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WORKSHOP ON THE SPACE ENVIRONMENT: THE EFFECTS ON THE OPTICAL PROPERTIES OF AIRLESS BODIES

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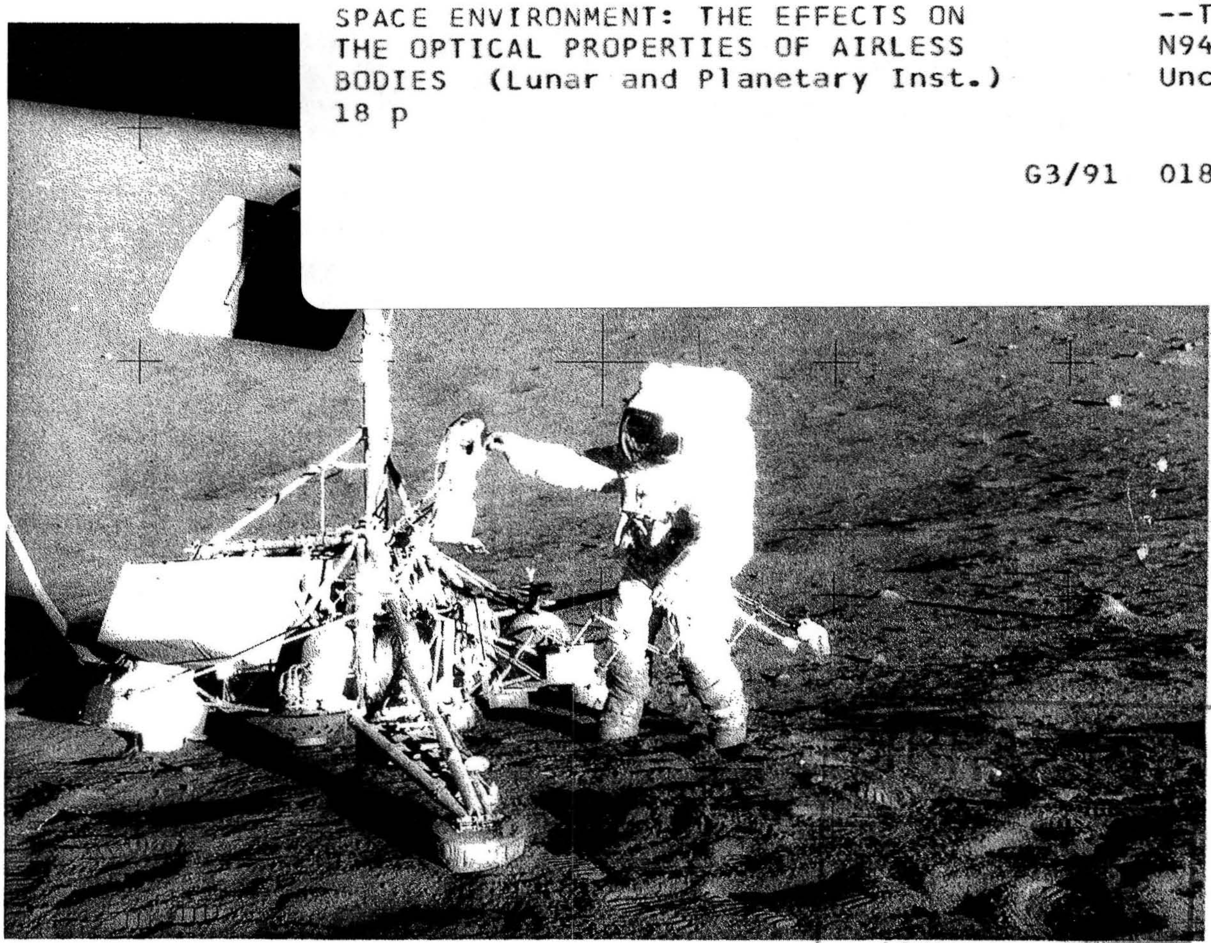

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MINS: / LUNAR ROCKS/ LUNAR SOIL/ POLARIMETRY/ SOLAR SYSTEM/ SPECTRAL REFLECTANCE
       / SPECTROPHOTOMETRY/ WEATHERING
ANN:  Reflectance spectrophotometry and polarimetry are major tools in remote
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 component responsible for alteration of the optical properties, the
 process that produced this component, and how reliably the effects of
 these processes could be extrapolated to other bodies of the solar system.
 For individual titles, see N94-14299 through N94-14303.









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WORKSHOP ON
THE SPACE ENVIRONMENT:
THE EFFECTS ON THE OPTICAL PROPERTIES OF AIRLESS BODIES

Edited by

B. Hapke, B. Clark, G. Benedix, D. Domingue, and M. Cintala

Held at
Lunar and Planetary Institute
Houston, Texas

November 9–10, 1992

Sponsored by
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Cover: This photograph, taken on November 20, 1969, during the second Apollo 12 extravehicular activity, shows two spacecraft on the lunar surface. The Surveyor III spacecraft is in the foreground and the Apollo 12 Lunar Module is approximately 600 ft in the background. Examinations of Surveyor III were made in an endeavor to understand the effects of 31 months of exposure to the lunar environment on a spacecraft. The television camera and several other pieces of Surveyor III were removed and returned to Earth. This photograph shows Astronaut Charles Conrad Jr. examining Surveyor III's television camera prior to detaching it. The unmanned Surveyor III soft-landed in the Moon's Ocean of Storms on April 19, 1967.

Preface

On November 9 and 10, 1992, the Workshop on the Space Environment: The Effects on the Optical Properties of Airless Bodies was held at the Lunar and Planetary Institute, Houston, Texas. The intent of this workshop was to bring together a diverse group of scientists who have actively worked on this topic to assess recent advances in related scientific disciplines in a free-format, open-discussion forum.

Co-chairmen were Bruce Hapke *(University of Pittsburgh)* and Mark Cintala *(NASA Johnson Space Center)*. Other members of the organizing committee were Deborah Domingue *(Lunar and Planetary Institute)*, Michael Gaffey *(Rensselaer Polytechnic Institute)*, Wendell Mendell *(NASA Johnson Space Center)*, and Douglas Nash *(San Juan Capistrano Institute)*.

Of the 41 people invited to the workshop, 24 attended. The names and affiliations of the attendees are included at the end of this report. Feedback from the attendees indicated that the workshop met its goal and was a resounding success. A surprising degree of consensus on this controversial topic was reached among the workshop participants.

Program

Monday, November 9, 1992

9:00–9:30	Introduction *B. Hapke*
9:30–11:30	Laboratory Simulations of Darkening Processes *Speaker: B. Hapke* *Moderator: C. Pieters*
1:00–3:30	Effects of Impact Melting and Vaporization *Speakers: M. Cintala, D. McKay, and L. Keller* *Moderator: B. R. Hawke*
3:30–5:30	Discussion of Lunar Sample Suite *Speakers: D. McKay and L. Taylor* *Moderator: W. Mendell*

Tuesday, November 10, 1992

9:00–11:30	Extrapolations to Other Airless Bodies *Speaker: M. Gaffey* *Moderator: F. Vilas*
1:30	Future Directions *Moderator: L. McFadden*

Contents

Preliminary

3P

Summary of Technical Sessions

WORKSHOP RATIONALE

Reflectance spectrophotometry and polarimetry are major tools in remote sensing studies of surfaces of solar system bodies. The interpretations of such measurements are often based on laboratory studies of meteoritic, lunar, and terrestrial materials. However, the optical properties of regoliths are known to be affected by the space environment. These effects are not well understood, even in the case of the Moon, despite having had samples of lunar regolith for over two decades. Hence, any extrapolation of space weathering from the Moon to other bodies is highly uncertain.

An improved understanding of the effects of the space environment will lead to increased knowledge of all the airless objects of the solar system, from Mercury to the asteroids (in particular the Earth-crossers) and beyond. This understanding is pertinent to such problems as the parent body of the ordinary chondrites, the nature of asteroid regoliths, and the surfaces of outer solar system satellites.

Because the Moon is the only airless body from which we have documented samples of the regolith, the workshop was structured to emphasize our experience with lunar samples. Lunar soils are darker and redder than the pulverized rocks and minerals with which they are associated, and their diagnostic absorption bands are obscured. The dark component tends to be associated with the agglutinates, although not exclusively. Thus, some of the major questions addressed in the workshop include the identity of the soil component (or components) responsible for alteration of the optical properties, the process (or processes) that produced this component, and how reliably the effects of these processes could be extrapolated to other bodies of the solar system.

WORKSHOP STRUCTURE

The workshop was purposely structured to facilitate an open, informal, and interactive discussion of all the related questions. Consequently, the list of invitees was limited to those who have worked on such topics in the past or are actively working on them now. Included were experts on optical remote sensing, hypervelocity impact, meteorites, asteroids, and the petrology, geochemistry, and magnetism of lunar samples.

Each session was about two hours long and was led by an invited speaker and a moderator. The general task of each speaker was to present in a reasonably unbiased fashion a review of the state of their assigned subject, focusing on aspects that were unclear or controversial. Attendees were encouraged to interrupt the speaker at any time to present their own thoughts and to ask questions. During these interruptions, attendees were able to present slides or viewgraphs to illustrate the points they were trying to make.

The task of the moderator was to keep the discussions orderly and focused, which was sometimes difficult because of the unstructured format of the workshop; the moderators sometimes had to walk a fine line between maintaining order and inhibiting discussion. Nevertheless, each of the moderators managed to accomplish this task successfully.

Most of the invited speakers provided written abstracts of their talks, which are included in this volume.

HIGHLIGHTS OF THE PRESENTATIONS AND DISCUSSIONS

The workshop opened with introductory remarks by B. Hapke. In the two decades since the Apollo program there have been considerable advances in analytical techniques and in our understanding of the physics of light scattering by planetary regoliths. It is therefore worthwhile to reexamine the problem of the effects of the space environment on optical properties of regoliths, focusing on lunar samples.

Hapke was also the speaker for the first session on laboratory simulations of lunar darkening processes. Well before the Apollo program, groundbased observations had indicated that a process that darkens pulverized rock was operating on the Moon. Early speculations about the nature of this process included X-ray and gamma ray irradiation and direct reduction of silicates to free metal by the solar wind. However, none of these hypotheses were supported by laboratory experiments.

Once lunar soil samples became available, it was discovered that they contained large amounts of dark glass, suggesting that impact melting was the agent that darkened and reddened the soil and obscured the absorption bands associated with lunar materials. This seemed to be supported by laboratory experiments, and this hypothesis became so widely accepted that it is almost a paradigm. However, reexamination of these experiments showed that the fugacities during melting probably were well above the metallic iron-wüstite buffer, and that the low albedos of the glasses produced were due to a crystallized dark phase containing ferric oxide, probably magnetite. Hence, the glasses produced in these experiments would be extremely rare on the lunar surface, and so the paradigm is wrong.

Glasses made by melting actual and artificial lunar rocks under controlled fugacities similar to lunar conditions have high visual albedos and strong absorption bands. C. Pieters emphasized that the characteristic spectral features of glasses are even more obscured in the soil than those of the minerals, and that the fine fraction of lunar soil has a different spectrum than pulverized agglutinates. Thus, far from causing the darkening, the glasses appear to be even more affected by it than the minerals.

A considerable amount of time was spent discussing agglutinitic glass and how it differs from glass made by simple melting of indigenous lunar rocks. The main difference seems to be that agglutinitic glass contains finely dispersed metallic Fe.

The only known constituent of lunar soil that in principle appears to be capable of causing the darkening and reddening is submicroscopic metallic iron (SMFe), which is present at about the 0.5 wt% level in most soils. This material is responsible for the characteristic electron spin resonance (ESR) response of the soil, which is an indicator of soil maturity. The process that generates the SMFe and the exact location of the SMFe in the soil are not well understood. However, auger and X-ray photoelectron spectroscopy (ESCA) studies show that the surfaces of soil grains are enriched in Fe over the grain interiors. Acid leaching of fines lowers the albedo. Hence, the darkening appears to be associated with an Fe-rich surficial component of the soil.

The process that is almost universally accepted as producing the SMFe in lunar soil is reduction of FeO to free metal by impact heating of Fe silicates saturated by solar wind H. However, experiments that might support this hypothesis would be extremely difficult to carry out and none have been performed, so the hypothesis should be regarded as speculative.

Two other processes for producing SMFe that have stronger experimental support have been suggested: solar-wind-sputtered coatings and impact-vapor coatings. Most of the atoms sputtered from a grain of regolith by the solar wind will coat adjacent grains rather than escaping from the Moon. Hypervelocity impacts produce, in addition to melt, significant quantities of vaporized material, much of which travels downward and is trapped in the soil. Laboratory experiments show that vapor- and sputter-deposited coatings contain abundant SMFe and are dark. Estimates of the production rates of impact-generated vapor and sputtering on the Moon are comparable to the production rates of melt glass. However, because there is no direct evidence of their presence in soil samples, vapor-deposition hypotheses have not been widely accepted and thus are regarded as speculative.

M. Cintala reviewed the processes that occur during hypervelocity impacts on the Moon and Mercury. More melting and vaporization occur during an impact into a porous regolith than into a rock. He estimated that impacts on Mercury should be generating on the order of 14 times more melt and 20 times more vapor than on the Moon. Thus, glass should be even more abundant in the mercurian regolith. How this will affect the spectrum of Mercury depends on the FeO content of mercurian regolith, which is unknown.

If impact-generated vapor is evenly distributed over all soil grains, the thickness of vapor-deposited coatings in lunar regolith should on average be very small, less than 0.01 μm on the Moon. However, such coatings will be very unevenly distributed, and may be thicker on some grains and thinner on others.

Hapke emphasized that most of the material hitting the Moon is in the fine (~10 μm) particle size range. Because the optical properties of a material are determined by the mean size weighted by cross-sectional area, this is also the size that is most important for the spectral reflectance of the lunar regolith. However, experiments involving hypervelocity impact of micrometeorites into fine-grained powders are lacking.

D. McKay reviewed the morphology and wide variety of surface features of lunar soil particles, which affect the optical properties of the soil. Micrometeorite impacts onto larger particles create craters and spallation features. Most of the soil features seen in optical or SEM microscopes that appear to be vapor deposits seem to be the result of pyroclastic eruptions rather than impact vaporization.

A considerable amount of time was spent discussing agglutinates because the darkening agent appears to be particularly (though not exclusively) associated with them. They are irregular and vesicular, with much adhering material, and contain metallic Fe. Their main phase is crystalline fragments welded together by glass. Although glass is abundant, some agglutinates contain only 10% glass.

L. Keller reported on new studies of lunar soils by transmission electron microscope (TEM). It has long been known that a large fraction of lunar soil grains are coated with amorphous rims roughly 0.1 μm thick. These rims previously had been assumed to be due to metamictization by solar wind irradiation. However, new TEM analyses showed that the compositions of the rims are different from those of the host grains and are enriched in Si. Keller argued that the rims are vapor deposits. The rims also contain SMFe in highly variable amounts, although the amount is uncertain. Because of the low Ni abundance, it is believed that the Fe is not meteoritic.

During the discussion accompanying Keller's talk it was postulated that agglutinates might be formed by impact-shock welding of mineral and glass grains, many of which are vapor coated. However, present evidence seems to be insufficient to either refute or confirm this hypothesis.

L. Taylor discussed the Fe content of lunar soil and its relation to optical properties. The oxygen fugacities at which lunar materials formed are below the iron-wüstite buffer so that metallic Fe and FeO are both stable. The soil contains about 0.5 wt% of metallic Fe, most of which consists of single-domain ferromagnetic crystals, causing the characteristic ESR signal. The amplitude of this signal normalized to the FeO content (I_s/FeO) is a measure of the surface exposure age and maturity of the soil. Because glass is generally more friable than minerals, the finer fractions of the soil are enriched in agglutinitic glass and the SMFe. The older a soil is, the more solar-wind-implanted elements it contains. The top few centimeters of soil tend to be more mature than the material below it.

D. Britt and C. Allen described recent experiments in which heating Fe-silicates in reducing atmospheres produced metallic Fe armor on grains. However, such armor is not observed in lunar samples or in most meteorites.

McKay reviewed the physical properties of the lunar regolith in relation to various measures of maturity. Immature soils usually have bimodal size distributions, while pyroclastic soils generally have narrow unimodal size distributions. Impact comminution should simply grind the lunar surface materials more and more finely. However, the formation of agglutinates reverses this trend and causes a mature soil to have a broad, unimodal size distribution, which, when weighted by mass, peaks at around 40–60 µm. The agglutinate content increases with maturity. The I_s/FeO ratio correlates well with the agglutinate fraction. There are no known examples of a completely mature soil because vertical and horizontal mixing processes bring in fresh material.

M. Gaffey attempted to extrapolate the preceding discussions from the Moon to other bodies, particularly asteroids. Processes that potentially alter the optical properties of a regolith include impact fragmentation, impact vitrification and vaporization, impact reduction in solar-wind-implanted soils, impact mixing, frost deposition, differential evaporation of volatile and nonvolatile materials, radiation damage, and downslope migration.

The optical properties of Mercury are similar to those of the Moon. However, Mercury is complicated by the presence of a magnetic field that holds off the solar wind most of the time. The important question of whether the solar wind is necessary to a lunar type of darkening process is still unanswered.

On some satellites, e.g., Deimos and Phobos, much of the impact ejecta is trapped in the planet's gravity well and will eventually return to the satellite to be recycled, so the regolith should be fairly mature and well mixed (in the lunar sense). However, images from the Phobos mission analyzed by S. Murchie show that the surface of Phobos is heterogeneous.

It is not clear whether agglutinates should be expected on surfaces of asteroids. Some melting should occur, even with low-velocity impacts, but there should be little vaporization. Because of the low escape velocities and rapid renewal of the surface layer, asteroid regoliths should be well stirred and immature. There is no evidence for glass in asteroid spectra. Meteorites have abundant shocked materials, but little melt glass and few agglutinates.

Britt stated that some meteorites are dark because of the presence of shock-dispersed fine metallic Fe and troilite. However, R. Housley stated that examples of this type of meteorite that he has examined lack the SMFe ESR signal. The relationship between the ordinary chondrites and the asteroids, particularly the S-type asteroids, is not clear, nor is it clear whether some form of space weathering is obscuring any connection.

On some asteroids, aqueous alteration processes may be important, and on outer satellites there will be production and movement of volatiles, which will complicate remote sensing analyses.

The final session was led by L. McFadden and concerned future directions for research that would illuminate the problems discussed at the workshop. There seemed to be general consensus that the SMFe, rather than melt glass, was the agent that darkened and reddened the lunar soil, but the processes that produced SMFe on the Moon were not understood so extrapolation to other bodies was difficult.

A number of potentially fruitful research areas were identified, including the nature, composition, and origin of the amorphous rims, the chemistry and optical properties of the finest components of lunar soil, and the physics of micrometeorite impact into fine-grained regolith. Several attendees interested in theoretically modeling the effects of metallic Fe on the optical properties of regoliths noted that the complex refractive index of metallic Fe measured under nonoxidizing conditions is poorly known. Spectral observations of Mercury from above the atmosphere area are needed to determine whether the FeO band is present or not.

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Abstracts

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IMPACT MELTING AND VAPORIZATION IN PLANETARY REGOLITHS. Mark J. Cintala, Mail Code SN4, NASA Johnson Space Center, Houston TX 77058, USA.

The thermal phenomena attending high-velocity impact have profound effects on virtually every aspect of the physical, chemical, and optical evolution of planetary regoliths. Not only do impacts pulverize, redistribute, and mix the various components of a regolith, but they also fuse and vaporize them—changing crystalline material to glass, releasing trapped or implanted gases, and spreading vaporized products across the planet's surface, among many other things. Those wishing to understand the details of regolith evolution must incorporate the effects of impact into their approach to the problem. Derived from a more extensive contribution [1], this paper will constitute a short summary of the thermal processes accompanying impact into planetary regoliths, with the immediate acknowledgment that it is neither exhaustive in its consideration of the existing literature nor exact in any of its treatments. The reader desiring more information is directed to the relevant papers cited at the end of this paper; should they fail to provide satisfaction, he or she is then heartily encouraged to attack the problem immediately.

The Processes of Impact Melting and Vaporization: Primary impacts into planetary surfaces (at velocities of a few to, more typically, tens of kilometers per second) generate strong shock waves in both the impactor and the target. The process of generating and propagating a strong shock is highly irreversible, and thus a profligate generator of entropy [2–5]. Shock waves generally above 40–50 GPa begin to instigate melting in coherent silicate rocks, while stresses on the order of 100 GPa or higher are required to begin vaporization in those materials (1 GPa = 10^9 N/m^2 = 10^{10} dyn/cm^2 = 10^4 bar). Particulate silicates—regoliths, for instance—begin to fuse and vaporize at considerably lower stresses due to the role played by intergranular voids as stress concentrators [6], and possibly because of extremely violent shearing effects between grains. This permits impact melts to be generated at the relatively low velocities characteristic of light-gas and even powder guns [7]. A comparison between coherent silicates and regolith in terms of the stresses required for a progression of phase changes is presented in Fig. 1. Although the regolith melts and vaporizes at lower shock stresses than solid silicates, the more effective production of entropy also acts *against* melt and vapor production in that it causes the shock front to attenuate more rapidly in the porous target. This has the net effect of limiting the origins of shock-heated material to the region relatively near the point of impact. Even so, it is apparent from Fig. 2 that somewhat greater volumes of melt are produced in the porous target.

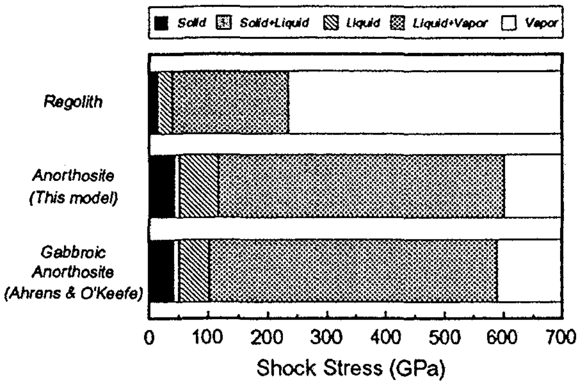

Fig. 1. Shock stresses required for the indicated phase changes for lunar regolith, Tahawus anorthosite, and gabbroic anorthosite. The values for the first two were calculated with a model using a Murnaghan equation of state [1], while the latter used a more sophisticated Tillotson equation of state [8]. Note the ease with which the regolith changes phase relative to the coherent anorthosites.

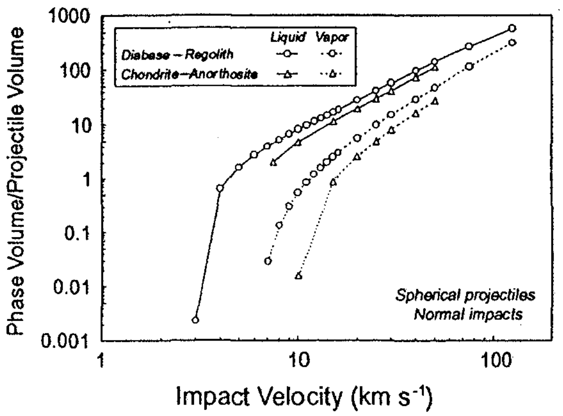

Fig. 2. Comparison of melt and vapor volumes for impacts into regolith and solid anorthosite. Note the greater volumes in the case of the regolith.

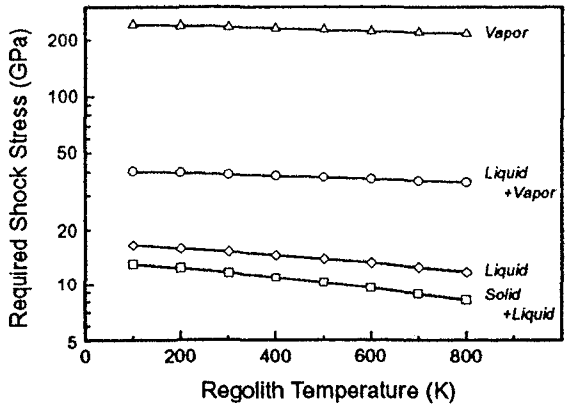

Fig. 3. Shock stress required to induce the labeled phase changes in a regolith target as a function of initial regolith temperature [1]. The range of temperature used here includes many asteroids and hottest regions of Mercury's surface. Note the relatively minor effect, particularly in the cases of the more energetic phases.

The additional factor of target temperature arises when impacts throughout the solar system are considered. It can be assumed that fusion or vaporization of a hot target would require a weaker shock than would a cold one. Figure 3 was generated in an attempt to address the effect of the thermal state of the target. It is apparent that only the lower-energy phases—from partial to complete melting—are affected to any noticeable degree by higher target temperatures. The reason for this is straightforward: The temperature change necessary to reach the melting point is a large fraction of the energy required to begin or complete fusion. The energy increase necessary for melting is lower for a higher initial temperature, and therefore requires a smaller shock stress to attain the same end. Comparing Figs. 2 and 3, it is clear that the quantities of melt and vapor generated are more dependent on impact velocity than on initial target temperature, although the latter can account for differences of up to 30% in the volume of melt produced, for instance, between the hottest and coldest parts of the mercurian surface.

A Case Comparison: The Moon and Mercury: While they are similar in many respects, the Moon and Mercury are different in terms of their impact environments. As such, they permit an investigation into the different ways that their regoliths might be affected by impact. A few of these variations are presented below.

Impact fluxes. A method of extrapolating the terrestrial impact flux to other objects in the solar system was developed by Zook [8] and subsequently applied in other investigations [1,9,10]. A similar technique is used here; as was done earlier [9,10], the changing spatial density of particles as a function of distance from the Sun must also be included. Figure 4 illustrates the differential flux distributions for the Moon and Mercury obtained using Zook's method, where the greatly simplifying assumption of a circular mercurian orbit was used. When integrated over the applicable range for each planet, the curves indicate that the mercurian flux is 5.5 times greater than that at the Moon. This is due not only to the enhanced spatial density at the orbit of Mercury relative to that at the Moon [12], but also to the higher velocity distribution at Mercury [1,9,10].

Melt- and vapor-production rates. This greater flux, particularly when coupled with the higher impact velocity, will result in much greater volumes of shock-melted and vaporized regolith on Mercury when compared to the Moon [1,9,10]. A comparison between melt and vapor production on the two planets is given in Fig. 5, which uses diabase projectiles to simulate silicate meteoroids at average surface temperatures for the two planets. It is immediately obvious that the rate of melt production on Mercury is much higher than on the Moon, by a factor of more than 13. Vapor production on Mercury is higher by a factor of almost 20. Indeed, a factor of 3 more vapor is generated by impact on Mercury than is melt on the Moon. Although the absolute numbers would differ, similar relative results would occur for other projectile types. Integration of the curves in Fig. 5 over the range of impact velocities for the two planets and over the mass range of 10^{-18} to 1 g yields the results presented in Fig. 6. These curves represent the cumulative rate of phase production, and clearly indicate that projectiles around 10^{-5} g contribute most to the total volume of regolith melted or vaporized. It should be noted, however, that the regolith-melting relationship used in the calculations might not be fully applicable to the smaller impactors, which almost certainly collide with individual regolith grains. Insofar as the physics of melting and vaporization at that scale is probably dominated by the kinetics of the phase changes [13], the general model used here might not be accurate in that mass range. Nevertheless, even if the melt and vapor production were underestimated in the figure by a factor of 2 (which is unlikely, since more than half the kinetic energy of impact is already partitioned into heating), there would be little effect on the curves in Fig. 6.

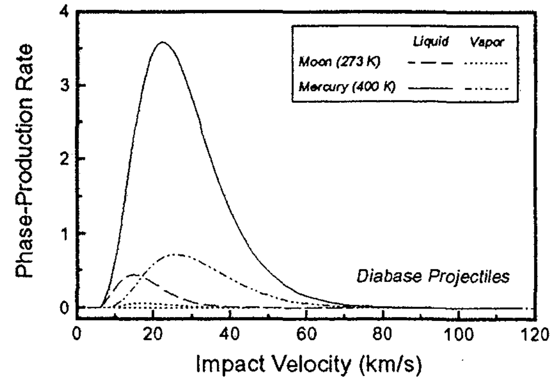

Fig. 5. Phase-production curves for the Moon and Mercury as a function of velocity at constant projectile mass. The area under each curve is proportional to the rate of melt or vapor production at all velocities. Units on the vertical axis are projectile volumes cm^{-2} s^{-1} (mass increment)$^{-1}$ (velocity increment)$^{-1}$.

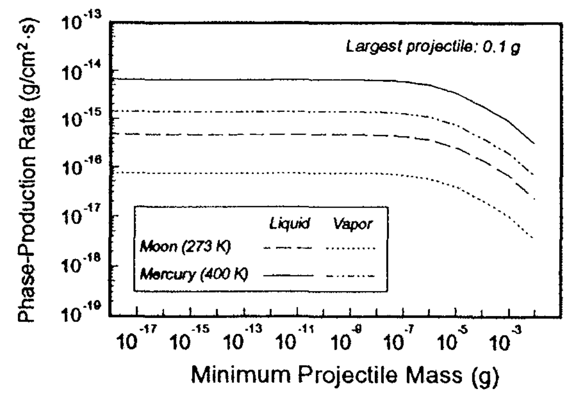

Fig. 6. Cumulative phase-production rate as a function of the minimum projectile mass in the range considered. The maximum projectile mass was always 0.1 g.

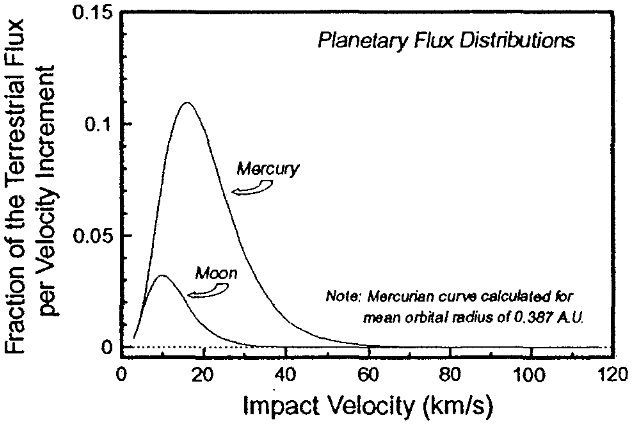

Fig. 4. The differential impact fluxes for the Moon and Mercury as a function of impact velocity. Integration of either curve will yield the flux between those two velocities in units of the observed terrestrial flux. These curves were generated with the flux measurements of Southworth and Sekanina [11], coupled with the analytical method of Zook [8].

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Implications—production of impact glass. While melting occurs much more rapidly and extensively on Mercury than on the Moon, another factor to consider in comparing the two regoliths is the efficiency of mixing by impact. Use of current scaling relationships [14] for craters formed in dry quartz sand (a good regolith analog) shows that, given otherwise identical conditions, craters on Mercury would be 1.07 times more voluminous than those on the Moon [1]. Using the velocity distributions for both planets in combination with the volumes of melt and excavation, the volume ratio of melt to excavation for the "average" crater is 2.5 times greater on Mercury than on the Moon. When the higher flux is included, mixing of the regolith occurs 5.5 times faster on Mercury, while melting is almost 14 times more rapid. Clearly, the mercurian regolith should mature much more rapidly if glass abundance is a factor. Under such conditions, it is not surprising that the most recent reflectance spectra of Mercury show no signs of unambiguous Fe^{2+} absorption features characteristic of some pyroxenes [15].

Production of impact vapor. With a vapor production rate almost 20 times higher than that on the Moon, and given the darkening ability of redeposited vapor [16], it is important to understand the effects of such a large difference. Briefly, Morris [17] has given an observational relationship for the depth of reworking on the Moon as a function of time. Since the volumes of "average" craters on the two planets differ only by 7%, their linear dimensions vary only by about 2% [1]. This implies that the geometries of mixing on the two planets can be compared directly with little error, and that the mixing relationship can be adapted to Mercury by decreasing the characteristic mixing time by a factor of 5.5, which is the ratio of the impact fluxes between the two planets. The expression for this reworking depth can be coupled with an estimate of the surface area contained in a unit volume of lunar regolith [18] to obtain the rate at which new surfaces are exposed to space, and hence to any impact vapor during its redeposition. This rate can then be combined with the vaporization rate to yield the curves presented in Fig. 7. (The range of values on the time axis comes from a summary of regolith exposure ages by Taylor [19].)

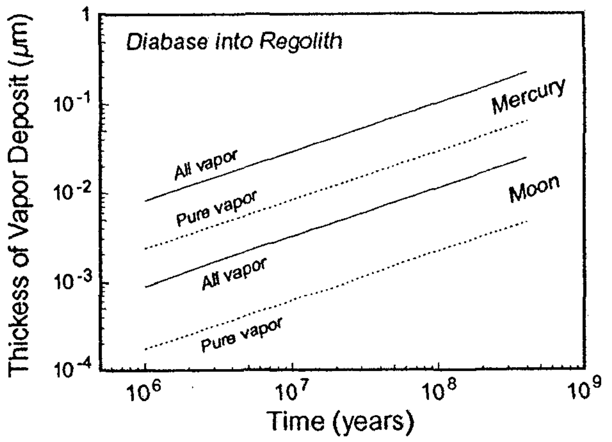

Fig. 7. Thickness of vapor deposits on the Moon and Mercury as a function of time. Two curves are given for each planet: one for the deposition of only completely vaporized target material, and the other for all impact-generated vapor (including partially vaporized material).

Using a typical exposure age of around 10^7 yr for a lunar regolith, it is apparent that any vapor deposits would be very thin. Even in the case of Mercury, where exposure ages are probably lower because of the higher flux, vapor deposits should be slight.

Effects on albedo. Adams and Charette [20] noted that the visible reflectivities of different Apollo 16 soils are correlated with their magnetic fractions. Since the magnetic fraction is correlated, in turn, with agglutinate abundance [21], the reflectivities of these soils are associated with their agglutinate contents. At magnetic fractions above about 50 wt% (implying an agglutinate content of about 34 wt%) [21], soils with 1.5% and 4.9% FeO are indistinguishable in terms of their reflectivity [20]. In light of the arguments presented above, a mercurian regolith with such a low agglutinate content would appear to be very rare. Thus, if the abundance and variation of FeO in the mercurian crust were similar to that at the Apollo 16 site [22], the absence of strong albedo contrast across the planet could be due to intense agglutinate formation.

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EXTRAPOLATIONS OF SPACE WEATHERING PROCESSES TO OTHER SMALL SOLAR SYSTEM BODIES.

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A diverse range of processes have been invoked as the dominant factor or as important contributory factors in the modification of the optical surface and regolith of the Moon. These include impact vitrification by large and small projectiles [1,2], solar wind implantation and the reduction of oxidized iron during energetic events [3], sputtering and crystal lattice damage by energetic cosmic rays [4,5], shock metamorphism of minerals [6–10], mixing of diverse lithologies by impacts [11,12], and contamination by external materials. These processes are also potentially important on the rocky surfaces of other small solar system bodies [6–15]. For icy bodies, several additional processes are also possible, including formation of complex organic compounds from methane and ammonia-bearing ices by ultraviolet irradiation [16,17] and the condensation of vapor species to form frost layers in the polar or cooler regions of objects at appropriate heliocentric distances.

The lunar case, even when completely understood, will not extend in a simple linear fashion to other small rocky objects, nor will the optical surfaces of those objects all be affected to the same degree by each process. The major factors that will control the relative efficacy of a possible mechanism include the efficiency of ejecta retention and the degree to which the regolith materials experience multiple events (primarily a function of body size, escape velocity, and impactor velocities); the mean duration of typical regolith particle exposure at the optical surface and within reach of the micrometeorite, cosmic ray, solar wind, or UV fluxes (a function of the rate and scale of regolith mixing, production, and removal processes); the incident flux of solar (low energy) cosmic rays, solar wind, or UV radiation (inverse square of heliocentric distance) or of galactic (high energy) cosmic rays (slowly increasing flux with heliocentric distance); and the compositional and mineralogical nature of the surface being affected.

In general, those processes that depend upon either the retention of impact ejecta or on the presence of multigenerational regoliths should be substantially less effective on smaller bodies with lower escape velocities [e.g., 11–15]. However, there are important exceptions to this generalization. For example, a process that involves the hypervelocity impact of small particles into a fine-grained regolith may be able to effectively retain highly shocked or melted material due to the nature of shock wave propagation in such a heterogeneous material [e.g., 2].

The potential capability of these proposed mechanisms to spectrally modify the regolith and the optical surface of small solar system bodies is generally not in question. Rather, the major issue is the relative importance of these processes on particular objects. The following briefly considers the probable major surface alteration processes for specific small airless solar system objects:

Phobos and Deimos: Their location within the martian gravitation field allows reaccretion of ejecta and the accumulation of relatively high levels of shocked and vitrified minerals in the surface regolith. There may be examples of shock-blackened materials [8].

Asteroids: Small sizes prevent effective retention of ejecta and result in relatively rapid regolith renewal that should generally limit the accumulation of agglutinates or radiation damage to the low levels observed in asteroids [14] and meteorites [18]. Mineralogical variation between asteroid classes should lead to significant differences in sensitivity to various alteration mechanisms. The dust bands associated with several asteroid families may contaminate surfaces of members of those families suppressing the spectral signatures of any actual differences. Understanding regolith is important for resolving the issue of ordinary chondrite parent bodies.

Satellites of Jupiter: The small inner satellite Amalthea shows contamination by sulfur compounds from Io. The albedo range of crustal units of varying age on Ganymede and Callisto indicates long-term contamination by dark material (infalling cosmic dust?). A frost cap is present on Callisto.

Satellites of Saturn: The leading hemisphere of Iapetus appears to be surfaced by a dark residue left after vaporization of ice [19]. Frost deposits on a trailing hemisphere are present.

Satellites of Uranus and Neptune: Low albedos appear to be due to production of dark organic compounds in methane-bearing ices subjected to energetic photon or charged particle irradiation.

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LABORATORY SIMULATIONS OF LUNAR DARKENING PROCESSES.

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It was clear long before the Apollo missions that a darkening process occurs on the Moon [1]. However, its nature remains controversial and elusive. Current evidence implies that the darkening is associated with, and is probably caused by, submicroscopic metallic iron in the regolith.

When samples of the lunar regolith became available, it was noted that glass was a major and ubiquitous component of the regolith. This led Conel and Nash [2] to suggest that the lunar darkening process was simple impact vitrification. This suggestion seemed to have been verified by several experiments [2–4] in which dark glasses with very subdued absorption bands were produced by melting lunar and terrestrial rocks in a nitrogen atmosphere. As a result, the mechanism has been widely accepted and is almost regarded as a paradigm.

However, when Wells and his colleagues [5–8] attempted to simulate the lunar surface environment more realistically by melting rocks in vacuum, the glasses produced were invariably found to have high albedos and strong absorption bands. Dark glasses could only be produced under oxidizing conditions. Hence, the impact vitrification mechanism remains doubtful and certainly highly controversial.

When the solar wind was discovered it was suggested [9] that this agent could darken lunar materials by direct reduction of oxides to metals. Subsequent laboratory simulations [10–12] showed that H irradiation darkened silicates by coating the undersides of powder grains with an absorbing material. The absorption was shown to be caused by submicroscopic metallic Fe (SMFe) in the sputtered coatings [7]. Other experiments in which absorbing coatings were produced by condensing silicate vapor from rocks heated in vacuum produced materials with similar optical properties [7,13]. Both types of vapor-deposited coatings were enriched in SMFe and depleted in volatile elements [8].

Thus, Hapke [13] suggested that the darkening process is the deposition of vapor produced by a combination of solar wind sputtering and impact vaporization, and that the darkening agent is

2 P

the SMFe. However, no component of the regolith that could be vapor-deposited coatings has been identified, and the hypothesis has not been widely accepted.

However, there appears to be a correlation between SMFe, maturity, and albedo in the regolith [14,15]. At least five ways of producing SMFe on the Moon have been suggested: (1) shock reduction [16], (2) heating in a thermal blanket in vacuum [17], (3) shock heating of solar-wind-impregnated grains [18], (4) coatings deposited by solar wind sputtering [7], and (5) coatings deposited by impact vaporization [7]. Processes (1) and (2) have been refuted by laboratory experiments. Processes (4) and (5) have produced SMFe in laboratory simulations. Although no experiments have been done to simulate process (3), it is widely accepted.

Questions for the workshop include

1. Under what conditions will impact vitrification produce a dark glass?
2. What is the role of the SMFe in the lunar darkening process?
3. How is the SMFe produced?
4. Is there a significant component of the regolith that has been deposited from a vapor? If so, what form is it in, and how can it be recognized? What are its effects on the chemistry of the regolith?
5. How do the processes of impact vitrification, vaporization, sputtering, and SMFe production vary as a function of distance from the Sun and location in planetary magnetospheres?
6. What other processes might affect optical properties?

Ices have lower melting and boiling temperatures and sputtering yields several orders of magnitude larger than silicates [19]. Hence, analogous processes will occur to an even greater extent on satellites of the outer planets, and these questions are relevant to those bodies as well.

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DEPOSITION OF IMPACT-GENERATED VAPORS IN THE LUNAR REGOLITH.

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Introduction: The composition and structure of the finest grain sizes in lunar soils are strongly influenced by impact-associated processes such as comminution, melting, and vaporization. These factors in turn exert a strong influence on the optical properties of the materials. In this abstract, we review the literature regarding the fractionations that accompany the evaporation of silicate materials during impacts, consider the evidence for vapor deposits in the lunar samples, describe our own efforts to characterize vapor deposits in lunar soils using electron microscopy, and discuss the implications of vapor deposits on the optical properties of the lunar fines.

Vapor Generation and Fractionation: An extensive literature exists regarding the vaporization process and the chemical fractionations that occur during the evaporation of lunar basalts or basaltic analogs [e.g., 1,2]. In general, these studies have shown that during evaporation, volatile elements (mainly Na, K, Si, and Fe) are preferentially vaporized relative to the more refractory elements such as Ca, Al, and Ti, which tend to be concentrated in the residual material. Direct evidence for this process comes from studies of impact glasses in the lunar samples that reveal that refractory glass compositions (e.g., the high-Al, Si-poor, or HASP, glasses of [3]) occur in several lunar samples [3–6]. Transmission electron microscope studies of the finest fractions of lunar soils show that the compositions of the submicrometer glasses are dominated by refractory compositions (e.g., the HASP compositions) and volatile-rich glasses whose compositions are complementary to the refractory glasses [5,6]. These volatile-rich glasses are refractory poor, are strongly enriched in Si and Fe (and to a lesser degree Na, K, and S), and are believed to have formed as condensates of impact-generated vapors, mainly because of their compositional similarity to experimentally produced vapor condensates [5].

Evidence for Vapor Deposits: Early theoretical work indicated that considerable amounts of vapor are produced by micrometeorite impacts and that much of the vapor must have recondensed on nearby grains [7]. Additional vapor species are believed to be derived by solar wind sputtering of exposed surfaces [8]. However, questions still remain regarding the fate of the impact-generated vapors: If so much vapor is being produced, then where is it?

There is a considerable body of evidence that the surfaces of lunar fines are enriched in some elements relative to the bulk soil. Although there is agreement that the surfaces are compositionally different from the bulk, there is no consensus on the degree of enrichment or on the mechanism responsible for the surface enrichments. Hapke et al. [9] showed qualitatively that most of the lunar fines are surrounded by acid-soluble Fe-enriched opaque coatings. They proposed that sputter deposition was the dominant process controlling the optical properties of the surfaces, but they did not rule out that a component of vapor deposition was present in the coatings. Later, surface-sensitive spectroscopic techniques (auger and X-ray photoelectron spectroscopy) were applied to this problem by several groups. Gold et al. [10] found 2 to 3 times enrichment in surface Fe relative to the bulk composition. A slight enrichment in Ti was also reported although no observable increase in Ca or Si was detected [10]. ESCA studies also found Fe enrichments, but not of the same magnitude as that in the auger studies [11]. Housley and Grant [11] report strong surface enrichments in Si, moderate enrichments in Fe, moderate depletions in Ca and Al, and strong depletions in Mg. Housley and Grant suggested that the relative enrichment/depletion pattern was not consistent with either vapor deposition or sputtering, but could be generated by a process similar to agglutinate formation in the fines. Ion probe studies of the lunar fines by Zinner et al. [12] indicate surface enrichments of Fe, Ti, and Mg, but the authors were unable to attribute the result to any specific mechanism.

We have recently reported our analytical electron microscopy analysis of amorphous coatings on fine-grained plagioclase from lunar soils [13]. The amorphous coatings we observe are from 20 to 200 nm thick with an average thickness of 60 nm. A major result of our study is quantitative analyses of amorphous coatings and their underlying substrates, which show that the rims are compositionally distinct from the host plagioclase. The amorphous coatings are strongly enriched in Mg, Fe, and Si and are depleted in Ca and Al. The Fe in the amorphous coatings typically occurs as 1- to 5-nm crystalline inclusions sparsely distributed throughout the thickness of the coating. Rare Fe metal inclusions up to 50 nm in diameter also occur. The fate of the highly volatile elements (e.g., Na and K) is ambiguous. We do not observe enrichments of Na or K in the amorphous coatings. Alkali elements are known to be mobile during analysis in the electron microscope, so the lack of an alkali enrichment may be an artifact of the analysis procedure. An interesting alternative is that Na and K may not recondense with the other, less volatile elements, which could explain the Na and K that occur in the lunar atmosphere [14]. A third explanation is that Na and K are preferentially sputtered from the amorphous coatings during their exposure to the solar wind.

Although strong arguments have been made for sputtered ion deposition as the major process in producing surface deposits [e.g., 8,15], the observed enrichments are not consistent with this model because of the mass dependency of the process. We believe that any contribution of sputtered ion deposition is only a minor component of the rims and that deposition of impact-generated vapors is the dominant process. Others have argued that the amorphous coatings are produced by solar wind radiation damage [e.g., 16] and have shown experimentally that amorphous coatings can be produced by exposing fresh surfaces to a high flux of low-energy ions. However, the compositional differences between the amorphous coatings and the host grains combined with the distribution of Fe particles in the coatings indicates that solar wind radiation damage can only have a minor effect.

Vapor Coatings and Optical Properties: Hapke et al. [15] showed that the optical properties of coatings produced by vapor deposition and by sputtered ion deposition resemble those of the lunar fines. Hapke et al. [15] also showed that sputtering of lunar fines produces the requisite darkening. In all these cases, it appears that the most important factor influencing the optical properties of the coatings is the presence of submicroscopic Fe metal grains, which are strong absorbers of visible wavelengths.

Conclusions: Vapor condensates are present in the lunar regolith as distinct glasses in the finest size fractions and as thin amorphous coatings on soil grains. The main characteristics of these condensates are an enrichment in volatile elements (particularly Si and Fe), a marked depletion in refractory elements, and Fe in the form of metallic particles on the order of a few nanometers in size. Contributions to these amorphous coatings by sputtered ion deposition and radiation damage are of minor importance relative to the contribution of direct condensation of impact-generated vapors. An experiment where vapor coatings are prepared and reflectance spectra are obtained and subsequently analyzed in the TEM should help put the issue to rest.

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THE STATE OF Fe IN THE LUNAR REGOLITH AND ITS RELATIONSHIP TO THE SPECTRAL REFLECTANCE PROPERTIES OF THE MOON.

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Space weathering may have altered the surfaces of airless bodies, such as asteroids and the Moon, and effectively shock-darkened their surfaces, resulting in much lower reflectance and shallower absorption bands compared to those of simple, comminuted, and powdered rocks produced in the laboratory. Studies of lunar samples from the Apollo missions have led to the suggestion that these reflection properties are inherent to the fine-grained regolith, which has recorded a wide variety of shock-metamorphic effects. In particular, the lunar soil (i.e., that part of the regolith with grain sizes below 1 mm) contains native Fe in quantities above those present in the rocks from which the soil was formed. This abstract addresses the origin and nature of the native Fe in the soil, and presents speculations concerning its effects upon the soil's optical properties. Portions of this discussion draw heavily from earlier papers by our research group [see 1–3 and citations therein].

Native Fe in Lunar Rocks: Fe^0 occurs in both highland and mare rocks, where it may have formed in at least three different ways: (1) Fe^0 is a stable phase during crystallization of magma at lunar oxygen fugacities, which were at or below the iron-wüstite buffer [4]. While Fe^0 is more abundant in the mare basalts and commonly contains well above 1 wt% Ni and from 0.2 to 1 wt% Co, this native Fe constitutes $<<1$ vol% of these rocks. (2) Fe^0 also occurs in association with troilite (FeS), where it probably formed from an immiscible sulfide melt that crystallized at the Fe-FeS eutectic. This Fe^0 typically constitutes <1 wt%. (3) Reduction of Ti-rich spinels during subsolidus cooling of most mare basalts yielded Fe^0 and ilmenite [4]. Similar processes have been reported for other minerals. Fe^0 formed by reduction contains <1 wt% siderophiles.

Native Fe in Lunar Soils: Native Fe occurs in lunar soils in several forms: (1) Primary Fe^0 derived from the parent rocks during comminution. These grains are commonly attached to fragments of the rocks from which they have not been completely liberated. (2) Mounds in surface coatings on beads of volcanic glasses [5]. This Fe^0 may have formed by vapor deposition from sulfur-bearing volcanic gases. (3) Grains on beads of impact glass. Although they are not common, these grains often show evidence for the mobilization of S, with the desulfurization of FeS leaving native Fe. (4) FeNi grains derived directly from impacting meteorites. This type is more common in highland soils, which have been subjected to a longer bombardment; highland soil typically contains about 2 wt% meteor-

3 P

itic components. (5) Small Fe^0 crystals in agglutinitic glass. Agglutinates are impact-produced constructs, and their contribution to the Fe^0 in the lunar regolith will be addressed below.

Single-Domain Fe^0 in Lunar Soil: Early electron-spin resonance (ESR) studies of lunar materials showed a very strong signal that was interpreted as due to either Fe^{3+} or Fe^0 [6–8]. Subsequent work determined conclusively that it was due to single-domain crystals of Fe^0, and that it was 3 orders of magnitude greater than any possible paramagnetic signal from Fe^3 [9]. These crystals are typically <300 Å in dimension, compared to much larger, 1–100-µm grains in the rocks. Ferromagnetic resonance (FMR) further demonstrated that the signal from soils was an order of magnitude greater than that from rock samples, indicating that the Fe^0 content of soils is a factor of 5–10 times greater. Since the soils are composed of comminuted rock, this implied an unknown mechanism operative during soil formation.

Excluding volcanic contributions, such as fire fountaining, there are three basic processes that form the lunar soil: (1) simple comminution, which is disruption of rocks and minerals into smaller particles by impact; (2) agglutination, which is welding regolith fragments together with the glass produced by quenching impact melt; and (3) solar wind spallation and implantation, which produces only minor amounts of weathering, but provides significant additions to the regolith, as discussed below. Cirlin et al. [10] and Housley et al. [11] showed that the resonance characteristic of Fe^0 in soils is associated almost exclusively with agglutinates and larger samples of impact-produced material, the regolith breccias. The agglutinates are the carriers of practically all single-domain Fe^0 in the soil.

Origin of the Single-Domain Fe^0: As discussed in numerous early studies [9,12–15], the soil is effectively saturated with solar wind elements, notably H and C. When a portion of the soil is melted by impact, these elements impose a very reducing environment such that Fe^{2+} in the melt is effectively reduced to Fe^0. This Fe^0 then nucleates and grows as myriad tiny Fe^0 spheres, which are disseminated in the quenched melt. This "autoreduction process" is responsible for the production of the additional Fe^0 that resides in the agglutinates and distinguishes the soil from the rocks. Since this process should be cumulative, it was suggested that observed variations in Fe^0 content could be related to differences in exposure time to both the solar wind and the impacting flux [9]. In this way, the concept of "exposure age" for a lunar soil was established as a function of the length of time of reworking at the surface, and can be correlated with soil maturity.

Soil Maturity: The specific FMR intensity normalized to the total Fe-content of a soil is commonly used as a quantitative gauge of soil maturity [10,11]; the range of this parameter for immature, submature, and mature soils is correlated with the same maturity classification in terms of petrographic agglutinates and mean grain size. Indeed, the value of I_s/FeO for a soil is a direct function of its agglutinate content. Thus, the maturity of a soil and its exposure age are directly related. In addition, it has been shown that I_s/FeO is correlated with concentrations of the implanted solar wind gases N, C, ^{36}Ar, and ^{4}He [16], as well as ^{20}Ne, ^{34}Kr, and ^{132}Xe, all of which are also functions of the soil's exposure time at the surface.

Darkening of Soils: It is generally agreed that the darkening of soils is shock-induced, and should therefore be a function of soil maturity. Insofar as the Fe^0 described above is optically very dark, it is pertinent to discuss the agglutinates further. A typical agglutinate is about 40–120 µm in size, and consists of shock-produced glass (whose composition is approximately that of the bulk soil) bonding regolith fragments into an aggregate. The amount of glass in an agglutinate is usually less than 50 wt%, and sometimes much less than that. Therefore, study of the reflectance properties of these particles may not give a true picture of the possible effects of the glass, in that they can be masked by the more abundant mineral and rock fragments in the agglutinates. As a soil matures, its average grain size decreases: As a rule, about 50% by weight of a given mature soil is smaller than 50 µm. Because the majority of exposed mare soils are mature, it is this <50-µm fraction that may be the most important in influencing the reflectance properties of the soil. As comminution proceeds, the relatively fragile agglutinates are more readily crushed and the glass shattered into fine particles. It is known that the finer fractions of the soils contain greater amounts of agglutinitic glass, free from attached minerals and rock fragments [3]. Consequently, the glass loses its signature of being agglutinitic, except, of course, for the myriad tiny Fe^0 grains. The I_s/FeO values of the finer fractions of a mare soil thus should be distinctly higher than those of the coarse fractions, and this does indeed appear to be the case [17].

Conclusions: It is the finer fractions of the lunar soil that contain the higher contents of agglutinitic glass, and therefore the larger amounts of Fe^0. The amount of this glass in the finer fraction increases as a function of the maturation process. Indeed, if it is the presence of single-domain Fe that is influencing the spectral reflectance properties of the regolith, profitable research should be directed at the finer fractions of the soils, not simply at agglutinates of any size.

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