Reports

Lunar Surface: Identification of the Dark Mantling Material in the Apollo 17 Soil Samples

Abstract. *Evidence indicates that Apollo 17 sample 74001, a soil consisting of very dark spheres, is composed almost entirely of the dark mantling material that covers a large region of the southeastern boundary of Mare Serenitatis. Other Apollo 17 samples contain only a component of this material. The underlying basalt in the Taurus-Littrow valley appears to be an extension of material forming the low-albedo ring around part of Mare Serenitatis and much of the surface of Mare Tranquillitatis. The surface of this basalt region is spectrally distinct from areas with dark mantling material. These results are derived from telescopic and laboratory measurements of the optical properties of lunar soil. Digital vidicon color images are used to map the extent of these material units in the Taurus-Littrow region.*

The Apollo 17 spacecraft landed on the floor of the deep, narrow Taurus-Littrow valley that embays the mountainous highlands at the eastern rim of the Serenitatis basin (*1*). This landing site was chosen partly because it is located near an area covered by a thin, dark mantle which was believed to be young and possibly pyroclastic in origin (*2*). After the mission, it was surprising that no obvious evidence was found of a dark mantling material (DMM) component in the samples (*3*).

Before the Apollo 17 mission, the visible and near-infrared reflectance spectrum of an area of DMM 10 km in diameter and 50 km from the landing site was measured by means of ground-based telescopes (*4, 5*). It was found that the reflectance spectra for the DMM near the Apollo 17 site and for at least four other lunar areas are distinguishable from the spectra of nearly 200 other lunar regions (*5, 6*). Evidence was presented which demonstrated that the DMM differs in mineralogy from the surrounding material and can be considered a distinct unit.

It has been shown that the diffuse reflectance spectrum can yield information on the mineralogy of the reflecting material (*7*). We have used laboratory and telescopic spectral reflectance measurements of soil from the Apollo 17 site and its surroundings to identify the DMM as a unique component in the samples and to map the regional extent of the deposit. The validity of comparing measurements of Apollo samples with telescopic measurements of areas 10 km in diameter has already been demonstrated (*8, 9*).

We measured the diffuse reflectance spectra for 25 Apollo 17 samples, using standard techniques (*10*). Four lunar sample spectra are presented in Fig. 1A. All spectra are scaled to unity at 0.56 μm to eliminate the effects of brightness and to emphasize wavelength-dependent effects. Also shown in Fig. 1A, curve 5, is a spectrum for an area 15 km in diameter in central Mare Serenitatis (MS-2: 18°40′N, 21°25′E), which is used as a calibration standard for telescopic observations of the moon (*11*). Superimposed on the laboratory and calibration spectra is the telescopic spectrum for a DMM area 10 km in diameter, Littrow DMM (21°15′N, 29°40′E), located 50 km west of the Apollo 17 landing site.

Most lunar reflectance spectra are similar, but important differences exist

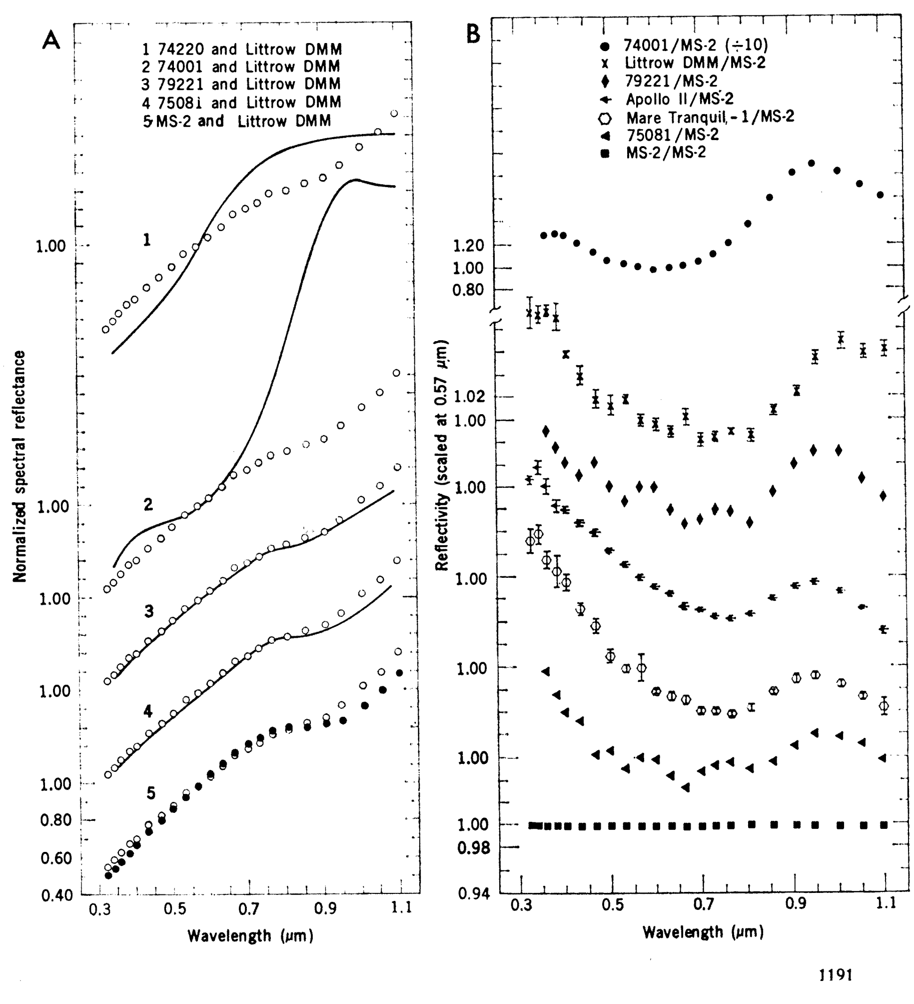

Fig. 1. (A) Spectral reflectance of four lunar samples (solid lines) and Mare Serenitatis-2 (MS-2) (closed circles), a lunar area 15 km in diameter used as a telescopic standard. All spectra are scaled to unity at 0.56 μm. Superimposed on the five spectra is the telescopic spectrum for Littrow DMM (open circles), an area 10 km in diameter in the Taurus-Littrow region. (B) Relative spectral reflectance of three lunar samples and four lunar areas, each 10 to 20 km in diameter. All spectra have been divided by the telescopic spectrum for the standard lunar area, MS-2. The scale for sample 74001 has been reduced by a factor of 10 to allow comparison with the other relative spectra.

(*11, 12*). These small differences between spectra are more easily seen if *relative* reflectance spectra are used. The seven relative reflectance curves shown in Fig. 1B were obtained by dividing the spectrum for a lunar area or a soil sample by the spectrum of MS-2. For example, the relative reflectance curve for Littrow DMM was produced by dividing the two superimposed spectra in curve 5, Fig. 1A.

The Littrow DMM relative spectrum is the characteristic spectrum for the telescopically observed DMM (*5*). Relative to the standard lunar area, the DMM is brighter at ultraviolet and blue wavelengths and also at near-infrared wavelengths, with the greatest infrared color difference occurring beyond 0.95 μm. Other relative reflectance spectra of interest for this report are included in Fig. 1B.

The Apollo 17 subfloor basalt, which forms the basement of the Taurus-Littrow valley and from which much of the surface soil appears to be derived, is similar in composition and age to the basalts found at the Apollo 11 site in Mare Tranquillitatis (*13*). A soil such as sample 75081, which is derived from the subfloor basalt, has a reflectance spectrum very similar to the telescopic spectrum for the Apollo 11 site. Telescopic measurements have been used to show also that the Apollo 11 site material in Mare Tranquillitatis is nearly identical to the material forming the Mare Serenitatis dark ring, a telescopic area named Mare Tranquillitatis-1 (*11*). This can be seen from a comparison of the Apollo 11 relative spectrum with the relative spectrum for Mare Tranquillitatis-1 in Fig. 1B. It follows, then, that the Apollo 11–like basalt in the Taurus-Littrow valley is likely to be the same compositional unit as the dark ring between Mare Serenitatis and Mare Tranquillitatis. This subfloor basalt, however, is not the same unit as the central Mare Serenitatis material, such as is found at the telescopic standard area, MS-2. On the basis of earlier spectral analyses of returned Apollo samples, the soil which most closely corresponds to the central Serenitatis mare material has been shown to be Apollo 12 soil (sample 12070) (*9*).

Two Apollo 17 samples that we have examined have reflectance spectra resembling the telescopic spectra for the DMM. The dark soil, sample 74001, found beneath the orange soil in a drive tube at Shorty Crater, has the spectral features of the DMM, but the amplitude of these features is ten times greater than those in the telescopic spectra (Fig. 1A). Sample 74001 is composed largely of fine-grained, nearly opaque spheres. The spheres contain abundant thin plates of ilmenite and, in some cases, parallel bars of ilmenite and olivine, with minor amounts of brown glass (*14, 15*). The optical properties of these dark spheres are those of the exterior glass, with the interior olivine being only a minor contributor. These spheres are similar in morphology and bulk chemistry to the orange soil particles and appear to be the devitrified equivalent of the orange glass (*15*).

The reflectance spectrum of the orange soil (sample 74220), shown in Fig. 1A, is characteristic of an iron- and titanium-rich glass (*16*). A broad absorption feature near 1.1 μm is due to Fe^{2+} on octahedral sites, whereas the weak band near 0.5 μm probably arises from Ti^{3+}. The steep slope toward the ultraviolet is due primarily to iron and titanium charge transfers, which, at present, are poorly understood. The spectrum of the black soil (sample 74001) also has bands near 1.1 and

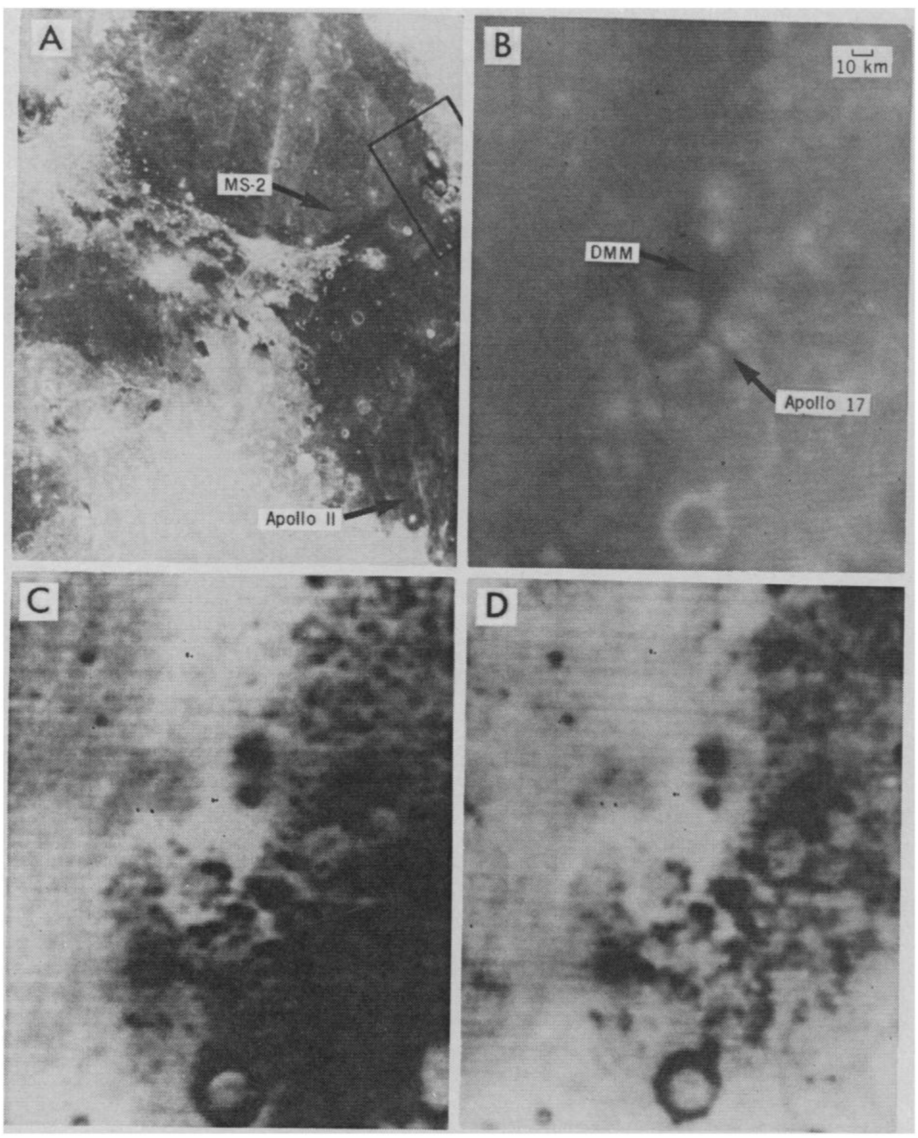

Fig. 2. (A) Full moon photograph of part of Mare Serenitatis and Mare Tranquillitatis. [Photograph supplied by the Lunar and Planetary Laboratory, University of Arizona.] The area for which vidicon images are shown is enclosed in solid lines. (B) Vidicon image of the Taurus-Littrow region taken through a filter centered at 0.56 μm; DMM, the center of the Littrow DMM area 10 km in diameter. The resolution is 1 to 2 km. (C) A ratio image formed by dividing an image taken through a 0.34-μm filter by the 0.56-μm image. The ratio image has been greatly contrast-enhanced to bring out the small color differences. Bright areas are those that are brighter at 0.34 than at 0.56 μm. (D) An enhanced ratio image formed by dividing an image taken through a 0.95-μm filter by the 0.56-μm image.

0.5 μm; however, these bands are deeper and narrower, and the overall curve is steeper, than for the orange soil. These optical properties are consistent with the interpretation that the black spheres are the partially devitrified equivalent of the orange glass. The steeper curve for the black soil is in part an expression of enhanced charge-transfer processes in the mineral ilmenite.

The reflectance spectrum for sample 79221, a soil taken from the upper part of a trench dug in the dark ejecta from Van Serg Crater, also has characteristics of the DMM. However, the amplitude of the spectral features, especially in the infrared, is not quite as great as those found in telescopic spectra of the DMM (see Fig. 1B). The bulk chemical composition of sample 79221 is that of a subfloor basalt, but one fine-grained fraction (90 to 150 μm) contains 3.3 percent barred spheres like those in sample 74001 (*3*). This component of barred spheres in the mare soil is apparently responsible for the trend in its spectral characteristics away from those of a soil derived from the basalt and toward the characteristics of Littrow DMM. From the relations between the spectral characteristics of samples 74001 and 79221 and Littrow DMM, we conclude that sample 74001 containing barred spheres is essentially a pure sample of the DMM.

Sample 74001 has essentially no ($<$ 1 percent) glass-welded aggregates (agglutinates) (*3*), an indication that this soil was not produced by the normal aging process of regolith formation. However, since its deposition, the DMM has been mixed with the underlying basalt forming agglutinate-rich soil, as seen in sample 79221. Where the mantle was relatively thin, the subfloor basalt has generally been the main contributor to the resulting surface soil. As the initial soil aged, it became more thoroughly mixed by meteoroid impact and the mantling material became increasingly diluted on the surface. In the region northwest of the landing site, where the telescopic spectrum of the DMM was obtained, the surface soil retains more of the original mantling material. The variation in the amount of DMM in the surface soil, however, is most likely the result of variation in the thickness of the original deposits (*17*).

Three compositional units have been mentioned here: (i) subfloor basalts similar to Apollo 11 material, (ii) DMM rich in dark barred spheres, and (iii) central Mare Serenitatis material (*18*). The regional distribution of these units around the Apollo 17 site is necessary information for an understanding of the history of the area. We have mapped the extent of these compositional units, using their spectral characteristics. We obtained the maps from an experimental version of a digital imaging camera and digital image-processing technique developed at the Massachusetts Institute of Technology (*19*).

A photographic representation of a digital image of the southeastern edge of Mare Serenitatis taken through an interference filter centered at 0.56 μm is shown in Fig. 2B. Similar images were taken through filters centered at 0.34 and 0.95 μm. Color maps were produced by dividing the ultraviolet and the infrared images by the 0.56-μm image; the resulting ratio images are also shown in Fig. 2, C and D. The ratio images are a display of the two-dimensional distribution of the values of the relative spectral reflectance curve at 0.34 and 0.95 μm.

The DMM unit is easily seen as a bright region near the center of both ratio images. A distinguishing spectral characteristic of the DMM is that the relative reflectance is high at both these wavelengths (Fig. 1B). The Mare Serenitatis dark ring, which is interpreted to be Apollo 17 subfloor basalt material, clearly appears as a bright region in the blue color image but it is not distinguishable in the red image. The MS-2 material (Fig. 2A) appears as a background gray in both ratio images (Fig. 2, C and D) because the density scale of the image was set with the use of this unit as a standard, just as is done in calculating the relative spectral reflectance curves in Fig. 1B. These photometrically precise ($\sim$ 1 percent) vidicon image ratios allow direct numerical comparisons between the spectral characteristics of the Apollo 17 valley, the Littrow DMM area (Fig. 2B), the Serenitatis dark ring, and the central Serenitatis Mare. The distinction between the three compositional units is substantiated by an examination, picture element by picture element, of the values of the ratios. The spectral characteristics of the dark Apollo 17 valley are midway between those of the Littrow DMM and those of the dark Serenitatis ring.

The telescopic and laboratory evidence strongly supports the conclusion that the hypothesized DMM does indeed exist in the Taurus-Littrow region. Although most of the mature soil samples from the valley floor contain only a small component [5 to 20 percent orange and black soil (*14*)] of the original DMM, sample 74001 is an essentially pure sample of the DMM. The underlying basalts in the Taurus-Littrow valley are an extension of the material forming much of Mare Tranquillitatis and the dark ring around a part of Mare Serenitatis. Basalts forming the center of Mare Serenitatis have not been identified in the samples of the Apollo 17 site, and from the vidicon image data are not exposed at the Apollo 17 site, at least over areas larger than a few square kilometers.

The DMM appears to have been superimposed on the Apollo 17 subfloor basalts in the Taurus-Littrow region but probably is not genetically related to them. Supporting this conclusion are telescopic studies (*5, 20*) of other lunar regions where the same mantling material has been identified but where it does not appear in conjunction with the titanium-rich basalt of the Apollo 11 and Apollo 17 sites. These results are in agreement with the report of the Preliminary Examination Team (*14*), which indicates that the rubidium and strontium abundances in the orange glass are higher than those in the Apollo 17 basalts, thus precluding a direct relationship.

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Polarized Magnetic Field Fluctuations at the Apollo 15 Site: Possible Regional Influence on Lunar Induction

Abstract. *High-frequency (5 to 40 millihertz) induced lunar magnetic fields, observed at the Apollo 15 site near the southeastern boundary of Mare Imbrium and the southwestern boundary of Mare Serenitatis, show a strong tendency toward linear polarization in a direction radial to the Imbrium basin and circumferential to the Serenitatis basin, a property that could be indicative of a possible regional influence on the induction.*

Time-dependent magnetic fields recorded by the lunar surface magnetometer (LSM) at the Apollo 15 site (~ 26°6′N, 3°39′E) near Hadley Rille on the southeastern margin of Mare Imbrium show a noteworthy response to electromagnetic induction by variations in the interplanetary magnetic field. Above approximately 5 mhz, magnetic field oscillations at the LSM are strongly linearly polarized in a direction roughly northwest-southeast and tangent to the lunar surface at the Apollo 15 site. This direction is approximately radial with respect to the circular Imbrium basin and is also approximately parallel to Montes Haemus, forming the southwestern boundary of Mare Serenitatis. The local steady magnetic field at the Apollo 15 site is small [3.3 ± 1.5, 0.9 ± 2.0, and 0.2 ± 1.5 gammas in the vertical, easterly, and southerly directions, respectively (*1*)], thus bearing no obvious relationship to the phenomenon. In a brief report of the Apollo 15 lunar inductive response Smith *et al.* (*2*) did not consider polarization effects. We speculate that these linearly polarized magnetic field oscillations oriented along a northwest-southeast line may be a regional inductive response to interplanetary field variations, associated with the close proximity of either the Imbrium basin or the Serenitatis basin, or both.

Striking evidence for the almost invariant orientation of magnetic field oscillations seen by the LSM is the mirror-image symmetry of the time series of magnetic field fluctuations in the plane tangent to the surface and in the eastward and northward directions at the Apollo 15 site, B_y and B_z, respectively. Three separate 30-minute time swaths shown in Fig. 1 display obvious mirror-imaging, resulting from the east-west, north-south decomposition of strongly linearly polarized magnetic field fluctuations oriented northwest-southeast. During the half-hour intervals shown in Fig. 1, the moon was in the solar wind and the LSM was located just beyond the dusk limb on the nightside. Time series records of magnetic field oscillations observed by the Ames magnetometer on the Explorer 35 (Ex 35) satellite in lunar orbit, during the identical time intervals used in Fig. 1, showed no evidence of a similar preferred polarization. The Ex 35 magnetometer measures the interplanetary magnetic fields driving the lunar inductive response. Thus, either the global induction somehow introduces a preferred northwest-southeast polarization from the field of interplanetary polarizations whose only preferred direction is north-south [this report and (*3*)], or the induction is dominated locally by spatial variations in physical properties which cause eddy currents to flow in preferred directions.

For a more quantitative study of the Apollo 15 magnetic field oscillations, we have carried out Fourier analyses of the time series records of the instrument during its first lunation of operation. Power spectral densities have also been computed for simultaneous Ex 35 magnetic field data. The data reduction techniques are identical to those used in the analyses of the Apollo 12 LSM data (*4*). Figure 2, A and B, shows the directional properties of the power spectral density (in gammas squared per hertz) of the fluctuations in the magnetic field tangent to the lunar surface at the Apollo 15 site for frequencies of 1.66, 4.97, 7.45, 9.94, 19.9, and 39.7 mhz. Directional characteristics of the power spectral density of the interplanetary magnetic field oscillations projected on the plane locally tangent at the Apollo 15 site are also shown in Fig. 2 (Ex 35). In the polar plots of Fig. 2, 0°, 90°, 180°, and 270° are local east, north, west, and south, respectively, at the Apollo 15 site, and in any particular direction the length of the vector is proportional to the power spectral density. The data used in Fig. 2 were obtained when the LSM was in daylight, exposed to the solar wind. Local times were approximately midmorning and midafternoon for Fig. 2, A and B, respectively.

The power at the LSM and at Ex 35 have qualitatively similar directional behavior below about 5 mhz. At these frequencies the Apollo 15 magnetic