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Optical and High-Frequency Electrical Properties of the Lunar Sample

Abstract. *Reflectivity and polarization laws for the powder sample and its spectrum are close to the mean for the lunar maria. Solid samples show a marked absorption feature at 1 micron. The low albedo appears to be due to a surface coating on dust grains rather than to volume absorption. The high-frequency electrical properties resemble those of a fine powder made from typical dense terrestrial rocks and are consistent with previous estimates from ground-based radar observations. The differential mass spectrum is almost constant from 100-micron particles down to 0.1-micron particles; most particles are smaller than 0.3 micron. Their shapes disclose a variety of processes of generation.*

Lunar dust and rock chip samples have been analyzed in the lunar laboratory of the Cornell Center for Radiophysics and Space Research; our concern has been with the optical and electrical properties of the sample and their relation to those known for the lunar surface as a whole, and with the questions surrounding the origin of the lunar dust. Four salient points have emerged.

1) The optical scattering law and polarization properties of a surface of lunar dust generally correspond closely to these properties as observed for the moon as a whole. The rock chip sample shows a strong absorption feature at 1 μm which is not prominent in the lunar scattered light. It is probable, therefore, that most of the lunar surface is covered with a material similar to the powder that was investigated.

2) The dielectric constant is within the range that had been estimated for the moon as a whole by radar methods.

3) The particle size distribution indicates that the differential mass spectrum as a function of radius is almost constant from 100 μm down to 1000 Å. The shapes of the particles indicate a variety of sources. Some have the sharp edges that are characteristic of fracture; others are rounded, indicating processes of melting or condensation. Some cannot readily be attributed to either of these mechanisms.

4) The darkness of the lunar dust is mainly due to dark surface deposits on the grains, probably metallic, rather than to absorptivity of the bulk material.

The optical scattering law as a function of phase angle and the optical polarization law were measured with the same instrument that had been used for measuring many sample powders in the past and in the same manner (*1*). The lunar powder proved to resemble, both in appearance and in the measured optical properties, the lunar maria as observed from the earth and the terrestrial powders previously proposed (*1*) as being most closely representative of the moon. These powders also proved to be similar under optical microscope examination. The particle size was similar, the great majority of the particles being less than 10 μm in diameter. The adhesion of the small particles to each other indeed created the "dendritic growth" appearance under the microscope that has been given the name "fairy castles." It appears that the large part of the pronounced lunar opposition effect—that is, the brightness surge toward zero phase—can be attributed to the shadows cast by this lacy surface structure.

Figures 1 and 2 summarize the optical properties of the Apollo 11 samples. Each data point represents the mean of several observations of different portions of a sample, and the measurements repeated very well. In Fig. 1 the photometric phase function of the lunar dust sample is generally steeper than the mean lunar case (*1*) for phase angles less than 15°, but the difference is very small. The curve for polarization plotted against phase angle (Fig. 1) also demonstrates the similarity of the dust sample to the moon as a whole, but, again, there are minor differences; the crossover from negative to positive polarization occurs at a lower phase angle, and polarization in the positive branch is greater.

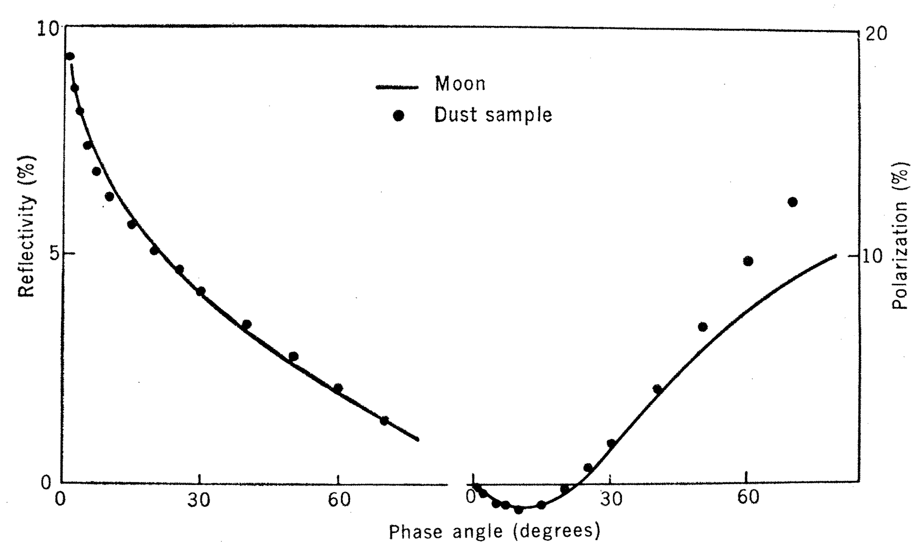

Fig. 1. The dependence of reflectivity and polarization on phase angle at wavelength of 5600 Å and at normal viewing. [Curve for the moon from Wattson and Danielson (*3*)]

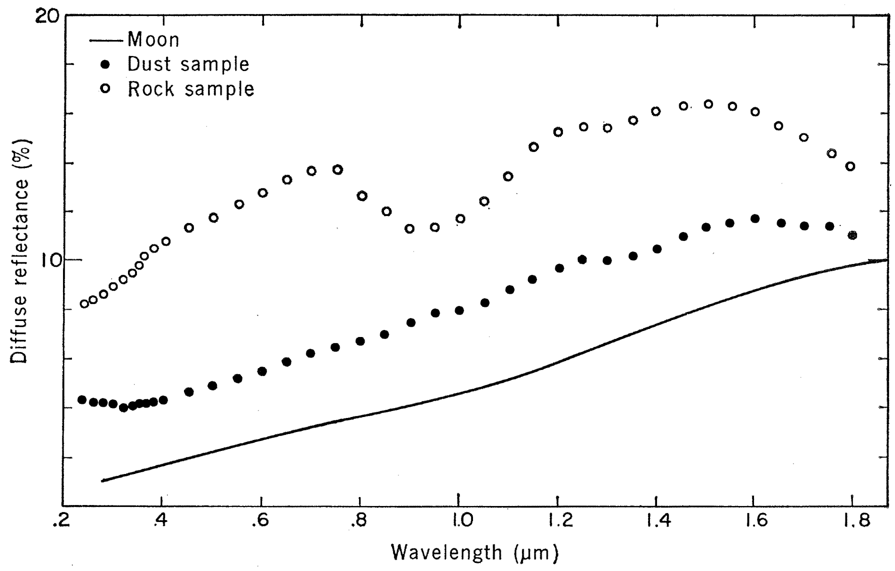

Fig. 2. The spectral reflectance of Apollo 11 lunar samples. [Curve for the moon from Hapke (*1*), with arbitrary normalization of reflectivities]

The normal albedo of the dust sample at 5600 Å was measured as 10.2 ± 0.2 percent. This value is in close accord with the value 9.96 percent for the Apollo 11 site, as derived from Apollo 10 orbital photography (*2*). Moreover, in the hemispherical reflectance measurements performed on a Cary 14 spectrophotometer, the albedo values of the dust sample in the visible and near-infrared were similar to lunar maria values obtained from earth-based observations. Both spectra are featureless, climbing steadily in albedo from ~ 0.3 to 1.5 μm (Fig. 2). Lunar rock chip samples were also measured on the spectrophotometer, and a strong absorption band, not present in the powder sample, appeared near 1 μm. A weak band in this region had previously been suggested, from earth-based observations of the moon (*3*, *4*). Further details of the optical properties of the Apollo 11 samples will be presented in the near future (*5*).

Rock powders in the size range of a few microns tend to be very light in color. Most rocks have too low an opacity to absorb much of a light ray, which is generally scattered out of the surface after having traversed only a few microns of material. Trying to account for the very low albedo of the lunar surface has been a long-standing problem, in view of the indication, from the optical scattering and polarization properties, of a very small particle size, since even the darkest rocks tend to be quite light when powdered. We have previously, in this laboratory, undertaken sputtering experiments with kilovolt protons and with α-particles on powdered rock surfaces, which have indicated darkening. It has been suggested that this darkening was due to the deposition of reduced metals, perhaps chiefly iron, on the surface as a result of the dissociation by the sputtering process, the partial escape of the oxygen, and the slowness of surface recombination limited by diffusion.

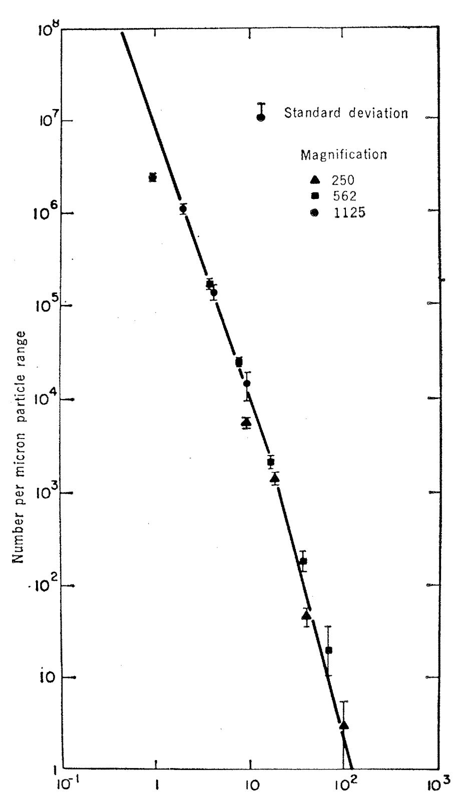

Fig. 3. The differential particle size distribution for the bulk sample.

Metallic surface coatings of as little as 30 Å can provide much opacity but would make only an insignificant contribution to the bulk chemical composition. We have seen strong evidence for such coatings, but we have not yet been able to analyze them adequately. Whether they are indeed the result of sputtering or of other metal evaporation (vacuum plating) processes, or whether perhaps they are just the reduction by the hydrogen of the metallic surface layers produced by solar wind, is not yet clear. However, we have had the following indications of the presence of metallic layers.

We observed under the microscope that some larger particles in the size range 50 to 200 μm that could be found in the lunar soil sample had a metallic appearance, sometimes over only a certain part of their surface. Some particles could be clearly seen as translucent glass in which a well-defined area appeared metallic. One sphere, for example, looked like a honey-colored glass from one side but like a steel ball from the other. When treated with the common acids (hydrochloric and nitric) that attack metals, the metallic appearance was generally reduced but not completely removed. Hydrofluoric acid generally tended to remove the metallic appearance entirely, even before a visible erosion of the particle had taken place.

For most of the material an optical examination is not feasible because the particles are too small. Nevertheless, when the same acids were applied to a microscopic sample of fine powder it quickly turned very much lighter, almost white. It seems likely, therefore, that in the finer material a metallic surface coating is also normally present, and responsible for the low albedo.

The measurement of a particle size distribution for such small grains is not an easy matter. The cohesion of the grains prevents analysis of the smaller sizes by sieving, as was pointed out by the preliminary investigators (*6*). We have used three techniques: (i) making microscope slides of the powder mixed into a transparent varnish and smeared out into a thin layer, which permits us to count the particles with an oil emersion microscope down to sizes of about 2 μm; (ii) constructing a water sedimentation column in which the descent of particles as small as 1 μm can be photographically registered; (iii) determining the size distribution of the smallest particles from the scanning

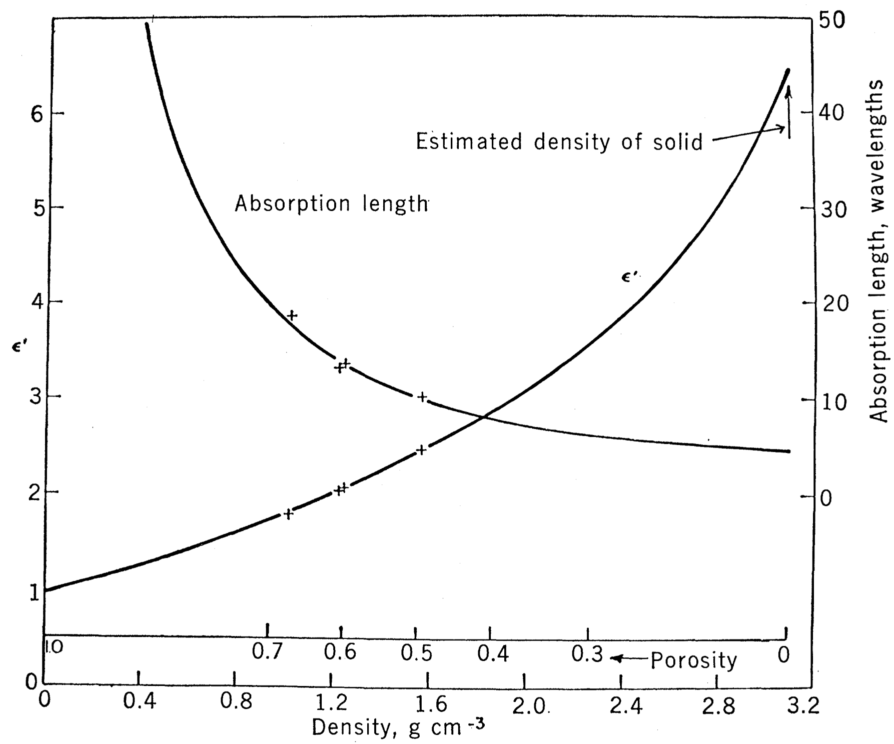

Fig. 4. The dielectric constant and absorption length of the bulk sample at 450 Mhz as a function of the powder density. The solid curves are the Rayleigh formula (*7*). The estimated density of solid is from Lunar Sample Preliminary Examination Team (*6*).

electron micrographs referred to below. The three methods give consistent results (Fig. 3).

The detailed shapes of particles can be seen to a resolution of 300 Å in numerous scanning electron microscope pictures that were taken to see whether the origin of the material was revealed by the particle shapes.

Our studies indicate that various different effects have been active in producing the fine material. Some particles are spherical and rounded, suggesting condensation from a vapor or freezing of a liquid in free fall. Others are sharp-edged and angular, undoubtedly the result of fracture. They lack, in general, any obvious indication of a crystalline structure, as neither cleavage planes nor preferred angles are seen. It would appear that most of the fractured material is amorphous, or, if any of it is crystalline, that the size of the crystals is below the limit of resolution.

The spherical or compact round particles seen are less frequent but may form a continuous sequence from the 100-μm range down to very small sizes. The great majority of particles in the 10- to 1-μm size range have, however, more intricate shapes that are not readily understood. There are many rounded surfaces, and yet the particle as a whole is not compact. Elongated objects with rounded ends, surfaces where the sense of the curvature often changes, rough spots occurring in smooth surfaces, and various other features argue against any single explanation—liquid droplets, condensation, or fracturing. Additional processes such as erosion by sputtering, partial melting, and partial evaporation must be considered, and scanning electron microscope study of these mechanisms is needed before all the responsible processes can be identified.

Measurements were made by means of the technique used for determining the electrical properties of terrestrial rock powders (*7*). The dielectric constant (ε') and loss tangent of lunar dust at several stages of compaction were measured at 450 Mhz. The measurement in each case included a measurement of the density of the sample, and the porosity was calculated from the quoted specific gravity of the rock of which the powder is composed (*6*). The dielectric constant and the absorption length (Fig. 4) are consistent with the values deduced from ground-based radar and radiometric observations, respectively. As with terrestrial rock powders, the dielectric constant and loss tangent as a function of porosity follow the Rayleigh mixing formula and, by extrapolation, suggest a permittivity for the solid rock of the same composition as the lunar dust which is near the average for dense terrestrial rocks (about 7). The permittivity is about 3 for the dust at a typical "loose packing" porosity of 0.6. The absorption length at the same porosity, in this sample, is about 10 wavelengths.

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Magnetic Resonance Studies of Lunar Samples

Abstract. *Electron spin resonance searches at 9.5 gigahertz on several fines samples and portions of several rocks have yielded signals whose lineshapes and temperature dependences show that the samples are principally ferromagnetic in nature. Proton magnetic resonance searches at 60 megahertz of these samples have not revealed any signals ascribable to water or any other types of hydrogen in concentrations greater than 0.0001 percent by weight contained in narrow lines (5 oersteds wide or less) and 0.01 percent by weight in wide lines (as wide as 100 oersteds).*

We are conducting magnetic resonance studies of the lunar samples returned by the Apollo 11 mission in order to (i) determine by nuclear magnetic resonance (NMR) the total proton concentration along with the distribution of any protons detected between water, hydrated minerals, organic