The cause of experimental proton irradiation darkening is not understood, but contamination is suspected to play a role (*12*). We are thus cautious in asserting that proton irradiation produces significant lunar darkening. Alternatively, vitrification may be an important darkening process. Except in the ultraviolet, neither the experimental irradiation dose nor the artificial vitrification alone produces material with the reflectance properties of lunar soil.

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References and Notes

1. Lunar Receiving Laboratory rocks numbered 10058 (medium-grained igneous), 10020 (fine-grained igneous), 10057 (fine-grained vesicular), 10059 (microbreccia), and fines < 1.0 mm. All samples were received packaged in N_2, rock samples as 1- to 1.5-g chips from top exterior, bottom exterior, and interior of each rock.
2. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
3. Energy efficiency is defined as the ratio of integral luminescence energy to applied proton energy. Thermoluminescence storage efficiency is defined here as the ratio of total thermoluminescence energy observed to total applied x-ray, ultraviolet, or proton energy prior to trap saturation.
4. D. B. Nash, *J. Geophys. Res.* **71**, 2517 (1966); J. E. Geake and G. Walker, *Geochim. Cosmochim. Acta* **30**, 929 (1966).
5. D. B. Nash, *ibid.*; D. B. Nash, in *Thermoluminescence of Geological Materials*, D. J. McDougall, Ed. (Academic Press, New York, 1968), p. 587.
6. Glass was fused in dry nitrogen using a platinum vessel after slow heating to drive off adsorbed atmospheric constituents.
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9. Thermoluminescence was measured using an RCA 6199 photomultiplier and a heating rate of 80°C min^{-1}.
10. K. H. Sun and J. L. Gonzalez, *Nature* **212**, 23 (1966); M. Sidran, *J. Geophys. Res.* **73**, 5195 (1968).
11. Hemispherical spectral reflectance was measured with a Beckman DK-2A spectroreflectometer modified to accept horizontal, uncovered samples. Albedo, defined here as the bidirectional integral reflectance (0.4 to 0.7 μm) measured with vertical illumination and phase angle of 15°, was determined with a goniophotometer. All measurements were made relative to fresh smoked MgO.
12. D. B. Nash, *J. Geophys. Res.* **72**, 3089 (1967).
13. We thank Clay Seaman, Warren Rachwitz, Fraser Fanale, Elsa Abbott, Edgar Bollin, and Charles Fisher for their assistance. This research under NASA contract NAS 7-100.

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Thermal Radiation Properties and Thermal Conductivity of Lunar Material

Abstract. *The thermal radiation properties were measured for lunar fines and chips from three different lunar rocks. Measurements for the fines were made at atmospheric pressure and at a pressure of 10^{-5} torr or lower. The directional reflectance was obtained over a wavelength range of 0.5 to 2.0 microns for angles of incidence up to 60 degrees. The bidirectional reflectance—the distribution of reflected light—was measured for white light angles of illumination up to 60 degrees. The thermal conductivity was measured over a temperature range 200 to 400°K under vacuum conditions.*

Directional reflectances of Apollo 11 lunar fines and rock chips are presented for white light and for wavelengths from 0.5 to 2.0 μm. The measurements include the directional reflectance (*1*), $\rho(\psi)$, and the normalized bidirectional reflectance (*2*), $\rho_b(\psi, \theta)$. The directional reflectance subtracted from unity gives the absorptance as a function of angle of illumination; the bidirectional reflectance indicates the distribution of reflected light as a function of angles of illumination and viewing. Both quantities are needed for calculations of thermal energy balance.

Table 1. Total directional reflectance of Apollo 11 material. The source was a 1000 watt DXW tungsten-iodine lamp.

Angle of viewing ψ	Sample				
	No. 10084,68,1		10057,29,1	10047,68,2	10048,21,1
	Vacuum run	Atmospheric run			
10°	0.102	0.098	0.137	0.118	0.162
20°	0.101	0.096	0.163	0.126	0.166
30°	0.117	0.103	0.145	0.124	0.168
45°	0.115	0.113	0.135	0.128	0.175
60°	0.148	0.135	0.129	0.129	0.183

A second thermophysical property, the thermal conductivity of the fines, *k*, was measured under vacuum conditions for temperatures from 205° to 404°K. This property, like the reflectance, is needed for thermal energy balance calculations.

The directional reflectance was obtained with a sample center-mounted in an 8-inch diameter integrating sphere reflectometer. The sphere coating was magnesium oxide. The sphere system is constructed so that the sample can be held in a horizontal position—a necessity for powders—while the sphere and external optics can be rotated so that angles of illumination or viewing up to approximately 75° can be obtained. The system can be evacuated to pressures in the 10^{-7} torr range.

The integrating sphere was operated in the reciprocal mode, that is, the sample was illuminated by diffuse light from the sphere walls. The directional reflectance $\rho(\theta)$ was obtained as the ratio of intensity when the sample was viewed to intensity when the wall was viewed (*1*). This measurement is equivalent (*1*) to illuminating the sample at an angle of incidence ψ equal to the angle of viewing θ. For the total or white light measurements a 1000 watt tungsten-iodine lamp (DXW) with a reflector was used. The detector was a Kipp-Zonen CA-1 thermopile. The spectral results were obtained with a Perkin-Elmer 112U spectrometer and a lead-sulfide cell detector.

Measurements were made on samples 10084,68 (powder), 10047,23 (basalt) (*3*), 10048,21 (breccia), and 10057,29 (crystalline). The spectral results are shown in Fig. 1 only for angles of 10° and 60°, but measurements for angles of viewing of 10°, 20°, 30°, 45°, and 60° were also obtained. All samples received were packaged in dry nitrogen.

The directional reflectance of the lunar powder shows no absorption bands over the spectral range studied. Sample 10084,68,1 was mounted in the integrating sphere and the system evacuated to pressures below 10^{-5} torr. Sample 10084,68,2 was run at atmospheric pressure 2 months after No. 1 sample and No. 2 had been resealed and stored in the original shipping container for these 2 months. The measurements obtained in a vacuum are higher than those at 1 atm. The difference could possibly be caused by the surface roughness or texture, contamination, or material packing. These measurements point out the need to study a vacuum packaged sample (*4*) so that the clean surface can be investigated before it is exposed to the atmosphere. Under these conditions surface texture would be the same. The reflectance increases with increasing angle of viewing (θ), and this corresponds to what one would expect of a dielectric material.

Total directional reflectances were obtained for the powder under vacuum and dry nitrogen atmospheres. The vacuum results are higher for these measurements than for the atmospheric pressure results as in the case of spectral measurements. The results are given in Table 1. Here we can see that the reflectance increases as the angle of viewing increases, as is common for dielectrics.

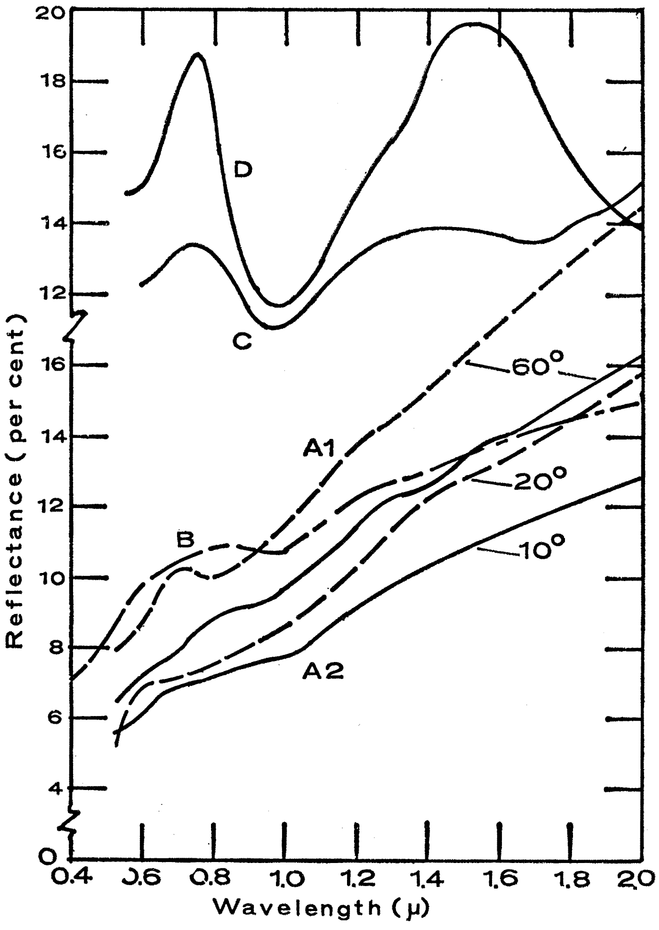
Sample 10047,23,2 shows a reflectance spectrum most similar to the lunar powder (Fig. 1, B). There are no major absorption bands in the spectrum but possibly a minor one around 1 μm. This rock chip, as well as the others, was run under atmospheric conditions. Photographs of all rock chips were taken for documentation, and the area used for study on each sample has been recorded.

It should be noted here that the measurement of the reflectance on the rock chips as a function angle is somewhat questionable because of the irregular shape and condition of the surface. However, for those rock chips where it was reasonable to make these measurements, they were obtained.

The remaining rock chip measurements in Fig. 1, C and D show very pronounced absorption bands. Sample 10084,21,1, a breccia type, has a minimum reflectance centered at 1.0 μm and an apparent band centered beyond 2.0 μm. The reflectance spectrum of sample 10057,29,1, a crystalline type of material with a cinder-like appearance, also has a strong band at 1.0 μm but has no other strong bands. However, the data suggest a weak band around 1.7 μm. A second sample, 10057,29,2, was also tested. Its reflectance over the wavelength range was between 10 and 20 percent below that of 10057,29,1. These measurements again show the strong band at 1 μm but a much weaker one, if any, at 1.7 μm. The difference in reflectance is most likely due to the greater density of surface holes and craters of 10057,29,2.

The bidirectional reflectance measurements were made with a goniometric system designed so that the sample could be viewed and illuminated while under vacuum conditions. The complete system including the optics is described elsewhere (*5*). The measurements were obtained for wavelengths of 0.6, 0.8, 1.0, 1.5, and 2 μm and with tungsten-iodine lamps of 650 and 1000 watt outputs. Because of some unexpected problems with equipment no vacuum measurements will be reported here. Bidirectional infrared measurements are being obtained.

Two types of bidirectional measurements were made, one where we held fixed the angle of viewing θ and varied the angle of illumination ψ, and one where we held the angle of illumination fixed and varied the angle of viewing. For the fixed θ mode of operation, the area of illumination varies as $1/\cos \psi$; in the fixed ψ mode, the area of viewing varies as $1/\cos \theta$. For both modes the detector output can be interpreted as an intensity measurement. Because it is very difficult to obtain absolute bidirectional reflectances, the data have been normalized by the specular read-



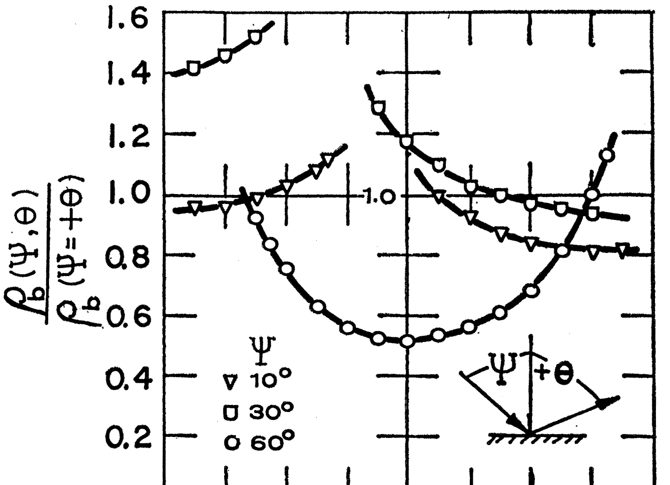


Fig. 1 (left). Reflectance spectra of lunar fines and rock chips. A1 (dashed lines), powder, sample 10084,68,1, vacuum run ψ = 10°, 60°. A2 (solid lines), powder, sample 10084,68,2, atmospheric run ψ = 20°, 60°. B (dash-dot line), basaltic type, sample 10047,23,2, ψ = 10°. C, crystalline type, sample 10057, 29,1, ψ = 10°. D, breccia type, sample 10048,21,1, ψ = 10°. Note ordinate for C and D shifted. Fig. 2 (above). Normalized bidirectional reflectances for lunar fines sample 10084,68,2 as a function of angle of viewing with the angle of illumination fixed at 10°, 30°, or 60°. The light source was a 1000 watt tungsten-iodine lamp.

ing where the angle of illumination ψ equals the angle of viewing θ. The angles were scanned automatically and the output of the detector was recorded on a strip chart recorder.

In the fixed θ mode, the blockage of the area of view of the detector by the primary illuminating mirror was too large to be acceptable, so the measurements were not available for this paper. Figure 2 shows the normalized bidirectional reflectance results for the fixed ψ mode. For such a presentation a Lambertian surface would be a horizontal line. The lunar powder shows strong back-scatter in the direction of illumination and a much weaker forward-scatter (if any) in the specular direction. The spectral measurements obtained show the same general characteristics but do indicate a slight dependence on wavelength.

The thermal conductivity of sample 10084,68,2 was measured with a line heat source technique. A Teflon cell was constructed, the sample volume being approximately 25 by 13 by 13 mm. A Nichrome heating wire 0.203 mm in diameter was used as the line heat source as well as a resistance thermometer to measure the powder temperature at the wire. An iron-constantan 36-gage thermocouple, placed 0.2 mm from the wire, was used to monitor the temperature of the powder as well. The thermal conductivity cell was placed in a vacuum chamber and surrounded by a blackened copper shroud. The shroud could be heated or cooled so that we could control the average powder temperature. Pressures of 10^{-3} torr and lower were generally used when data were obtained. The thermal conductivity of a powder is, in general, independent of pressure for pressures below 10^{-2} torr.

The general scheme for obtaining data was to heat or cool the sample to the desired temperature. When equilibrium was reached, a steady heat flux from the wire was started by electrical heating. A temperature-time recording was then obtained for the wire. From the heat input and the temperature-time characteristics the thermal conductivity of the sample can be calculated (*6*).

Sample 10084,68,2 was loaded and settled by tapping lightly onto the cell. The measured density was 1.265 g/cm³. Only three data points over the temperature range used are presented here. The thermal conductivity in watts per meter per degree Kelvin was found to be 1.71×10^{-3} (205°K); 2.07×10^{-3} (299°K); and 2.42×10^{-3} (404°K). The data would seem to indicate a dependency on temperature, but because of experimental uncertainties in the measurements no comment can be made at this time concerning temperature effects.

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References and Notes

1. The directional reflectance: If a surface is illuminated by a beam of light at an angle ψ from the surface normal with energy $de_i(\psi)$ and the reflected light is collected over the hemispherical space $de_r(\psi)$ the directional reflectance is $\rho(\psi) = de_r(\psi)/de_i(\psi)$; or the surface can be illuminated hemispherically with diffuse light $e_{i,h}/\pi$ while the reflected intensity $I_r(\theta)$ is collected in a specific angular direction (θ) in a small solid angle. The directional reflectance is $\rho(\theta) = I_r(\theta)/[e_{i,h}/\pi]$. It can be shown then $\rho(\psi) = \rho(\theta)$.
2. The bidirectional reflectance $\rho_b(\psi, \theta)$ is expressed as the intensity of reflected light in the direction (θ) divided by the incident light per unit time and surface area contained within a solid angle $d\Omega_i$ in the direction ψ, $\rho_b(\psi, \theta) = dI_r(\psi, \theta)/de_i(\psi)$. Intensity is defined as $dI(\theta) = de(\theta)/d\Omega \cos \theta$.
3. This descriptive terminology was taken from *Apollo 11 Preliminary Science Report* (NASA SP-214, 1969).
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7. We thank C. Neville, C. Allen, E. Yates, E. Hoover, and W. Buchholtz for assistance and support with the design and construction of the equipment, and C. Cremers, M. Birkebak, and T. Birkebak for assistance with data reduction. Supported by NASA grants NAS9-8098 and NGR 18-001-026.

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Elastic Wave Velocities of Lunar Samples at High Pressures and Their Geophysical Implications

Abstract. *Ultrasonic measurement of P and S velocities of Apollo 11 lunar samples 10020, 10057, and 10065 to 5 kilobars pressure at room temperature shows a pronounced increase of velocity (as much as twofold) for the first 2 kilobars. The travel times predicted from the velocity-depth curve of sample 10057 are consistent with the results of the Apollo 12 seismic experiments. At pressures below 200 bars, the samples are highly attenuating; for both P and S waves, the value of* Q *is about 10.*

Measurement of the velocities of elastic waves in lunar samples has two objectives: to provide the basic data necessary for interpreting lunar seismograms, and to study properties of rocks which were formed in extraterrestrial environments. Seismic data combined with laboratory data provide the most direct clues to the understanding of the lunar interior. In addition, mechanical, thermal, and chemical processes near the lunar surface may be inferred from the properties of the rocks. We present here the P- and S-wave velocities measured up to 5 kb pressure on the Apollo 11 samples. Comparison will be made with the results obtained in the Apollo 12 seismic experiments.

The samples were provided by NASA in the form of a rectangular cylinder [1 by 1 by 2 cm; see Table 1 and (*1*)]. Samples 10020 and 10057 are dense crystalline rocks with intrinsic densities of 3.2 to 3.4 g/cm³ (*2*). Sample 10057 is the largest and the most uniform, though probably weakly to moderately shocked, rock returned on Apollo 11 (*1*); it is similar to basalt. Sample 10020 is a fine-grained igneous rock containing plagioclase, pyroxene, and minor amounts of olivine and cristobalite. Sample 10065 is a fine-grained breccia (terrestrial analog, microbreccia) and has a bulk density of 2.35 g/cm³.

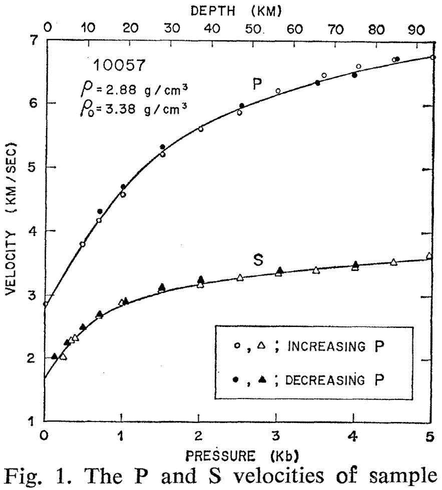

Fig. 1. The P and S velocities of sample 10057 as a function of pressure; ρ is bulk density and ρ_0 is estimated intrinsic density. The upper scale gives the depth in the moon converted from the pressure.