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/cm^3. 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).
4. A vacuum handling system was built by NASA but was not ready for the Apollo 11 mission.
5. C. B. Neville, Jr., thesis, University of Kentucky (1970).
6. J. H. Blackwell, *Can. J. Phys.* **34**, 412 (1956).
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/cm^3 (*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/cm^3.

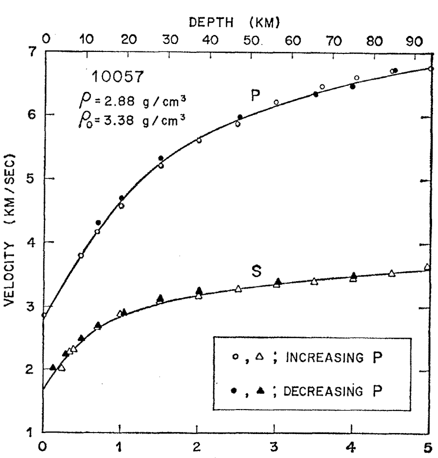

Fig. 1. The P and S velocities of sample 10057 as a function of pressure; ρ is bulk density and ρ_0 is estimated intrinsic density. The upper scale gives the depth in the moon converted from the pressure.

The standard pulse-transmission technique of Birch (*3*) with 1-Mhz barium titanate transducers for both P and S waves was used. High-pressure measurements were made in a simple piston-cylinder high-pressure cell with petroleum ether as the pressure medium. Samples were jacketed by copper foil or rubber tubing, or encapsulated with Sylgard. The average values of the results obtained by several runs with different sample-transducer assemblies are listed in Table 1. The estimated accuracy is 2 to 3 percent for P waves and 5 percent for S waves. Because of the small size of the samples and the high attenuation, these accuracies are considerably lower than those normally achieved. The example given in Fig. 1 is typical of the behavior of the velocity with pressure of lunar rocks. The velocity increase of about twofold for the first 2 kb pressure increase is much more pronounced than in earth rocks.

The elastic properties of the Apollo 11 crystalline rocks appear to be representative of the material in the Sea of Tranquillity. A second set of observations may be obtained from the data of Surveyor 5, recorded about 25 km northwest of the Apollo 11 landing site. Simulated Surveyor 5 lunar rocks were synthesized (*4, 5*) with the chemical composition given by the alpha backscattering experiment. Because the velocities of elastic waves measured on the simulated rocks ($\rho = 2.8$, $V_P = 6.2$, and $V_S = 3.5$) closely approximate the intrinsic properties of the Apollo 11 rocks (extrapolated to zero pressure to eliminate the effects of microcracks), neither having been corrected for porosity, we believe that our results apply to the entire area of the Sea of Tranquillity.

The densities and the P-wave velocities at 10 kb extrapolated from the data of sample 10057 fall on the curve of mean atomic weight of about 23 in Birch's (*6*) plot of velocity, density, and mean atomic weight. This value of mean atomic weight agrees reasonably well with that calculated from the chemical composition (*5*) of the Apollo 11 samples, 23.0 to 23.7. This agreement suggests that Birch's diagram can be used for the interpretation of the lunar interior.

The extremely low velocities at normal pressures are probably due to the presence of microcracks between grains; these cracks may have formed either by the large temperature fluctuations of the lunar surface or by shock metamorphism. Microscopic examination of the thin sections revealed cleavage fractures but no through-going fractures.

Table 1. Bulk density and velocity (in km/sec) of samples.

Sample	Wave	Pressure (kb) 0.0	0.5	1.0	2.0	3.0	4.0	5.0
10020	P	3.50	4.80	5.55	6.30	6.80	7.00	7.20
$\rho = 3.18$ g/cm^3	S	2.20	2.88	3.25	3.67	3.87	4.00	4.08
10057*	P	2.82	3.80	4.65	5.62	6.18	6.52	6.78
$\rho = 2.88$ g/cm^3	S	1.70	2.45	2.82	3.20	3.39	3.50	3.62
10065	P	1.50	2.90	3.50	4.05	4.30	4.40	4.50
$\rho = 2.34$ g/cm^3	S	1.05	1.70	2.00	2.28	2.42	2.65	2.78

*This sample is densely pitted. The estimated density is 3.38 g/cm^3 (see *2*).

The lunar samples have a very high attenuation (low Q) at low pressures for elastic waves. Although we could not measure precisely the value of Q, we estimated its order of magnitude by measuring the ratio of the amplitude of the signal through the sample to that through a steel test piece having the same size and shape as the sample. If we assume that the effect of Q dominates over those of geometrical ray spreading and internal reflections and that the steel has a much higher Q than the sample, then the value of Q can be calculated approximately from the amplitude ratio a by $a = \exp[-\pi f t/Q]$ where f is frequency and t is travel time through the sample. At low pressures ($P < 200$ bars), the values of Q are of the order of 10 for both P and S waves for all the samples. At high pressures, all the samples, and in particular 10020, showed an appreciable increase in Q. It was not possible, however, to determine the value of Q because the assumptions made above are not valid for high-Q samples.

The fact that two of the samples (10020, 10057) have densities nearly equal to the bulk density of the moon, 3134 g/cm^3, is noteworthy; rock samples collected, at random, on the earth's surface would represent the density of neither the bulk earth nor the mantle. One implication of this finding is that the vertical differentiation process in the moon may have been much less extensive than that in the earth; the structure of the moon may be relatively homogeneous, without well-defined crustal layers. This idea can be tested by comparing our laboratory data with the results obtained in the Apollo 12 seismic experiment. If the dense samples 10020 and 10057 are representative of the lunar material, we can predict, ignoring the temperature effect, the depth variation of seismic waves in the moon

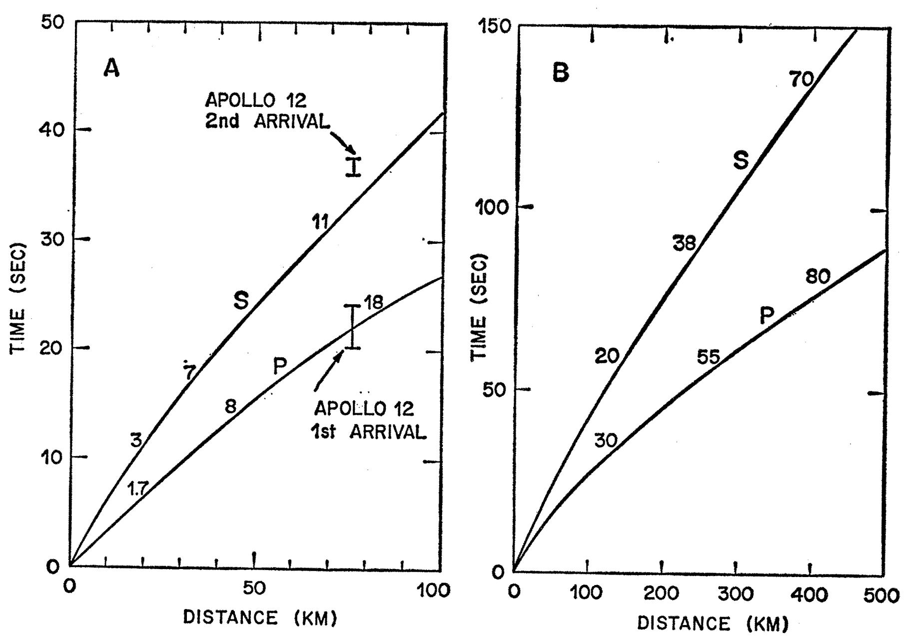

Fig. 2. The travel-time curve for the moon predicted from the velocity-depth curve of 10057 (Fig. 1), the most uniform sample. The times of the first and second arrivals in the Apollo 12 seismogram (*7*) are shown in *A*. The numbers on the curve indicate the depth (in km) of the penetration of the ray. *B* shows the travel-time curve to a larger distance.

(see Fig. 1), from which the travel-time curve of seismic waves can be predicted as shown in Fig. 2. In the Apollo 12 seismogram which recorded the impact of the ascent module, two distinct arrivals were detected (*7*); the first at 20.1 to 24.1 seconds and the second at 37.5 seconds after the origin time. The epicentral distance is 75.9 km. As is shown in Fig. 2, these arrival times agree remarkably well with the predicted P and S arrival times. Although the second arrival has not been confirmed as S, our proposed undifferentiated moon model is at least compatible with the seismic results. This agreement also suggests that the special textures (probably microcracks) of the samples also prevail at depths down to 20 km or so. These microcracks may have important bearings on the physical processes that have taken place on the lunar surface, and therefore deserve more extensive investigation.

If the samples 10020 and 10057 are representative of the lunar material, an efficient wave guide must exist near the lunar surface because of the sharp velocity increase with depth. Calculations of surface-wave dispersion curves made for the structure predicted from the velocity-pressure curve of the sample 10057 show a relatively constant group velocity (velocity, 1.57 km/sec) of Rayleigh waves over a period range 0 to 5 seconds. If future seismic experiments confirm this dispersion character, the evidence for an undifferentiated moon will be strengthened. If, on the other hand, significant deviation from the predicted dispersion curves is found, it will indicate the existence of structural heterogeneity at depths due to temperature, phase change, and compositional change.

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1. NASA Lunar Sample Information Catalog, Apollo 11, Manned Spacecraft Center, Houston (1969).
2. The bulk density of any of these rocks is the ratio of its mass to bulk volume. We also estimated the intrinsic density of sample 10057, which contains numerous voids. Assuming that the ratio of the total cross-section area of the voids on the surface to the total surface area of the sample is equal to the porosity, we obtained a porosity of 17.4 percent and intrinsic density of 3.38 g/cm^3. Sample 10020 has few visible voids; the intrinsic density probably does not exceed the bulk density by more than 10 percent.
3. F. Birch, *J. Geophys. Res.* **65**, 1083 (1960).
4. Full details on synthesis and other physical properties of the simulated Surveyor 5 rocks are to be reported elsewhere by Chung, Horai, Simmons, and Wones. The mineralogical composition of the simulated rocks closely approximates that of the Apollo 11 rocks. The composition (in mole percent) of the Apollo 11 rocks and the simulated rocks are, respectively, for plagioclase, 25 to 40 and 30 to 44; for pyroxene, 46 to 56 and 45 to 60; for olivine, 0.6 to 3 and none; for ilmenite, 10 to 17 and small; and for free silica, 5 to 11 and 6 to 10. The composition of the simulated rocks was based on the recent analysis of Surveyor 5 [see *Science* **165**, 277 (1969)] as well as analyses given for A-22 and B-50 (*5*).
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7. G. Latham, personal communication, December 1969.
8. We thank Ki-iti Horai for his help, Lotfi Mohsen for the porosity measurements, and William Brace for valuable suggestions. We benefitted from discussions with Frank Press, Nafi Toksoz, and Ralph Wiggins concerning various seismological problems. Gary Latham made available to us some of the results of the Apollo 12 seismic experiments. Supported by NASA contract NAS 9-8102.
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Infrared and Thermal Properties of Lunar Rock

Abstract. *The infrared absorption properties of lunar rock throughout the range 2 to 2000 micrometers were investigated and, in addition, direct measurements of specific heat and thermal conductivity of rock samples were made. The results suggest that pure radiation is an important, if not dominant, process in heat flow in the lunar surface layer. A new method for determining the mean conductivity of this layer gives somewhat lower values than earlier earth-based measurements. There is also evidence to suggest that, at depths of about 10 meters, the rock is still of a porous and fragmental nature.*

There is a strong connection between the infrared and thermal properties of the lunar surface layer. The infrared emissivity is a controlling factor on the rate at which heat leaves the moon's surface. It is also apparent that, within the regolith, a considerable fraction of heat transfer takes place by radiation rather than by conduction, and measurements of the particle size and infrared absorption in the 2- to 200-μm range now make determination of the relative efficiencies of the two processes possible. Similar measurements at longer wavelengths, together with microwave results from earth-based telescopes, now give the thermal conductivity of the lunar surface regolith. Previously the conductivity could be estimated only from measurements at 8 to 14 μm.

An increase of temperature with depth in the top few meters of the lunar surface is implied by the longer-wavelength ($\gtrsim 5$ cm) earth-based microwave measurements; now that we have direct measurements of the thermal conductivity of the rock, the infrared and thermal measurements can be used to determine the actual thermal gradient in the layer and to compare this gradient with that predicted from internal radioactive heating.

Thermal sintering as well as mechanical shock may be involved in the formation of the breccia; continuous measurement of the thermal conductivity of a heated sample should be a means of watching the breccia formation process at an enhanced rate.

We describe here infrared and conductivity measurements now in progress. The infrared transmission throughout the range 2 to 2000 μm has been measured for the type D material with (i) double-beam spectrometers with Nernst sources and Golay detectors (range, 2 to 50 μm); (ii) Fourier transform spectrometer with a mercury source and Golay detector (range, 50 to 1000 μm); and (iii) grating spectrometer of the type described by Bloor *et al.* (*1*) with a mercury lamp source and Golay detector (range, 200 to 2000 μm).

In addition, a check at 1300 μm has been made with a 1.5-m Cassegrain telescope with the sun as source and an InSb photoconducting detector. A similar spot measurement at 338 μm is being made with a cyanogen laser with a Golay cell as a detector. The fines were compressed to a density of 1.8 g/cm^3. In each case we measured the attenuation or extinction coefficient μ defined by the equation

$$\frac{I_x}{I_0} = e^{-\mu\rho x} \qquad (1)$$

where I_x is the intensity after passage through a thickness (x) of material, I_0 is the incident intensity, and ρ is the sample density. Below 50 μm, measurements were also made with crushed fines in a transparent substrate, and, in this way, the coefficient of pure absorption K_λ was determined. Because of the tendency for the dust to shake down and form macroscopic cracks, the far infrared measurements were