The x-ray analyses of traverses across particle interfaces of lapped and polished crystalline specimens are typical of material formed from high-temperature phases. Low-temperature sintering (*5*) has not been found in the fine grained vesicular material from the powder 10084,93, in the coarse fines 10085,36, or in the rock specimen 10065,33. However, the Apollo 11 samples that were exposed to N_2 may have already disrupted at sintered interfaces.

JACK J. GROSSMAN, JACK A. RYAN
NALIN R. MUKHERJEE
MARY W. WEGNER
McDonnell Douglas Astronautics Company, Western Division, Santa Monica, California 90406

References and Notes

1. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969); Surveyor Program, NASA SP-184 (1969).
2. C. Young III, *Amer. J. Sci.* **267**, 841 (1969); C. B. Raleigh, *J. Geophys. Res.* **73**, 5391 (1969); M. W. Wegner, J. J. Grossman, *Trans. Amer. Geophys. Union* **50**, 676 (1969).
3. J. A. Ryan, J. J. Grossman, W. M. Hansen, *J. Geophys. Res.* **73**, 6061 (1968).
4. P. J. Bryant, L. H. Taylor, P. L. Gutshall, Transactions of the 10th National Vacuum Symposium, (Macmillan, New York, 1963), p. 21; B. V. Deryagin, M. S. Metsik, *Soviet Phys., Solid State* **1**, 1393 (1960); J. J. Grossman, *J. Vac. Sci. Technol.* **6**, 233 (1969); J. A. Ryan, *J. Geophys. Res.* **71**, 4413 (1966); J. W. Salisbury, P. E. Glaser, B. A. Stein, B. Vonnegut, *ibid.* **69**, 235 (1964).
5. R. Smoluchowski, *Science* **150**, 1025 (1965).
6. We thank W. M. Hansen, A. D. Pinkul, W. B. Edwards, L. V. Marmaduke, G. Prather, Mrs. M. J. Dobson, A. R. Lopez, E. L. Miller, A. Phillips, Mrs. B. Tooper, and Dr. N. N. Greenman for their contributions to the program. Supported by NASA contract NAS9-8082 and NAS 7-307.

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Solar Radiation Effects in Lunar Samples

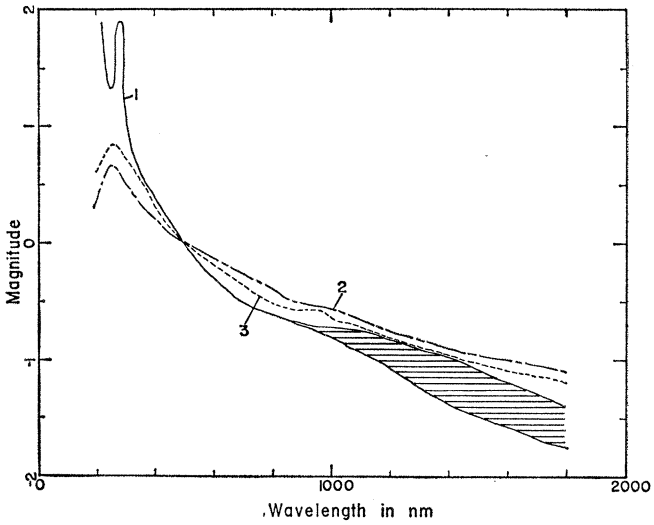
Abstract. *Optical properties of the pulverized crystalline rocks from the Apollo 11 samples are different from the optical properties of lunar soil. Changes in these properties were induced in the samples by ultraviolet and x-irradiation, standing, and heating. The albedo and spectrum of the soil differed significantly from expected values.*

The purpose of our work is to ascertain the possible role that various types of radiation may have played in determining the optical properties of the lunar surface. We investigated the effects of low-energy protons, ultraviolet and x-ray irradiation, heating, particle size, composition, and packing on the albedos and spectra of the samples.

The particle size distribution in fines sample 10084,81 was measured by sieving and sedimentation. The median particle size, weighted by mass, was about 40 μm, with over 35 percent of the mass contained in particles smaller than 20 μm. These results are in agreement with a previous size determination (*1*) and with estimates of "mean particle size of a few tens of microns or less" (*2*), based on telescopic optical data.

According to Wildey (*3*) the 0° phase angle albedo of the moon in the vicinity of the Apollo 11 site is approximately 0.099. Correcting this value for photometric function to a 6° phase angle gives 0.079. However, the subsurface soil appears to be darker than the surface material by 5 to 30 percent, depending on location (*4*). Since most of the sample presumably came from below the surface, a 6° albedo in the range of 0.060 to 0.076 is thus to be expected. The actual measured value relative to MgO is 0.090. The degree of compaction of the material cannot reduce this value sufficiently. We conclude that the returned sample of fines may not be representative of the general region of the moon around Tranquillity Base, at least as far as the factors that determine albedo are concerned.

The reflection spectrum of the fines, as measured by a Cary 14 spectrophotometer, is shown in Fig. 1 along with the general spectrum of the moon (*5*). The general lunar spectrum is considerably redder than the spectrum of the fines. We are not certain of the reason for this discrepancy; it may reflect errors in our measuring techniques, or it may indicate that this material is not typical of the surface of the moon as a whole, possibly because of alteration processes acting on the lunar surface or changes which occurred during or after collection. There is no sign in the fines of the 290-nm band reported in the lunar spectrum. We caution that the apparent peak at 250 nm in our data may be spurious. However, an absorption band at 900 to 1000 nm due to Fe^{2+} is clearly present in the spectrum of the fines.



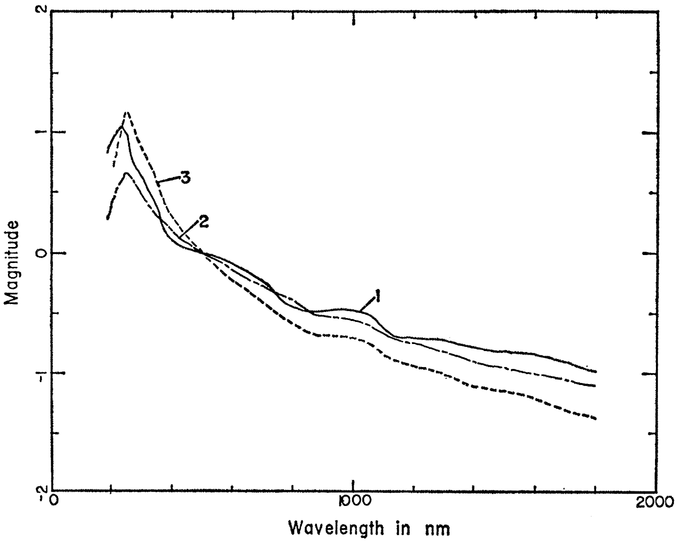


Fig. 1 (left). Relative reflection spectra, in magnitudes, of lunar materials, normalized at 500 nm; curve 1, average moon; curve 2, fines; curve 3, fines after ultraviolet irradiation. Fig. 2 (right). Relative reflection spectra, in magnitudes, of lunar materials, normalized at 500 nm; curve 1, pulverized crystalline rock 10022; curve 2, fines; curve 3, powdered rock after H-ion irradiation.

The lunar soil is commonly thought to be derived from larger fragments of lunar surface material by meteorite comminution. We attempted to ascertain whether the parent rocks of the soil could be identified by reflection spectra. Chips of all rocks received in our original allocation (numbers 10017 and 10022, crystalline, and 10048 and 10065, breccia) were ground to finer than 37 μm. The spectra and albedos of the powdered breccias are similar to those of the fines; however, these rocks are probably daughter products of the soil, formed by impact, rather than the parent rocks.

The crystalline rock powders are twice as bright as the fines, with albedos of 0.183; also the spectra of the two materials show significant differences (Fig. 2). However, the rocks and the fines are chemically quite similar (*1*). We emphasize that four rocks constitute too small a sample on which to base firm conclusions. However, if the crystalline rocks are indeed representative of the parents of the fines, then the optical properties of the crystalline rock powder must have been altered by some factor in the lunar environment.

It is suggestive that the albedo of the crystalline rock flour is similar to the albedo of the brighter rays on the moon. We also point out that several of the small differences between the spectra of various regions on the moon (*6*) can be accounted for if varying amounts of unaltered crystalline rocks or flour are exposed on the lunar surface.

It has been suggested that the solar wind is responsible for the low albedo and reddish color of the lunar soil (*7*). Therefore, a pulverized sample of crystalline rock 10022 was irradiated by approximately 20 coulomb/cm^2 of 2-kev hydrogen ions. This treatment reduced the albedo of the flour from 0.18 to 0.12, and the spectrum became more red, as shown in Fig. 2. This irradiation was conducted in a vacuum system constructed only of metal and ceramic components and evacuated by a sputter-ion pump with molecular-sieve roughing.

A sample of fines was subjected to intense ultraviolet and visible radiation from a 200-watt Oriel xenon-mercury lamp for 16 hours. This treatment (the dose has not yet been calibrated) increased the albedo from 0.090 to 0.096 and altered the spectrum of the soil (Fig. 1). Probably Fe^{2+} ions in the material were oxidized to Fe^{3+} by radiation, with a resulting decrease of absorption in the visible and near-infrared and increase in the ultraviolet.

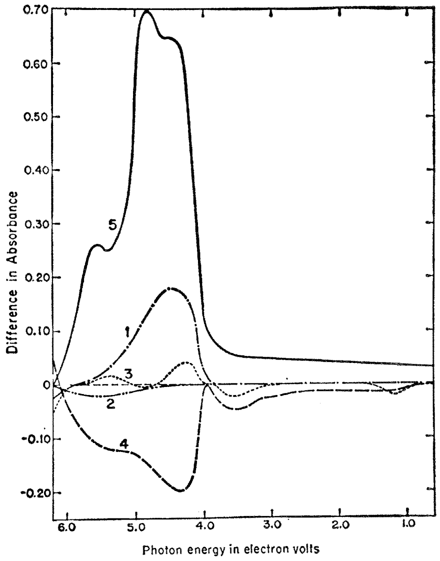


Fig. 3. Changes in absorption spectrum of lunar rock 10017 caused by radiation; curve 1, difference after ultraviolet treatment; curve 2, difference after x-irradiation from ultraviolet treatment; curve 3, difference after standing 330 hours after x-irradiation; curve 4, difference after heating at 200°C from standing; curve 5, difference after heating at 500°C from heating at 200°C.

The ultraviolet irradiation was carried out in air, and during this time the sample was heated to 160°C. To ascertain that the oxidation was not due to heating, another sample of soil was heated to 200°C in air; no change in albedo or in reflection spectrum occurred.

These radiation-induced changes were studied more quantitatively by measuring the changes in the absorption spectrum of a polished thin section of crystalline rock 10017, approximately 1 by 1 by 0.001 cm (*8*). The polished specimen of crystalline rock contained opaque ilmenite and three major transparent minerals: colorless plagioclase and two varieties of light brown pyroxenes. The spectra reported here are most probably spectra of the pyroxenes.

The spectrum of the sample before any treatment other than cutting and polishing showed the typical spectrum of ferrous ions in the near-infrared region and intense absorption due to ferric ions in the far-ultraviolet.

Because these spectra were similar to spectra of ferrous and ferric ions in synthetic quartz (*9*), we decided to use quartz as a lunar model and to perform experiments similar to earlier experiments.

Treatment of the specimen with unfiltered light of the xenon-mercury lamp for 23 hours resulted in the change shown in Fig. 3, curve 1. By subtracting the spectrum obtained before this ultraviolet treatment from the spectrum taken after treatment, we obtained the difference spectrum, which illustrates changes in the 1- to 6-ev region of the spectrum. Although no noticeable decrease had taken place in the ferrous region between 1 and 1.5 ev, there was a growth in the ferric region of the spectrum centered near 4.5 ev. The lunar rock wafer was next x-irradiated at 45-kv peak, 35 ma, with a Machlett AEG50T tube for 6 hours about 2 cm below the beryllium window. The difference induced by the x-ray treatment is shown in Fig. 3, curve 2. A decrease in the absorption spectrum took place in the ferric region centered near 5.5 ev. The specimen was allowed to stand at room temperature for 330 hours in subdued light. A decrease in the ferrous band occurred, accompanied by increase in two bands in the ferric region as shown in Fig. 3, curve 3. Heating the specimen for 2 hours at 200°C caused a large decrease in the region of the same two bands that increased previously (Fig. 3, curve 4). The specimen on standing showed decreased absorption on the deep ultraviolet and in the 3- to 4-ev region. This region decreased further on heating although the far ultraviolet showed an increase. As shown in Fig. 3, curve 5, heat treatment at 500°C in air for 2 hours caused an intense development of the α, β, and γ bands of the ferric ion (*9*). We interpret these results as follows.

If we take iron in quartz as a model, (i) ultraviolet treatment caused oxidation of ferrous ion with development of the β and γ ferric bands; (ii) x-ray treatment caused a reduction of ferric ion as shown by decrease in the α ferric band; (iii) standing caused slight oxidation of ferrous to ferric as shown by increase of α and γ ferric bands and decrease in the ferrous band; (iv) heating at 200°C caused a readjustment in the structure with possible oxidation of titanium, as indicated by increase at the ultraviolet cutoff, and decrease in the intensity of the ferric α, β, and γ bands; (v) heating at 500°C for 2 hours caused oxidation of probably most of the remaining ferrous ion with appearance of intense α, β, and γ bands of ferric ion. The trace ferric ion with high oscillator strength shows greater total change in absorbance than the abundant ferrous ion of low oscillator strength.

We conclude that these effects take

place primarily in the iron-containing pyroxenes, which are quite sensitive to radiation and temperature (in air) and should be a dynamic system when subjected to the direct solar wind even in vacuum.

Ever since the successful landing of Surveyor 1 it has been observed that gentle disturbance of the lunar soil, except by compression, results in a material which is as much as 30 percent darker than the undisturbed surface (*4*). We attempted to test several of the proposed explanations for this effect.

1) *Ultraviolet bleaching* (*10*). Ultraviolet irradiation of the soil caused albedo increases of approximately 6 percent; this value is of the same order as the disturbance effect observed by Surveyor 5.

2) *Packing.* The albedo of the soil is affected by the micromorphology of the surface in the sense that the looser the packing, the lower the albedo. The following albedos were obtained, depending on surface preparation: (i) sifted, 0.085; raked with a needle, 0.087; spooned onto a plate, 0.090; jarred by dropping the container from a height of about 5 cm, 0.094; tamped by pressing gently with the flat side of a spatula, 0.10. Since the lunar soil is continually stirred by micrometeorites it is doubtful that the natural condition of the surface is similar to that produced by tamping. Thus packing effects apparently are capable of altering the albedo by up to 10 percent.

3) *Particle size* (*11*). The albedos of fractions of fines separated as to particle size by dry sieving were measured with the following results: >149 μm, 0.089; 74 to 149 μm, 0.081; 37 to 74 μm, 0.080; < 37 μm, 0.079; unseparated, 0.090. Hence albedo differences of about 10 percent might be possible if the upper layer of particles are larger on the average than those below the surface.

4) *Lunar varnish* (*12*). Samples of the fines were examined with an optical microscope, a scanning-electron microscope, and an electron microprobe for coatings of dark material which might be scrubbed off by solar wind sputtering, but no definite evidence for such coatings was found. However, under high magnification the surfaces of many grains exhibited peculiar textures, which we were unable to interpret. These may indicate the presence of an amorphous coating on parts of some grains. In order to test the possibility that coatings of carbonaceous material might be present, a thermogravimetric analysis was carried out by heating a soil sample to 1200°C in air and measuring the change in weight (*13*). The weight of the sample increased continuously and monotonically with temperature because of oxidation, and no decrease, such as might be caused by ignition of a carbonaceous coating, was observed at any temperature.

5) *Conclusion.* Although several effects can alter the albedo of the lunar soil by up to 10 percent, none of the hypotheses yet advanced to explain the disturbance effect seem capable of completely accounting for all observations, but any or all of the hypotheses discussed here may contribute.

B. W. Hapke, A. J. Cohen
W. A. Cassidy, E. N. Wells
Department of Earth and Planetary Sciences, University of Pittsburgh, Pittsburgh, Pennsylvania 15213

References and Notes

1. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
2. B. Hapke, *Planet. Space Sci.* **16**, 101 (1968).
3. R. Wildey, private communication.
4. L. Jaffe *et al.*, *J. Geophys. Res.* **73**, 7165 (1968); E. Shoemaker *et al.*, *ibid.* **74**, 6081 (1969).
5. B. Hapke, in *Physics and Astronomy of the Moon*, Z. Kopal, Ed. (Academic Press, New York, ed. 2, 1970), vol. 1, p. 72.
6. T. McCord, *J. Geophys. Res.* **74**, 3131 (1969); ———, T. Johnson, H. Kiefer, *ibid.*, p. 4358; T. McCord and T. Johnson, *ibid.*, p. 4395.
7. B. Hapke and H. Van Horn, *J. Geophys. Res.* **68**, 4545 (1963).
8. Sample preparation by G. Moreland, U.S. National Museum.
9. A. J. Cohen and F. Hassan, *Science* **167**, 176 (1970).

→ A. J. Cohen and B. Hapke, *ibid.* **161**, 1237 (1968).

11. A. Felice, *J. Geophys. Res.* **72**, 5721 (1967).
12. E. Shoemaker *et al.*, *J. Geophys. Res.* **73**, 3989 (1968).
13. We thank G. Aubele and the Fisher Scientific Company for performing this analysis.
14. We thank B. Greenspan and F. Hassan for assistance. Supported by NASA contract NAS 9-9942.

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Determination of Manganese-53 by Neutron Activation and Other Miscellaneous Studies on Lunar Dust

Abstract. *A highly sensitive determination of spallogenic* ^{53}*Mn* (T = 2 × 10^6 *yr*) *was accomplished in 0.99 g of lunar soil. The chemical yield of Mn is determined with "carrier-free"* ^{52}*Mn tracer. During a 23-day reactor irradiation the* ^{53}*Mn is transformed into* ^{54}*Mn* (T = *300 days*). *Appropriate chemical recycling was done by ion exchange and distillation. Interferences of the (n,p) and the (n,2n) nuclear reactions were carefully studied. A* ^{53}*Mn disintegration rate of 30.3* ± *5.5 dpm/kg results. This extremely economic method is proposed for further detailed lunar profile measurements. The Re content, which is of possible cosmochemical interest, was determined to be 11 ppb. Appropriate separation techniques were used. The rather weak and complex thermoluminescence properties made a more basic study advisable. Thermogravimetric analysis, mass spectroscopy, and Moessbauer spectroscopy were applied. The presence of ilmenite, metallic Fe etc., and of an unidentified* Fe^{2+}*-containing compound was deduced. Natural thermoluminescence could not be proved with certainty in our surface sample. However, the complexity of the artificial thermoluminescence demands better defined mineral fractions. The fission track method was used to measure U distribution in glass spherules etc.*

Manganese-53, favored by its high production cross section and long half-life of about 2 × 10^6 years, is one of the most interesting nuclides in space research. However, detection of the ^{53}Mn nuclide is rather difficult because of its soft x-rays, and only sophisticated "low-level" techniques succeed. This contrasts with ^{26}Al, which can be detected nondestructively by its characteristic γ-cascade with fairly high sensitivity. (Even with our 5-g sample of lunar dust, we were able to detect the stronger γ-emitters.)

Working with meteorites, a very sensitive and therefore economic method was found in which we convert ^{53}Mn by neutron capture into γ-emitting ^{54}Mn (*1–3*), as Millard (*4*) had proposed some years ago.

In 1957 Sheline and Hooper (*5*) predicted that, in meteorites, the long-lived ^{53}Mn isotope should be produced in relatively high yield. Honda *et al.* (*6*) thereafter confirmed this experimentally. Although the half-life of ^{53}Mn is not yet fully established, a half value of (1.9 ± 0.5) × 10^6 years was suggested by Kaye and Cressy (*7*). They compared the ^{53}Mn activity of an iron meteorite of high terrestrial age with the ^{53}Mn activity of a chondrite with short radiation age. However, the method involves a number of uncertainties, which must be allowed for. Millard showed that the product of the