Density of the Lunar Surface

Abstract. *The evidence that the lunar soil is basaltic permits a closer estimate of its density from the radiothermal and radar data. The mean density at the surface is 0.6 ± 0.2 gram per cubic centimeter, increasing to 1.0 gram per cubic centimeter at a depth of a few centimeters; still higher densities at depths of up to meters are implied by the radar observations.*

Now that the Surveyor V experiment in chemical analysis has established (*1*) that part of the lunar surface has a composition resembling basalt, it is interesting to use the measured electrical properties of basalt, in conjunction with the lunar radar and radiothermal observations, to refine the estimates of the density of the surface layers.

Measurements in this laboratory on solid basalt at wavelengths of 68 cm and 8.6 mm have shown that the dielectric constant is almost independent of frequency. Furthermore, when these data were used to calculate the dielectric constant of powdered basalt, by use of the expression of Twersky (*2*), the results were almost independent of the source and variety of basalt; the sample-to-sample variations among our ten specimens of basalt from four sources produced an overall range of only ± 9 percent in our estimates of density. We have confirmed the validity of Twersky's expression by measurements on powdered basalt and other rocks.

It is well known that the lunar radar observations, interpreted as reflections from a rough, homogeneous, dielectric sphere, yield values for the dielectric constant that are significantly higher than those determined from Moon's radiothermal emission. This discrepancy has been discussed (*3*) in terms of a two-layer model, with a discrete increase in the dielectric constant at a depth that is small compared to an absorption length—a condition readily met in basalt powder—but that may be comparable to a wavelength. Other authors have considered models in which the dielectric constant increases linearly (*4*) or exponentially (*5*) with depth; always it was found that the radar reflectivity is augmented above the reflectivity due to the topmost, low-density layer, although it never reaches as high a value as would obtain if the deeper layers were exposed directly.

By contrast the radiothermal observations, especially when made by the polarization method on regions close to the limb, are a measure of the dielectric constant of the material at the surface. In particular, for a material whose dielectric constant is changing only slowly with depth, it is the topmost quarter-wavelength that principally determines the ratio of the polarized intensities.

By measuring these intensities, Soboleva (*6*) found a radiothermal dielectric constant of 1.65 at 3.2-cm wavelength, and Heiles and Drake (*7*) determined 2.1 at 21 cm. In powdered basalt these values are obtained at densities of 0.63 ± 0.14 and 1.0 ± 0.2 g/cm^3, respectively, where the errors correspond only to the limits quoted by these authors. We infer that the uppermost centimeter of the lunar surface has a typical density of 0.6 g/cm^3, which increases to 1.0 g/cm^3 over the next few centimeters, corresponding to powders about 25- and 35-percent solid.

These estimates agree closely with those made by Jaffe (*8*) from the landing dynamics at the Surveyor I site; they are consistent with the Surveyor III estimates of Christensen *et al.* (*9*), but not with the density of 1.5 g/cm^3 adopted by Scott *et al.* (*10*) for average mare material.

The absorption length in powdered basalt of these porosities is about 50 wavelengths—approximately 2 m for a wavelength of 3.6 cm and 30 m for a wavelength of 68 cm, where Evans and Hagfors (*11*) have measured radar reflectivities corresponding to dielectric constants of 2.72 and 2.79, respectively. The fact that these are significantly higher than the radiothermal determinations suggests that the density increases still further after the first 5 cm, although probably not very rapidly at depths greater than 1 to 2 m. On Evans' (*3*) model, the dielectric constant at this depth is intermediate between those of highly compressed powder (about 3 at a porosity of 40 percent) and solid basalt (about 8). A two-layer model, by neglect of slow changes in dielectric constant, tends to overestimate the density in the deeper layer, and we interpret the radar results as showing that the basalt is still powdered, although of almost minimum porosity, at depths of a few meters.

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References and Notes

1. A. L. Turkevitch, E. J. Franzgrote, J. H. Patterson, *Science* **158**, 635 (1967).
2. V. Twersky, *J. Math. Phys.* **3**, 724 (1962).
3. J. V. Evans, *J. Res. Nat. Bur. Std.* **69D**, 1637 (1965).
4. A. Giraud, *ibid.*, p. 1677.
5. Y. G. Matveev, *Astron. Zh.* **44**, 419 (1967).
6. N. S. Soboleva, *ibid.* **39**, 1124 (1962).
7. C. E. Heiles and F. D. Drake, *Icarus* **2**, 281 (1963).
8. L. D. Jaffe, *J. Geophys. Res.* **72**, 1727 (1967).
9. E. M. Christensen *et al.*, in *Surveyor 3 JPL Project Doc. 125* (15 May 1967), sect. 4.
10. R. F. Scott, F. I. Roberson, M. C. Clary, *ibid.*, sect. 5.
11. J. V. Evans and T. Hagfors, *Icarus* **3**, 151 (1964).
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X-ray Diffraction: New High-Speed Technique Based on X-ray Spectrography

Abstract. *A method has been developed for obtaining lattice spacings of powder samples by x-ray diffraction in times potentially as short as 1 second. The sample is irradiated with polychromatic radiation from an x-ray tube, and the energy spectrum of x-rays scattered at a given angle is observed with a semiconductor radiation detector, coupled with a pulse-height analyzer.*

The condition for the diffraction of x-rays by a crystal lattice can be expressed in the form of Bragg's law:

$$2d(hkl) \cdot \sin\theta = \lambda \tag{1}$$

where *d(hkl)* is the interplanar spacing of reflecting planes with the indices *hkl*, θ is the glancing angle of incidence on the plane *(hkl)*, and λ is the wavelength of the radiation used. It is generally applied to polycrystalline materials by use of the powder method of Debye and Scherrer and of Hull. Monochromatic radiation, normally K_α radiation of the tube anode material, is used, making λ equal to λ_{K_α}. The *d* spacings are derived from the observed θ values corresponding to diffraction maxima. The diffraction condition can be interpreted very simply by use of a reciprocal lattice construction (*1*).

If direct recording techniques, such as a diffractometer with a proportional or scintillation counter, are to be used, the scanning rate cannot exceed a certain limit set by the receiving slit width and the required signal-to-noise ratio. Thus, with conventional x-ray diffraction equipment, an angular range of $2\theta = 120$ deg can be recorded in less than about 1 hour only with some loss