Optical Effects of Space Weathering: The Role of the Finest Fraction

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The optical properties of lunar soils are different than those of rocks from which they are derived. As a consequence of lunar space weathering, soils are darker and exhibit a distinctive red-sloped continuum and weaker mineral absorption bands. The accumulation of dark glass-welded aggregates (agglutinates) has been thought to account for these optical effects of space weathering on lunar soils. Spectroscopic analyses of agglutinate separates and size fractions for a suite of lunar soils presented here indicate that the agglutinate paradigm is insufficient to fully account for lunar optical alteration. It is the finest fraction of lunar soils (<25 μm which constitute ~25 wt %) that dominates the optical properties of the bulk soil. Unlike size fractions of most silicates for which the finest fraction is the brightest, the lunar soil size fractions all have comparable albedos in the short-wavelength visible. In the near infrared, however, it is the finest fraction that exhibits the steep red continuum and weak absorption bands. The properties of the finest fraction cannot be duplicated by preparing a fine fraction by grinding larger agglutinate-rich soil particles. These results suggest space weathering on airless bodies is dominated by surface correlated processes (perhaps associated with the development of fine-grained Fe on or near the surface of grains), and the accumulation of the larger agglutinates is not necessarily required to account for lunar optical alteration.

INTRODUCTION

To the human eye the surface of the Moon appears without color, an apparently gray landscape evolved from aeons of exposure to the space environment. When observed with detectors sensitive to radiation from the visible through the near-infrared, however, the Moon is seen to be notably colored. Measured optical properties are distinctly red (increasing reflectance with longer wavelengths) with weak, but highly diagnostic mineral absorptions superimposed on the red continuum [McCord and Johnson, 1970; McCord et al., 1981; Pieters, 1986].

With the return of lunar samples it became clear that this unusual red lunar continuum was associated specifically with lunar soils [Adams and McCord, 1970, 1971a]. Lunar soils were also found to exhibit a lower albedo and weaker mineral absorption bands than particulate samples of rocks from the same site [Adams and McCord, 1971b, 1973]. Lunar rocks exhibit the diagnostic spectral properties of their constituent minerals (principally pyroxene, olivine, and plagioclase). Reflectance spectra of representative mature and sub-mature lunar soils are shown in Figure 1. It can be seen that the characteristic red lunar soil continuum continues to about 4.5 μm; at longer wavelengths the stronger absorptions in the infrared begin to dominate. (Natural 4.5 μm radiation from the sunlit lunar surface, of course, is principally thermal emission; reflected and emitted radiation are approximately equal near 3.5 μm and below 2.4 μm lunar radiation is reflected solar.)

Most of the lunar surface is covered with fine-grained soil. From data collected on the surface during the Apollo missions, together with images of the surface obtained from orbit, the thickness of this fine-grained particulate layer (regolith) was found to be 6-12 m [see Heiken et al., 1991, chapter 4]. Lunar soils represent the cumulative product of space weathering and are perhaps unique because of their environment. With no atmosphere or magnetic field to speak of, cosmic rays and energetic particles of the solar wind constantly wash the surface. Impacts by asteroids ≥1 km in diameter have created a highly cratered surface. In the current environment, the most frequent interaction of the lunar surface with solid bodies is with the smallest micrometeorite particles. An apparently continuous flux of these particles comminute, melt, vaporize, and churn grains and fragments of the uppermost surface. Multiple cycles of mechanical and irradiation processes alter the physical and compositional properties of local material thus producing the characteristic lunar soil [see Heiken et al., 1991, chapter 7]. The lunar soil is derived principally from local lithologies, but is also a distinct product produced by space weathering processes.
Is there evidence for comparable space weathering on other airless bodies? Meteorites and their presumed parent bodies, asteroids, were also studied with spectroscopic techniques during the 1970s. The first asteroid to be directly linked to specific meteorites by this method was the asteroid 4 Vesta, a 500 km main belt asteroid. T. McCord and associates [McCord et al., 1970] showed that not only did Vesta exhibit strong, well-developed absorption features in the near-infrared, but that these diagnostic mineral absorptions identified the surface composition of Vesta to be basaltic in character. Furthermore, Vesta's spectrum was almost indistinguishable from laboratory spectra of basaltic achondrites (differentiated stony meteorites). These observations directly linked the asteroid Vesta to basaltic achondrite meteorites. The fact that spectra of the asteroid surface were so similar to those of laboratory meteorite powder suggested that the optical effects of space weathering on asteroids were minor or perhaps nonexistent [Matson et al., 1977].

Further spectroscopic studies of asteroids and meteorites provided abundant information on their mineral composition [e.g., Gaffey, 1976; Chapman and Gaffey, 1977; McFadden et al., 1984; Bell et al., 1988; Gaffey et al., 1989]. These data suggest several additional relationships between asteroids and meteorites [e.g., Gaffey, 1984; Gaffey et al., 1989; Gradie and Tedesco, 1982; Bell et al., 1989], but unambiguous links have proven to be more elusive. It is perhaps wishful to expect a gram of material hand-prepared and measured in the laboratory to be representative of the surface of a body kilometers in diameter. In fact, with the exception of Vesta, when spectral properties of asteroid classes are compared directly with those of meteorites, it is readily noted that the asteroid and meteorite fields of properties are not superimposed [e.g., Britt et al., 1992; Clark et al., 1992; Fanale et al., 1992]. This discrepancy could be due several possible causes including the aforementioned difficulty in preparing a meteorite sample to be physically comparable to an asteroid soil, rapid alteration of the meteorite in the terrestrial environment, space weathering on the asteroid surface, or any combination of these. The case for weathering on asteroids remains unresolved, but will be returned to in a later section.

The well-documented suite of returned lunar soils should provide a baseline for space weathering concepts. Typical spectra of lunar rocks and soils returned from a feldspathic highland (Apollo 16) and a basaltic mare (Apollo 12) site are shown in Figure 2. Highland materials are brighter than mare materials due to their higher plagioclase feldspar content. Mare materials, on the other hand, are rich in mafic silicates and ilmenite. Returned soils are always darker than rock powders of comparable particle size. As can be seen in the continuum-removed spectra on the right, the absorption bands of the soils, although weaker, nevertheless have characteristics similar to those of local rocks, indicating that the distinct mineralogy of remnant lithologic fragments remains unchanged during the weathering process. This is important for remote compositional analyses because it allows a quantitative assessment of soil mineralogy once the optical effects of space weathering are sufficiently well modeled.
AGGLUTINATE PARADIGM

Many of the early studies of space weathering of lunar materials concentrated on evaluating processes that might account for the low albedo of lunar soils. Two widely discussed concepts were (1) mass-dependent sputtering and redeposition driven by energetic solar wind particles, and (2) fractionation through vapor deposition on soil grains following flash melting during micrometeorite impacts [Cassidy and Hapke, 1975; Gold et al., 1977; Hapke, 1977]. Experimental evidence with analogue materials [Hapke et al., 1975; Baron et al., 1977] suggested both of these processes occur during lunar soil formation and predict the enrichment of iron on grain surfaces. Iron was indeed found to be enriched on grain surfaces relative to bulk sample for several lunar soils [Gold et al., 1977]. At the time, the relative importance of these processes on albedo were not known, nor was it known whether they could account for the other effects of optical alteration on lunar soils.

One of the more distinctive properties of well-developed lunar soils is the high abundance (~50 % modal abundance) of complex glass-welded aggregates, called agglutinates [McKay et al., 1972; McKay and Basu, 1983]. These multicomponent, highly irregular particles are typically very dark and often contain lithic fragments imbedded in melt glass as well as abundant absorbing amorphous material too fine to analyze. During the early analysis of lunar materials, several lines of evidence suggested that these dark agglutinates were the principal carriers of the effects of optical alteration resulting from exposure to the lunar environment. Agglutinate abundance increases with increasing "maturity" (exposure age) of lunar soils as measured by indices such as abundance of implanted solar wind gases. This in turn is associated with the three properties of soil alteration: the soils darken, absorption bands weaken, and a red continuum develops.

A principal piece of evidence for the agglutinate paradigm came not long after the return of lunar samples, when it was shown experimentally that melting of lunar material in a sealed platinum tube with dry nitrogen purge produces a glass with optical properties resembling those of lunar soil [Adams and McCord, 1971a]. More detailed glass experiments were later performed in which composition and oxygen fugacity were carefully controlled [Bell et al., 1976; Wells and Hapke, 1977]. From these more detailed experiments and from analyses of the orange glass beads from Apollo 17 and green glass from Apollo 15 [e.g., Adams et al., 1974] it was recognized that although glass was indeed abundant in lunar soils, translucent (quenched) glass can not be the principal carrier of space weathering effects. The experiments of Bell et al. [1976] in fact showed the steepness of the continuum of lunar-like glass in the visible is directly dependent on the abundance of FeO and TiO2, inconsistent with the observed properties of lunar soils (feldspathic highland soils are typically redder than many of the more mafic mare soils [e.g., McCord et al., 1972]). Nevertheless, the dark “glass” content of lunar soils became the catch-all for lunar optical alteration. Without being explicit, the concept came to include melt glass, devitrified material, amorphous rims, and any dark (translucent or opaque) amorphous material identified by petrologists in soils. In short, it described the properties of agglutinates.

Although the optical properties of the complex agglutinates themselves had not been analyzed directly, the evidence available seemed to suggest that these unusual soil particles were the principal carriers of optical alteration during soil formation. The advantage of this paradigm was that agglutinates can, and probably do, accumulate the products of all the lunar weathering processes proposed, and it appeared not necessary to determine which of the processes dominates. If space weathering produces agglutinates, and if agglutinates produce optical alteration effects, then there were notable implications for other airless bodies. Since a moderately strong gravity field was thought to be required for cyclical soil gardening and the accumulation of agglutinates, this paradigm allowed the optical effects of space weathering to occur on Mercury, but not on asteroids.

In the discussion below, it will be shown that the agglutinate paradigm for lunar alteration cannot be the full story. Formation of the complex glass-welded aggregates alone is shown to be insufficient to account for the optical alteration of lunar soils. The finest fraction of natural lunar soils (<25 µm which constitute ~25% by weight), on the other hand, is shown to carry the properties associated with optical alteration and to dominate the optical properties of lunar soils. It is thus not agglutinate formation per se that alters lunar material. It is suggested that the process(es) responsible for the optical alteration effects is likely to be associated with the surface of grains (surface correlated) such as those processes that produce single-domain Fe6.
TABLE 1. Modal Composition of Size Fractions (μm) for Apollo 11 Soil 10084, Luna 16 Soil 1637, Luna 20 Soil 2014, and Luna 24 Soil 24085

<table>
<thead>
<tr>
<th></th>
<th>Apollo 11</th>
<th>Luna 16</th>
<th>Luna 20</th>
<th>Luna 24</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000-90</td>
<td>90-20</td>
<td>20-10</td>
<td>1000-250</td>
</tr>
<tr>
<td>Lithic clasts</td>
<td>26.3</td>
<td>1.5</td>
<td>--</td>
<td>13.6</td>
</tr>
<tr>
<td>Highland breccia</td>
<td>2.3</td>
<td>--</td>
<td>--</td>
<td>0.9</td>
</tr>
<tr>
<td>Basalt/gabbro</td>
<td>24.0</td>
<td>--</td>
<td>--</td>
<td>12.7</td>
</tr>
<tr>
<td>Agglomerates</td>
<td>59.5</td>
<td>35.2</td>
<td>12.6</td>
<td>62.1</td>
</tr>
<tr>
<td>Agglomerates</td>
<td>52.0</td>
<td>--</td>
<td>--</td>
<td>45.0</td>
</tr>
<tr>
<td>Regolith breccia</td>
<td>7.5</td>
<td>15.7</td>
<td>21.9</td>
<td>26.7</td>
</tr>
<tr>
<td>Light</td>
<td>1.4</td>
<td>3.1</td>
<td>3.4</td>
<td>20.6</td>
</tr>
<tr>
<td>Mineral grains</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyroxene</td>
<td>4.2†</td>
<td>27.5</td>
<td>28.1</td>
<td>3.8</td>
</tr>
<tr>
<td>Olivine</td>
<td>1.3†</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>1.9</td>
<td>13.1</td>
<td>20.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Silica</td>
<td>0.4</td>
<td>0.7</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Opaque</td>
<td>1.1</td>
<td>4.0</td>
<td>11.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Glass</td>
<td>4.8</td>
<td>14.9</td>
<td>25.6</td>
<td>6.6</td>
</tr>
<tr>
<td>Mare</td>
<td>3.5</td>
<td>9.8</td>
<td>16.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Highland</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>2.1</td>
<td>2.1</td>
<td>--</td>
<td>13.9</td>
</tr>
<tr>
<td>Number of points</td>
<td>625</td>
<td>472</td>
<td>285</td>
<td>700</td>
</tr>
</tbody>
</table>

*From Labotka et al. [1980] and Simon et al. [1981].
†This study.
‡Undifferentiated mafic mineral.

Figure 4b these spectra are scaled to unity at 0.75 μm along with the 250-500 μm agglutinate and residual separates for comparison.

None of the agglutinate-rich size separates exhibit a continuum slope as the bulk soil except for the finest fraction (<25 μm). Furthermore, all of the agglutinate-rich fractions larger than 25 μm have stronger absorption bands than the bulk soil. From these observations it is apparent that the fine particles dominate the optical properties of the bulk soil, even though they constitute a minor mass fraction. In addition, spectra of all size separates and the bulk soil appear to converge to the same albedo in the short wavelength visible (0.4-0.5 μm). As will be shown in a later section, this similarity in albedo is atypical behavior for size separates of geologic materials prepared in the laboratory.

LUNA SOIL SIZE SEPARATES

The composition and optical properties of three Luna soils were analyzed. New compositional analyses are presented in Table 1 for the specific Luna soils included in this study. Sample 1637 was obtained from horizon 20-28 cm of the returned Luna 16 core, sample 2014 was obtained from the 10-20 cm horizon of the Luna 20 core, and sample 24085 was obtained from horizon 85-86 cm of the Luna 24 core (18-19 cm from the beginning of the sample). After preparing a split of the bulk soil, each soil was wet sieved to four particle sizes. Grain mount sections were prepared for SEM and XRF analyses at the Vernadsky Institute to determine modal composition and chemical composition of mineral grains. Reflectance spectra for the size separates and the bulk soil for these three Luna soils are shown in Figure 5.

The same systematic relationships of spectral properties between size separates and bulk soil observed for 10084 are
laboratory for most geologic materials. As predicted by theory [i.e., Hapke, 1981], reflectance increases with decreasing particle size for all wavelengths. Even though this lunar sample exhibits a generally red-sloped continuum, the finest fraction does not exhibit the steepest continuum slope.

If the agglutinate paradigm were correct, then the optical characteristics of the finest fraction of natural lunar soil would be due to the presence of small agglutinates. For example, the smaller size might allow light to penetrate into and scatter also seen with these Luna soils. For all soils, the optical properties of the bulk soil (continuum slope and band strength) are dominated by those of the smallest size fraction. Also, as with 10084, the albedo of all Luna soil size separates <250 μm converges to approximately the same value in the short-wavelength visible. It is important to note that these soils show the same optical trends even though they represent a range of compositions (Luna 16 and 24 are mare soils; Luna 20 is highland soil) and exhibit a range of exposure ages (Luna 24 being the least mature).

**LUNAR REGOLITH BRECCIA 60019 AND ARTIFICIAL SOIL SEPARATES**

The spectral properties of naturally occurring lunar soils shown in Figures 4 and 5 are not observed when powders of other samples that are not lunar soils are prepared to comparable size fractions. Regolith breccia 60019 has been extensively studied with coordinated optical and petrographic analyses [Pieters and Taylor, 1989], and a particulate sample prepared from one matrix-rich chip is included in this study. Shown in Figure 6 are spectra for the bulk sample and size separates for this subsample of 60019. Spectra of this sample exhibit typical features of size separates prepared in the

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**Fig. 4.** (a) Reflectance spectra of 10084 size separates (wet sieved), bulk soil, and agglutinate separate. Spectra are listed in order of occurrence. (b) Scaled reflectance spectra of 10084 size separates shown in Figure 4a and agglutinate separates shown in Figure 3.

Also seen with these Luna soils. For all soils, the optical properties of the bulk soil (continuum slope and band strength) are dominated by those of the smallest size fraction. Also, as with 10084, the albedo of all Luna soil size separates <250 μm converges to approximately the same value in the short-wavelength visible. It is important to note that these soils show the same optical trends even though they represent a range of compositions (Luna 16 and 24 are mare soils; Luna 20 is highland soil) and exhibit a range of exposure ages (Luna 24 being the least mature).

**Fig. 5.** Reflectance spectra of (a) Luna 16, (b) Luna 20, and (c) Luna 24 bulk soil and wet sieved size separates. The spectrum for the largest size fraction (250-1000 μm) is shown as a dashed line and that of the bulk soil as a dash-dot line. Spectra are listed in order of occurrence.
Fig. 6. (a) Reflectance spectra of bulk sample and size separates from Apollo 16 breccia 60019. The spectrum for the bulk sample is shown with a dash-dot line and the spectrum for the largest size fraction (250-1000 μm) is shown as a dashed line. (b) Scaled reflectance spectra of bulk sample and size separates from Apollo 16 breccia 60019. Spectra are shown in the order listed. The spectrum for the bulk sample is shown with a dash-dot line and the spectrum for the largest size fraction (250-1000μm) is shown as a dashed line.

Fig. 7. (a) Reflectance spectra for a subsample of the 45-75 μm 10084 size fraction that has been ground and sieved to <25 μm. Shown for Comparison are the bulk soil sample, the natural <25 μm fraction, and the 45-75 μm fraction parent. (b) Scaled reflectance spectra for the same samples shown in Figure 7a. Spectra are shown in the order listed.
characteristic red-sloped continuum and weaker diagnostic absorption bands. The cause for the low albedo is apparently not dependent on particle size.

Several other properties of soils are pertinent to this discussion:

1. There is a suggestion that agglutinates decrease in abundance with decreasing particle size [Labotka et al., 1980; Simon et al., 1981]. Mineral grains appear to increase in abundance in the finest fraction.

2. For all lunar soils studied with ferromagnetic resonance in order to determine $I_F$/FeO values (index of maturity), there is an increase in of $I_F$ intensity (proportional to concentration of $<$300 Å iron) with decreasing particle size to $<$10 μm [Morris, 1977, 1980]. This increase of fine-grained single domain metallic iron in the finest fractions is observed for both mature and very immature soils.

3. Synthetic produced fine-grained metal in a silicate matrix [Allen et al., 1993] appears to mimic the effects of lunar optical alteration. If the particles are too large (as is the case for the $\sim$2 μm dispersed metal in the shock darkened chondrites [Britt, 1991]) they can produce darkening, but not reddening of the soil.

4. If Lunar soils are separated magnetically [Adams and McCord, 1973], the nonmagnetic separates of lunar soils typically are significantly brighter than the bulk sample. These magnetic and nonmagnetic soil separates, however, do not share the property of a common short-wavelength visible albedo as was observed for the soil size separates. This lends credence to the suggestion that space weathering optical properties are controlled by a magnetic component on or in the soil grains.

5. The smallest fraction of lunar soils ($\leq 10$ μm) exhibits a composition enriched in Al₂O₃ and depleted in FeO relative to the bulk composition [Laul and Papike, 1980]. On the other hand, the composition of agglutinitic glass (of the glass in agglutinates) is also different from the bulk composition of the soil, and instead exhibits a composition more comparable to that of the finest size fraction of the soil ($<$10 μm). This has led several researchers to propose that agglutinitic glass is derived from fusion of the finest fraction [Papike et al., 1981, 1982; Walker and Papike, 1981]. The origin of the compositional differences is consistent with an enrichment of plagioclase in the finest fraction. The increased abundance of plagioclase in the finest fraction could be due to differential comminution [Hötz et al., 1984] or to lateral transport of fine-grained material, most of which would be feldspathic due to the predominance of this crustal composition. (Although all agglutinitic glass also contains reduced iron, the term "agglutinitic glass" has sometimes been used in a circular shorthand definition to refer to materials containing fine-grained reduced iron, thus confusing the product with the process forming reduced iron.)

6. Recent multispectral images of the asteroid Gaspra obtained with the Galileo solid state imaging (SSI) camera [Bellon et al., 1992] show spectral variations across the surface. Specifically several small fresh craters exhibit a higher 0.40/0.56 μm ratio (are bluer) and a stronger 1 μm absorption strength relative to surrounding material. Although the spectral differences are small (~10 %), this association is highly suggestive of space weathering similar to that occurring on the Moon, but different in magnitude.

This combined evidence leads to the following conclusions.

1. It is not the accumulation of complex, glass-welded agglutinates per se that is responsible for the optical alteration of lunar soils.

2. The finest fraction of natural soils (with disproportionately large surface areas that have been exposed to the space environment) is the soil component principally responsible for the optical effects of space weathering of lunar soils.

3. The development of fine-grained (≤300Å) metal with exposure of surface materials to the space environment is currently the strongest candidate for causing the observed optical alteration effects.

There are several very important research directions, some of which are currently being initiated, that would maximize the scientific gain from this information. The physical characteristics of the fine-grained metal need to be quantified, and space weathering processes and the conditions necessary to produce fine-grained metal need refinement. Understanding both the resultant characteristics and the processes are required to be able to predict the effects of space weathering in different environments. From the perspective of remote compositional analyses, such information is essential to develop models that distinguish the optical effects of space weathering from those due to composition.

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