Measurement of the Optical Properties of Lunar Rocks in the Transition Zone, Resulting From Observations Made by Lunokhod 2

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While traveling in a southerly direction from the landing point, Lunokhod 2 passed through a region of gradually changing albedo when it entered the "dark" highlands. Photometric measurements were carried out directly on the lunar surface with the aid of a calibration device, a plate with fields of different brightness, placed in the field of view of the panoramic telephotometers. The brightnesses of the fields of the calibration plate were measured in preliminary studies, relative to the brightness of a magnesia screen. This permitted determination of the reflectance features of the surficial lunar material relative to the standard most widely used in brightness studies of natural substances. The total brightness of sections a few centimeters across was recorded in direct proximity to the apparatus. The total area investigated in one panorama was about one square meter. Several areas in the mare and highland regions were studied. The albedos of various surface objects were obtained. A comparison of the brightness measurements with data from the RIFMA-M instrument[1] discloses a correlation of the albedo change with change in chemical composition of the surface rock.

The reflectance feature of lunar rocks is one of the characteristics that identify them with mare or highland types. In this respect, direct photometric studies of the lunar surface in the "mare-highland" transition zone assist in tracing the transition from one type of rock to another, and in obtaining information on the processes of material exchange between these two types of lunar landscape.

Technique

To perform photometric measurements on the Lunokhod 2 self-propelled vehicle, plates with fields of different brightnesses were placed in the field of view of the panoramic telephotometers. The total number of brightness fields represents 39 gradations from black to white and permits the brightness of lunar surface objects to be measured by the comparison method, for a broad range of standard system ensures the possibility of angles of incidence and reflection, with respect to both the plane of the photometric chart and the position of the terrain detail being studied. As a rule, the working range was shifted, depending on the illumination and observation conditions, to the dark or light region of the photometric plate, and encompassed eight gradation fields during measurements. During preliminary studies of the field brightnesses of the photometric plates, the relative brightness of an "absolute white screen" coated with magnesium oxide was determined. This technique permits measurement of the reflectance of lunar material with the standardization most widely used in studies of natural substances. Thus, use of a

[1] RIFMA-M is an automatic X-ray fluorescence spectrometer, using nondispersive detectors and a radioisotopic exciting source. It was used on Lunokhod 2 to measure the chemical composition of several locations on the lunar surface.

more reliably comparing the reflectance of naturally occurring lunar material with similar properties of terrestrial rocks. It should be remembered that the standardization ordinarily used in planetary astrophysics is based on photometric calibration with reference stars.

Presentation and Discussion of the Data

Preliminary data on the reflecting properties of the lunar surface from Lunokhod 2 measurements contain the results of photometric processing of fragments of five panoramas that include images of the photometric plates. These panoramas were obtained during the second lunar day of operation of Lunokhod 2. Two of them are of mare-type regions inside Le Monnier crater about 4.0 km south of the landing site. Three panoramas were obtained in succession, during one session, on the wall of a crater 2 km in diameter, and located in the highland region south of the landing site. Each measurement section was located in direct proximity to the apparatus and occupied an area of about one square meter. The brightnesses of selected objects and areas within these sections were measured relative to the smooth surface. As an example, a diagram of the locations of brightness measurement sections in the highland region is presented in figure 1. The diagram is oriented to the points of the compass; I, II, and III indicate the positions of the camera when taking the panoramas and the directions to the center of the photometric charts; 1, 2, and 3 are areas where the brightness of surface details was measured; 4 is the track left by the wheels of the Lunokhod chassis; and 5 is the track of the ninth wheel, intended for measurement of the distance traveled. The brightness of a number of rocks and lumps of soil, of the soil displaced by the Lunokhod wheels, and of the track left by the ninth wheel were measured in sections 1 and 2. The separate measurements are the total brightness of an area several centimeters across.

The brightness of areas of comparatively smooth surface was distributed uniformly within the sections. Thus, the data in each area provide a small statistical sample that characterizes the brightness distribution. By means of directional light scattering indicatrices for the lunar surface (ref. 1), the measured brightness was recalculated to albedo values. The samples of individual sections were associated in pairs, for the mare and highland regions, respectively. According to these data, the weighted average albedo value for the mare turned out to be $\rho_0 = 5.85$ and, for the highlands, $\bar{\rho}_0 = 6.72$. A comparison with the albedo map for the region of Le Monnier crater, compiled from terrestrial observations in the photometric catalog system (ref. 2), as well as comparison with the albedo map (ref. 3) where the albedo values had been reduced to the catalog system (ref. 2), shows that there is the following linear relation $\rho_0 = 0.790\ \rho_0^k$. The superscript ℓ designates the albedo value with the magnesia screen standardization (Lunokhod 2 data), and superscript k designates the albedo value in the catalog system (ref. 2), standardized in the reference star system. The relation obtained indicates that the true albedo of the naturally occurring lunar material is somewhat less than the values which are usually given from ground astronomical observations.

During the investigations carried out by the Lunokhod 2 self-propelled vehicle, the chemical composition of lunar rocks was determined by the RIFMA-M instrument. According to these data (ref. 4), the content of aluminum with respect to silicon in the mare region (albedo $\bar{\rho}_0$) is 0.37 and, in the highland region (albedo $\bar{\rho}_0$) equals 0.48. The dimensions of the areas in which the chemical composition and albedo were determined were approximately the same. An overall curve of the dependence of albedo on chemical composition of the rocks is shown in figure 2 according to the Al/Si argument (1 indicates the data of the orbital selenochemical survey and the albedo map (ref. 5)). The albedo values in figure 2 are given in the catalog system (ref. 2). The albedo values for the

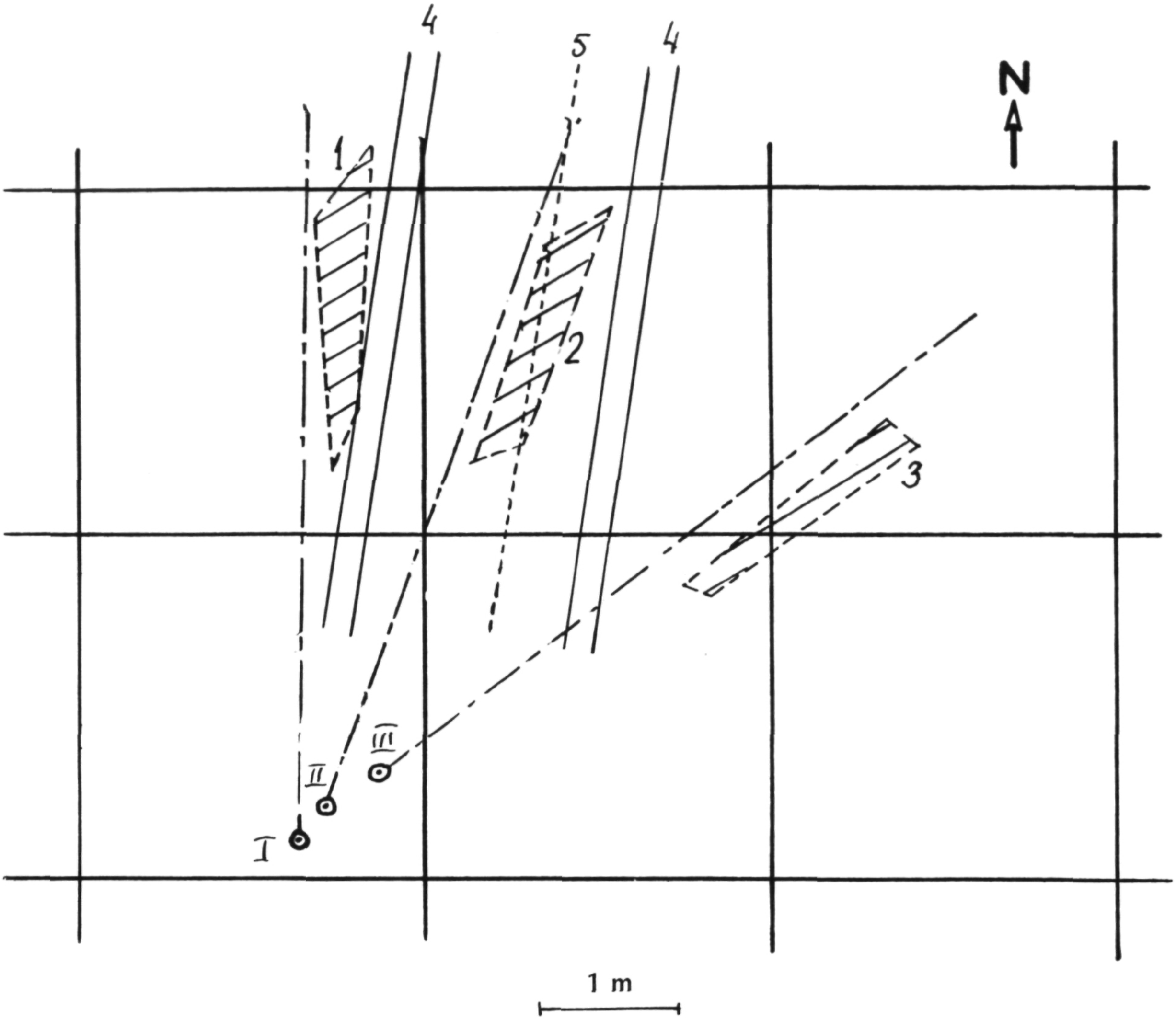

Figure 1.—*The locations of brightness measurement sections in the highland region. The arrow indicates north. Roman numerals I, II, and III indicate the positions of the camera when the panoramas were photographed, and the directions to the center of the photometric charts. Arabic numerals 1, 2, and 3 designate areas where the brightness of surface details was measured; 4 indicates the track left by the wheels of the Lunakhod chassis; and 5, the track of the ninth wheel.*

mare and highland regions in the area of Le Monnier crater, converted to this system, agree well with the overall relation of albedo to chemical composition of the rock (2 identifies data from the RIFMA-M chemical measurements and the Lunokhod 2 brightness measurements). This circumstance makes it possible to interpret the presence of material with different albedos in the regions being studied in terms of the local distribution of known types of lunar rocks. According to the data correlated by Shevchenko (ref. 5), the following albedo values correspond to different types of lunar rocks (in the Lunokhod 2 photometric measurement system): the albedo of mare basalts is less than 6.0–6.5; the albedo of noritic rocks is 6.5–9.5; the albedo of anorthositic rocks is over 9.5. Histograms showing the percentage distribution of albedos in "smooth" surface sections for

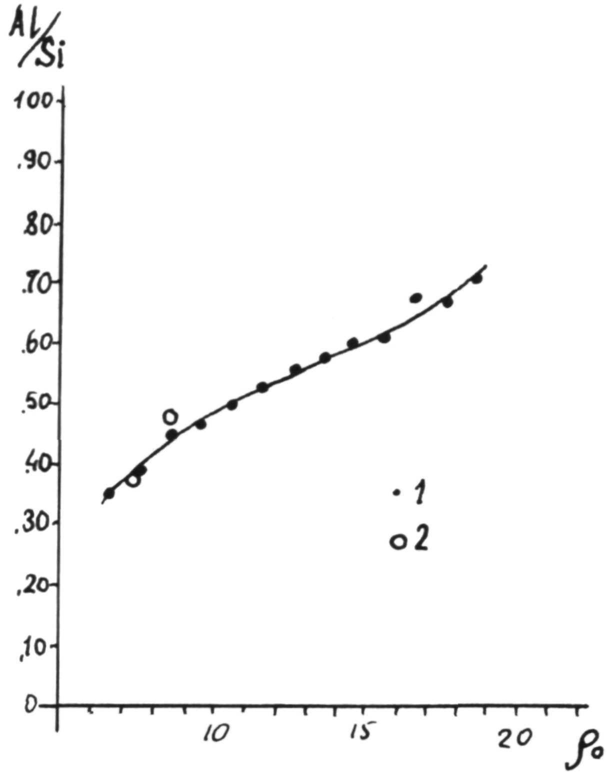

Figure 2.—*A general curve of the dependence of albedo on chemical composition of the rocks. 1—data from orbital surveys: 2—data from Lunokhod 2.*

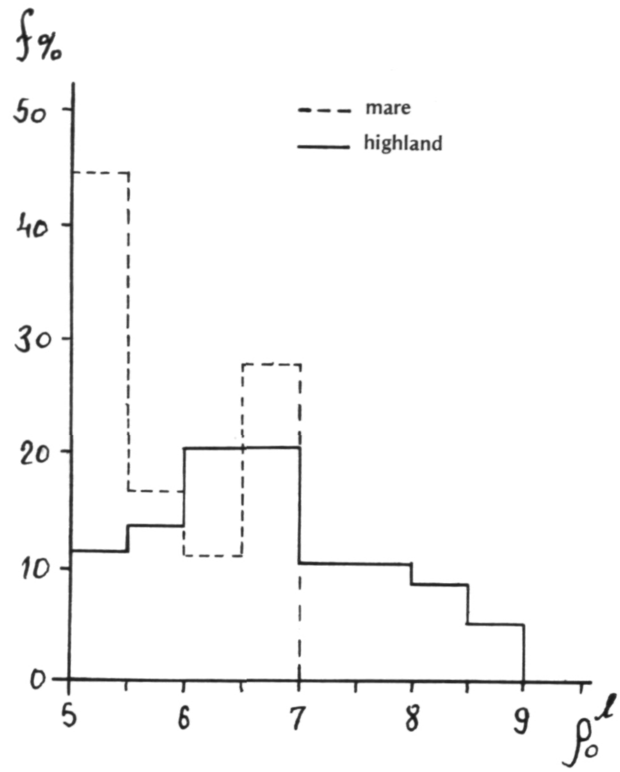

Figure 3.—*Histograms showing the percentage distribution of albedos in "smooth" surface sections for mare and highland samples.*

mare and highland samples, are presented in figure 3. A covering material with a low albedo predominates in the mare region, i.e., basaltic rocks. However, about one-third of the surface studied is covered with a lighter material, presumably of noritic composition. Both a dark material of basalt composition and a lighter material are encountered in the highland region where there is a clear predominance of rock of noritic composition. As was mentioned above, within the areas studied in the highland region, brightness was measured for individual objects differing in structure. As far as the resolution of the initial images permits, lumps of soil and rocks belong to different groups on the basis of outward appearance. In calculation of the albedo of these objects, change in brightness because of their shapes was taken into account. The albedos of the objects listed are presented in table 1.

Table 1.—*Albedos of Specified Objects*

Soil in Track of Lunokhod Chassis Wheels	Track of Ninth Wheel	Lumps of Soil	"Dark" Rocks	"Light" Rocks
9.5	11.5	8.0	11.0	12.2
	11.3	8.4	11.8	12.7
	10.8	9.0	10.5	13.2
			11.4	
			10.7	

It follows from the data of table 1 that objects distinguished as "lumps of soil" have the same albedo as a number of sections of "smooth" surface. In all likelihood, this circumstance may confirm the identity of their natures and chemical compositions. Soil compacted by the action of the chassis wheels and the ninth wheel of Lunokhod brightens considerably. A similar soil-brightening phenomenon, as a result of its compaction, was repeatedly noted earlier. In this connection, it might be concluded that the "dark" rocks do not differ in composition from the underlying surface. Their higher albedos may be explained by the greater density of the reflecting surface of the layer of material. The fact that the albedos of the "dark" rocks and compacted soil are the same confirms this hypothesis.

The nature of the "light" rocks is different. The high albedo values indicate that they may be crystalline fragments of anorthositic gabbro-type rocks. The nearest region with similar optical characteristics (Roemer crater) is at a distance of about 200 km from the Lunokhod 2 study location. The assumption of material transport does not agree with observational results in this case, since similar light fragments have not been found in the neighboring mare region. It is difficult to assume that the ejection mechanism accompanying formation of Roemer crater acted so selectively. The absence of "light" rocks on the mare surface might be explained by the formation of Roemer crater in the pre-mare epoch. However, structural characteristics of this crater and the high albedo are characteristic of post-mare craters. In figure 3, note the sharply differing distributions of rock types in the mare and highland regions. The distribution approaches the normal for the highlands. The mare region is characterized by a clearly expressed bimodal distribution. In the event of a mutual material transport mechanism, a uniform distribution might be expected.

The described characteristics of the distribution of lunar rocks in the transitional zone lead to the conclusion that a mechanism of vertical mixing of material may turn out to have the greatest effect. The fine fraction and individual fragments that differ from the rock typical of the place being considered may belong to deeper layers, uncovered in the process of crater formation. The depths of individual craters in this region are presented on a preliminary geologic map (ref. 6). Furthermore, crater depths may be obtained from their diameters by using the well-known average ratio between these parameters. It is evident that the depths of layers, differing in albedo from the surrounding terrain, can be estimated from the crater depths. In this case, the results of a lunar surface spectrozonal survey also were drawn on to reveal similar craters. The estimates show that, in the vicinity of the mare region of the study, the thickness of the upper basalt layer may reach a relatively low value of 50–100 m. Such a significant fraction (over 30 percent) of noritic rocks in the surface material apparently is explained by this circumstance. The Apollo 17 seismic study data can be introduced, for an order of magnitude comparison. In the vicinity of the landing point, located 200 km south of Le Monnier crater, the upper layer of the mare basalts proved to be 248 m thick (ref. 7). In the highland region of the Lunokhod 2 study, the noritic rock layer, in all likelihood, reaches a thickness of 200–300 m. A layer of anorthositic gabbro, individual fragments of which were found, can be assumed to lie below this depth. A thicker layer of rocks, with the chemical composition of the surface, explains the differing nature of the distribution histograms for the highland region.

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