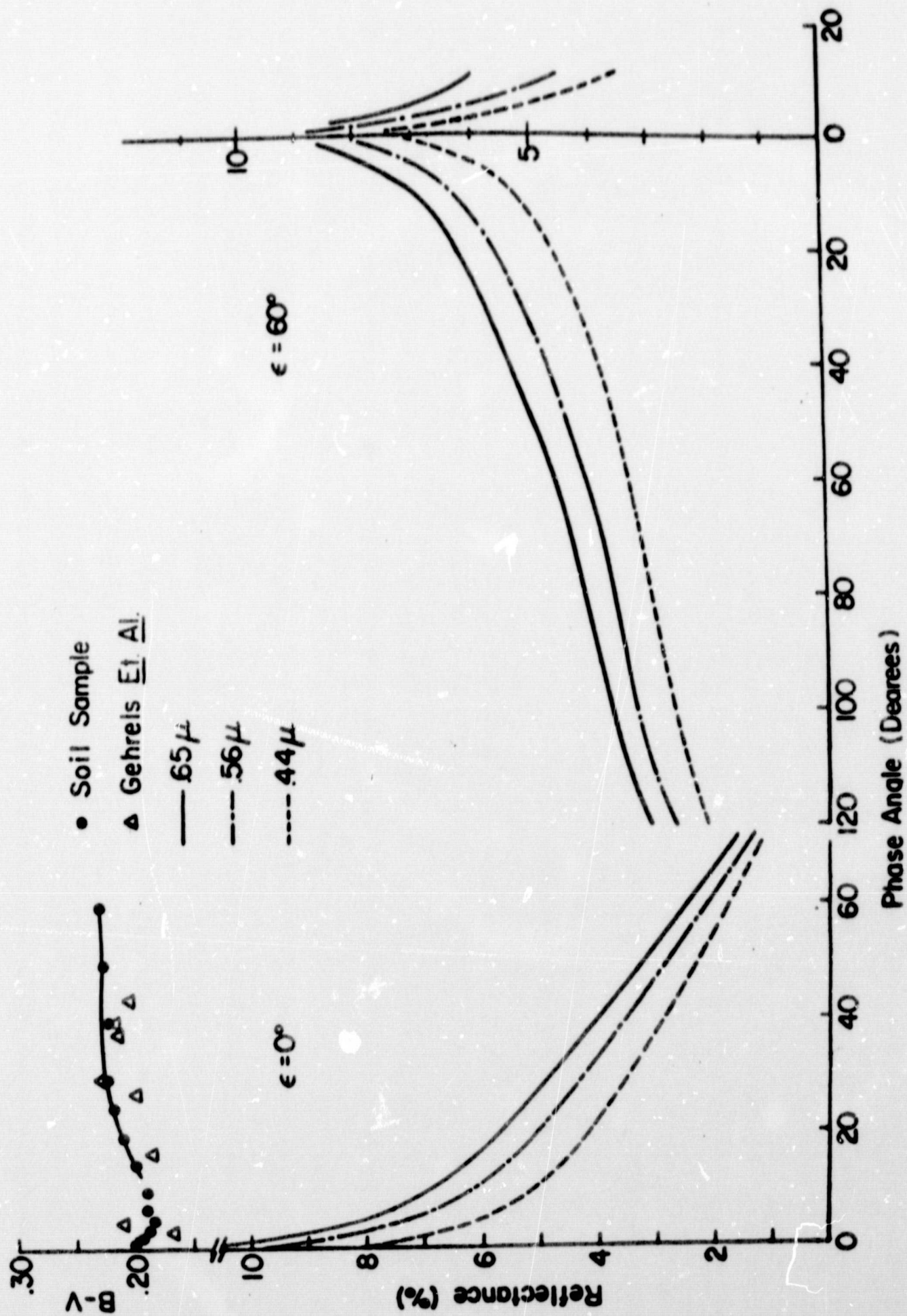


Figure 2.

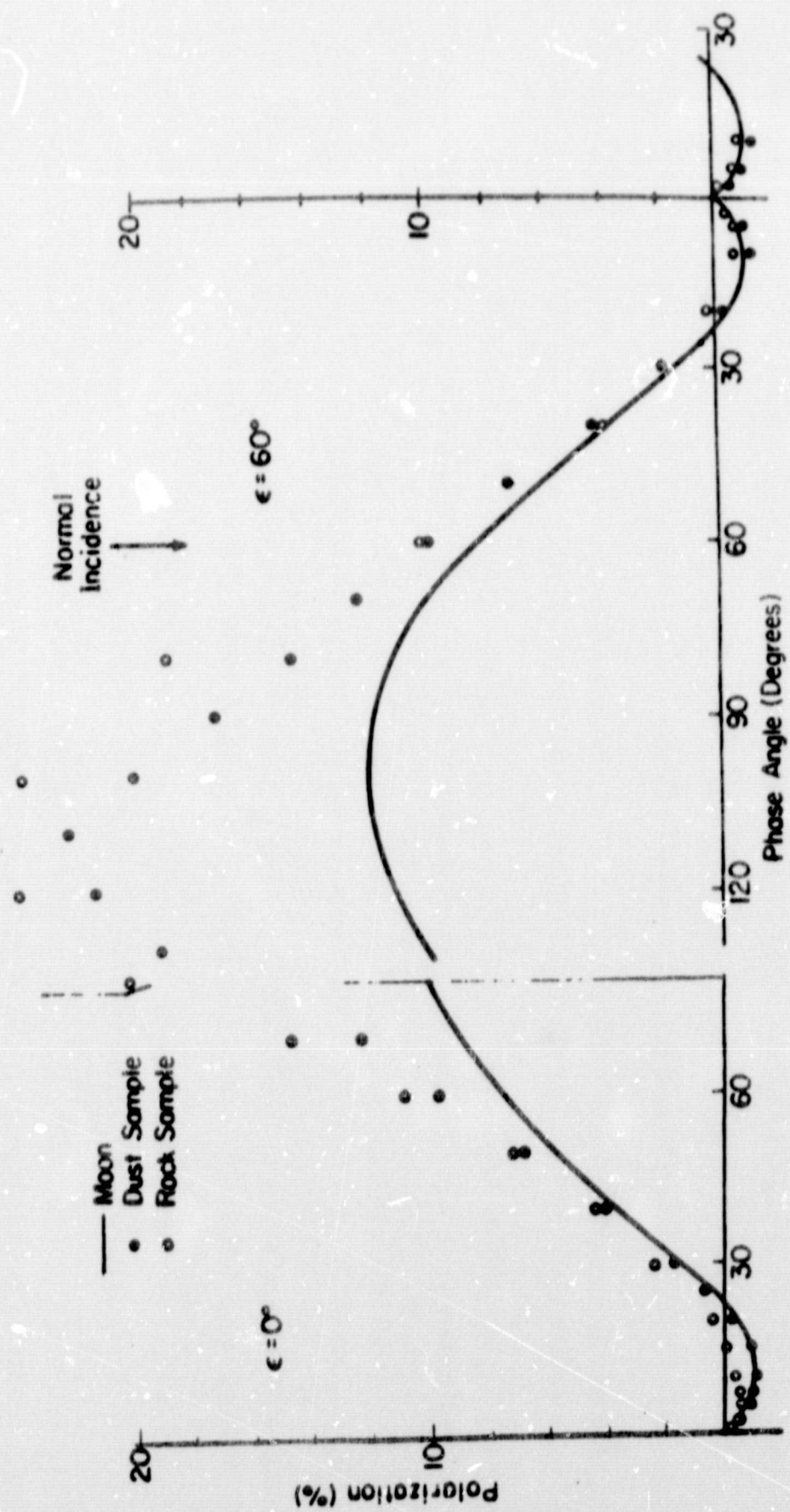


Figure 3.

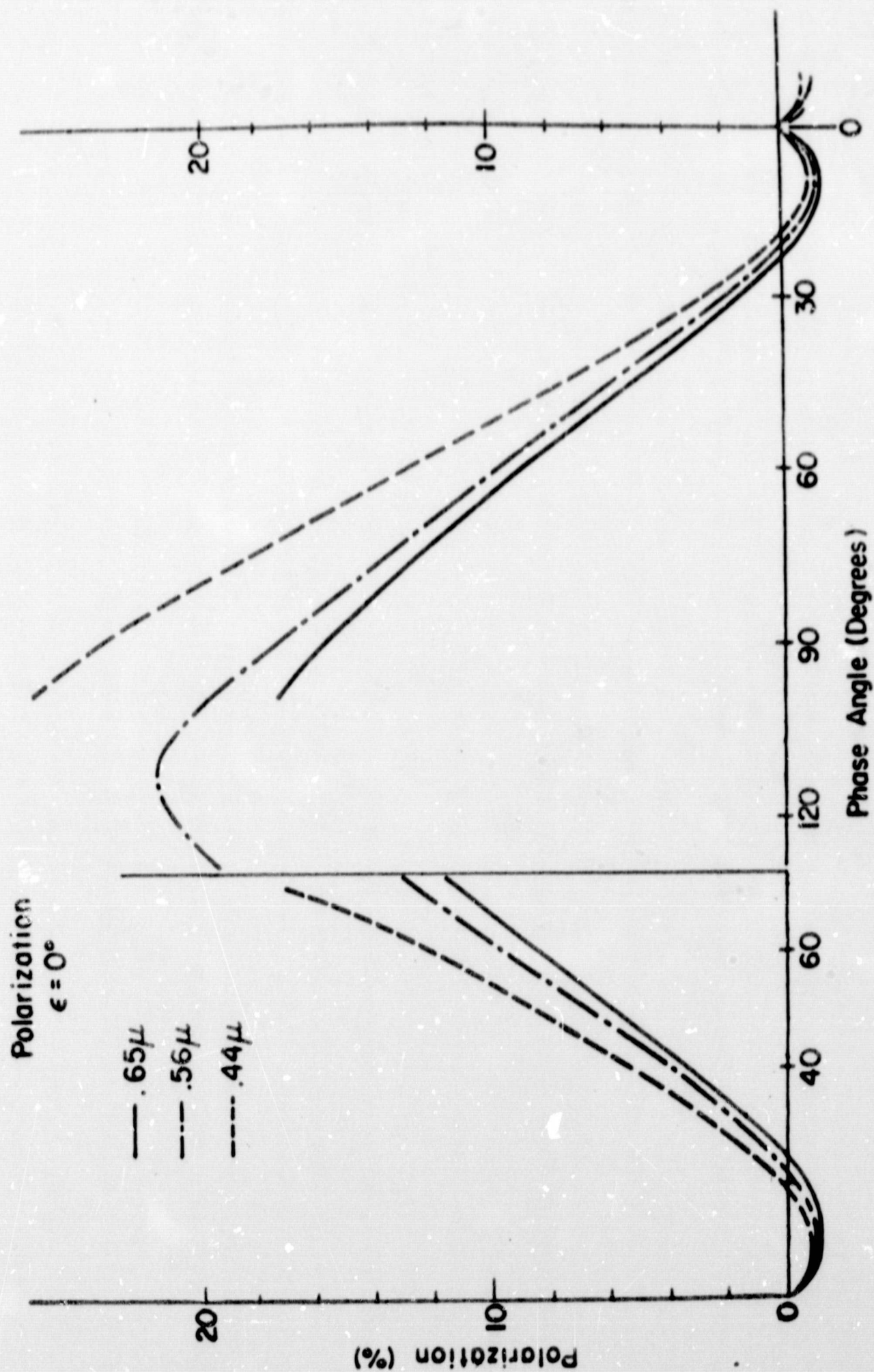


Figure 4.

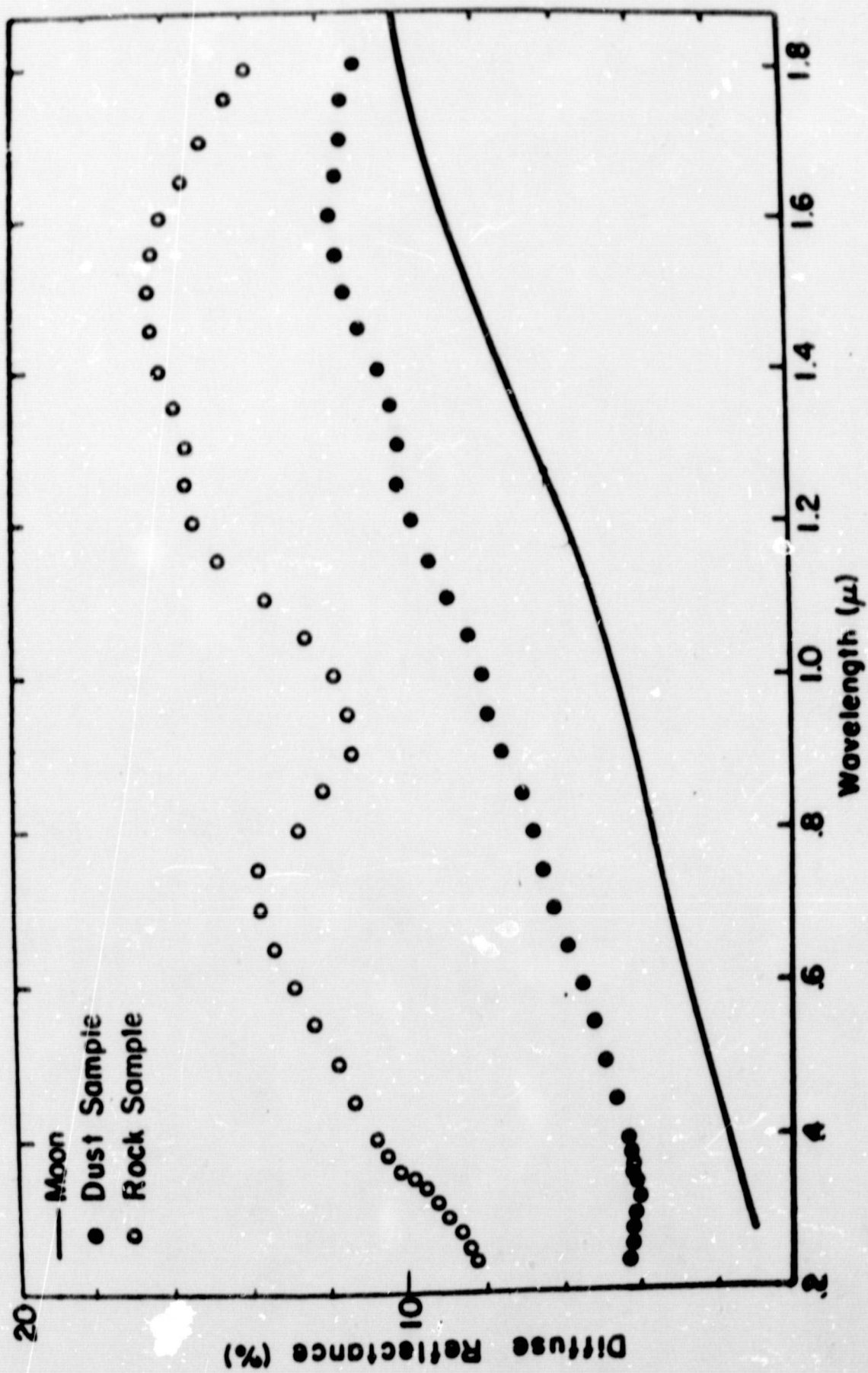


Figure 5.