Multi-band Polariometry of the Lunar Surface. II. Grain Size Evolutionary Pathway

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Abstract

To understand grain size evolution on the lunar surface in detail, we analyze the distribution of the average grain size \(\langle d \rangle\) for the lunar near side obtained by Jeong et al. Furthermore, we analyze the polarimetric properties of the regolith simulants SiC and JSC-1A in a laboratory. We find two characteristics of grain size evolution on the Moon. First, the lunar regolith has evolved on a specific evolutionary pathway in \(\langle d \rangle - \Phi\) space. Here, \(\Phi\) is defined as the ratio of the perpendicular \((I_p)\) and parallel \((I_\parallel)\) components of the reflectance. Second, we also find that the evolutionary pathway depends on the FeO abundance and selenographic latitude of the surface. The dependence on the FeO content seems to result from the different resistance to comminution of regolith materials, and the dependence on the latitude seems to result from differences in the resurfacing environment. We present the probable causes of these characteristics of grain size evolution on the lunar surface.

Key words: methods: laboratory; solid state – methods: observational – Moon – planets and satellites: surfaces – polarization – techniques: polarimetric

1. Introduction

The surfaces of airless bodies in our solar system are affected by various space environments such as meteoroids, solar wind particles, and cosmic rays. In particular, continuous meteoroid impacts cause grain size changes (Hörz et al. 1984; Melosh 2011). The effect of impacts differs significantly depending on the size and velocity of the impactor. Impactors large enough to excavate fresh soil under the surface cause the average grain size to become larger. However, continuous small impacts make the average grain size smaller. Because the impact flux of small meteoroids is much greater than that of large meteoroids, the average grain size gradually decreases (Melosh 2011).

The decreasing grain size of regolith on the lunar surface is a well-known effect of space weathering (Hörz et al. 1984; Shkuratov & Opanasenko 1992). Thus, the average grain size is known to be a maturity indicator for lunar regolith. The average grain size of lunar regolith can be estimated from the albedo, \(A\), and degree of linear polarization, \(P\). Shkuratov (1981) and Shkuratov & Basilevsky (1981) first suggested the possibility of estimating grain sizes from \(P\) and \(A\). Shkuratov & Opanasenko (1992) suggested a relationship between the average grain size \(\langle d \rangle\), \(P\), and \(A\) on the basis of laboratory experiments with lunar samples. Dollfus (1998) also derived a relationship between the median grain size, \(P_{\text{max}}\), and \(A\) for 11 lunar samples. Jeong et al. (2015) found that \(\langle d \rangle\) is a monotonically increasing function of selenographic latitude. They interpreted the latitude dependence as the result of a reduced microimpact flux at high latitudes.

\(\langle d \rangle\) can provide valuable information about space environments such as their maturity and space weathering properties. However, the details of grain size evolution are still not well known. The size distribution of lunar regolith can give hints about grain size evolution. According to the lunar sample analyses of McKay et al. (1974a, 1974b), mature regolith samples contain smaller grains than immature regolith samples, and the size distribution also changes with maturity. Furthermore, they suggested that the size distribution will reach an equilibrium among the processes of comminution, agglutination, and mixing with fresh soils. In conclusion, they suggested that the size distribution of regolith can be an indicator of the maturity degree. However, the size distribution of regolith particles cannot be determined from \(\langle d \rangle\).

In this paper, we present a correlation between the polarimetric reflectance ratio \(\Phi\) and the size distribution of various regolith simulants based on laboratory works in Section 2. We analyze the correlation between \(\Phi\) and \(\langle d \rangle\) using polarimetric observational data. In Section 3, we consider factors affecting regolith evolution. Our conclusions are given in Section 4.

2. Laboratory Experiments

To estimate the size distribution of regolith using remote sensing data, we employ a simple polarimetric parameter \(\Phi\), which seems to provide information about the grain size distribution of regolith. Here, \(\Phi\) is defined as the ratio of the perpendicular \((I_p)\) and parallel \((I_\parallel)\) reflectance components; i.e., \(\Phi = I_p/I_\parallel = (1 + P)/(1 - P)\), where \(P\) is the polarization degree. The polarization of reflected light is affected by the composition, size, and shape of the object grains. Therefore, light in different polarization states contains different information about the reflecting surface. \(I_\parallel\) comes mostly from light singly reflected from the first grain encountered, and the light is mostly from large grain surfaces; in contrast, \(I_p\) consists mainly of multiply scattered photons among the individual regolith grains, and it is mostly affected by small grains (Shkuratov et al. 2007). As a result of the scattering behavior, the dominant contributors to \(I_p\) and \(I_\parallel\) are larger and smaller grains, respectively. Thus, \(\Phi\) can be used to estimate the relative size distribution of the regolith. For larger \(\Phi\) values, the grains are larger. To understand the behavior of \(\Phi\) for various grain size distributions, we perform polarimetric experiments on four lunar regolith simulants in a laboratory.
The optical setup of the laboratory experiments is shown in Figure 1. As a light source, we employ a tungsten lamp that has a polarization degree of 0.8% at 544.8 nm. A 45 mm focal length Nikkor commercial product that has negligible polarization is employed as an objective lens. We use a 3325 × 2504 array charge-coupled device that has a readout noise of 19.8 e−. The signal-to-noise ratios of our measurements are at least 100.

In our experiments, we employ three sizes of SiC that have mean grain diameters of 37, 72, and 174 μm (hereafter, we refer to these SiC samples as SiC37, SiC72, and SiC174, respectively). To trace the different size distributions of the lunar regolith, SiC37, SiC72, and SiC174 are mixed at two different weight ratios with the same average grain size of 50 μm. Sample A contains SiC37, SiC72, and SiC174 at a ratio of 1:1.43:1.43 and sample B contains them at a ratio of 1:0.7:1.9. Then, we conduct polarimetric observations of the mixed samples at a phase angle of 100°. The experiments are performed under the conditions used by Kim et al. (2017). Table 1 shows the results of the laboratory experiments, i.e., the measured grain size, Φ, A, P, and 〈d〉. The measured values of Φ, A, P, and 〈d〉 for the SiC and JSC-1A sample groups differ significantly. The reason seems to be the surface roughness of individual grains. The grains in the SiC samples (SiC37, SiC72, and SiC174) have simpler and smoother surfaces than those of the JSC-1A samples (both of the samples have roughly spherical grains). This is why the SiC samples have large Φ, A, P, and 〈d〉 values.

Table 1 shows the results of the experiments for samples A and B. The two samples have the same average grain size and composition. However, they show different Φ values of 2.16 and 2.36, respectively (the variation range of Φ is approximately 0.4 for the entire lunar surface in our observational data, as presented in Section 3). In addition, we also perform laboratory work with JSC-1A, which is a lunar regolith simulant designed by the NASA Johnson Space Center. We measure the polarization properties of two sieved samples of JSC-1A. In the experiments, JSC-1AM and JSC-1A have similar average grain sizes of 45 and 41 μm, respectively. However, these two simulants have different size distributions. The first one has a relatively narrow size range of 25−75 μm, because this is a sieved sample of JSC-1A (JSC-1A has a relatively wide grain size range from submicrons to centimeter). Therefore, larger grains, which contribute to I⊥, are more abundant in JSC-1A. The two simulants have not only similar average grain sizes, but also the same composition. However, the Φ values of JSC-1A and JSC-1AM are different: 1.48 and 1.38, respectively (Table 1).

In both the JSC-1A and SiC simulant groups, the Φ values increase with large grain abundance despite the similar average grain sizes and compositions. Thus, we confirm that Φ can be an indicator of the size distributions of lunar regoliths that have the same average grain size.

3. Observations

3.1. Source Data

We analyzed polarimetric and photometric observational data that were obtained by Jeong et al. (2015) at the Lick Observatory in California, USA. The pixel scale of the observation is 1.34 km/pixel at the center of the lunar disk. The data were obtained in the U, B, V, R, and I passbands. Jeong et al. (2015) constructed a map of 〈d〉 using V-band data consisting of the maximum polarization degree and reflectance at a phase angle of 5°. The values of 〈d〉 were estimated using Equation (1), which was derived by Shkuratov & Opanasenko (1992) using laboratory results:

$$\langle d \rangle = 0.03 \exp[2.9(\log A + 0.845 \log P_{\text{max}})].$$  (1)

The units of 〈d〉, A, and P_{max} are μm, percent, and permil, respectively. We extract the perpendicular and parallel polarized reflectances, I⊥ and I∥, from the data, and then define Φ as the ratio of I∥ and I⊥. Mineralogically, the lunar surface can be categorized as maria and highlands, each of which have a relatively homogeneous chemical composition (Taylor 1975). Therefore, it would be desirable to analyze Φ separately for the maria and highlands. In this study, we classify these formations according to the FeO abundance estimated from the Clementine reflectance data (Lucey et al. 1995, 1998, 2000). The values for the maria and highlands are FeO ≥ 18 wt% and FeO ≤ 15 wt%, respectively. We use only the region with a selenographic longitude of |λ| > 15° for the quantitative analyses in this study because the regions |λ| < 15° have a relatively large uncertainty in 〈d〉 (Jeong et al. 2015).

3.2. Φ–〈d〉 Space

On the basis of our laboratory measurements, we develop a new polarimetric space, 〈d〉 versus Φ. Figure 2 shows the global distribution of lunar regolith in polarimetric space for the V band. As a representative example, we explain only the V band in this paper, because the trends of the figure for all of the passbands we used are similar. The data for the other passbands (U, B, and R) are presented in the Appendix (I band has large uncertainty to analyze). In Figure 2, gray dots indicate the global lunar near side, and red, orange, blue, and purple contour lines indicate four lunar regions, Mare Crisium, Mare Imbrium, the crater Tycho, and the
north-central highland region (41°9N 17°2E), respectively. The contour lines show the 50th, 75th, and 95th percentiles. We find that the lunar regolith is distributed on a specific radial slope line in the parameter space \langle d \rangle versus \Phi. The parameter \langle d \rangle has evolved from large to small under continuous microimpacts. Thus, the evolution of the lunar regolith might be started at large \langle d \rangle, and then \langle d \rangle seems to gradually decrease with time along the specific evolutionary pathway (slope line). Figure 2 shows that a mare regolith has a steeper slope than a highland regolith. This result implies that the mare regolith contained more large grains than the highland regolith when it was first excavated. Furthermore, it also implies that the production rates of small grains are probably different for maria and highlands. The reason seems to be the varying resistance to comminution of lunar materials. Cintala & Hörz (1992) showed that lunar regolith materials such as feldspar, pyroxene, and olivine have different resistances to comminution by laboratory experiments. Hörz & Cintala (1997) conducted impact experiments with rocks containing major lunar elements such as Si, Al, and Fe. According to these experiments, even when the materials are subjected to the same impact, mare materials (with high FeO and MgO contents) produce larger grains than highland materials (with high Al2O3 and SiO2 contents). Thus, the reason maria has larger \Phi values than the highlands seems to be the differences in resistance to comminution between mare and highland materials. This phenomenon is discussed in Section 3.3.

3.3. Factors Affecting the Evolutionary Pathway

Because FeO is an abundant metallic composition on the lunar surface, it would be desirable to analyze the effect of the FeO abundance on the grain size evolution. Figure 3 shows the variation in the evolutionary pathway with FeO abundance. The colored dots represent the average \Phi values calculated in 5 μm wide \langle d \rangle bins at a given FeO abundance. Red, orange, green, and blue plots indicate FeO ranges of 5 wt% ≤ FeO < 10 wt%, 10 wt% ≤ FeO < 15 wt%, 15 wt% ≤ FeO < 20 wt%, and 20 wt% ≤ FeO < 25 wt%, respectively. The error bars represent a standard deviation of 1σ for \Phi in this paper. The solid lines are the fitting results using the average \Phi values.

Figure 3 shows that as the FeO abundance increases, the evolutionary pathway becomes steeper. This seems to be why mare regions show a steeper evolutionary pathway in Figure 2. According to experiments by Hörz & Cintala (1997), FeO seems to be poorly broken up compared to other lunar regolith materials. Thus, regolith with more abundant FeO seems to show larger \Phi values and a steeper evolutionary pathway.

The evolutionary pathway is also correlated with the albedo. At higher albedos, the slope is shallower. The correlation between the albedo and the evolutionary pathway seems to arise from the close correlation between the FeO content and albedo (the Spearman’s rank correlation factor \rho between the FeO content and albedo is approximately −0.81). As shown in Figure 3, because the evolutionary pathway is affected by the FeO content, the albedo is also correlated with the evolutionary pathway. Furthermore, the albedo is correlated with the polarization degree and grain size because small grains have relatively low absorption. Thus, both \langle d \rangle and \Phi are related to the albedo.

Figure 4 shows another factor affecting the evolutionary pathway, the selenographic latitude; the colored dots represent the average \Phi values, as in Figure 3, but at a given latitude instead of a given FeO content. Red, orange, green, and blue plots indicate latitude ranges of 0° ≤ |\beta| < 30°, 30° ≤ |\beta| < 40°, 40° ≤ |\beta| < 50°, and 50° ≤ |\beta| < 60°, respectively.

Figure 4 clearly shows that the evolutionary pathways vary with the latitude. The evolutionary pathway is steeper at low latitudes. This result implies that the lunar regolith has a different size distribution depending on the latitude even when the value of \langle d \rangle is the same. P has only a very weak relationship with the
incident and reflectance angles (Lyot 1929; Kim et al. 2017). In addition, Jeong et al. (2015) showed that the latitude dependence of \( \langle d \rangle \) is not affected by the photometric conditions that are the incident and reflectance angles, by analyzing zero-phase angle albedo data obtained by Lucey et al. (2014) from the Lunar Orbiter Laser Altimeter. Thus, we conjecture that the latitude dependence of \( \Phi \) is not the result of the photometric conditions. A possible cause of the latitude dependence of \( \Phi \) is differences in the resurfacing conditions depending on the latitude. The grain size evolution is a result of both comminution and resurfacing processes. The value of \( \langle d \rangle \) decreases with continuous micro-impacts. Simultaneously, resurfacing processes resulting from large-scale impacts, which increase \( \langle d \rangle \), have also occurred. Therefore, regolith evolution is affected not only by the microimpact flux, but also by cratering. If the impact flux varies with the selenographic latitude, the rates of comminution and resurfacing can vary depending on the latitude. Therefore, the impact flux conditions can influence the grain size evolution.

The impact flux conditions on the lunar surface seem to vary with latitude. Jeong et al. (2015) found that \( \langle d \rangle \) is larger at high latitudes than in lower latitude areas. They interpreted this phenomenon as a result of reduced microimpact flux at high latitudes. Cremonese et al. (2013) estimated the microimpact flux in areas at various latitudes on the Moon with N-body numerical calculations. According to their calculations, micro-impacts are concentrated in low latitude areas. Furthermore, an asymmetric impact cratering flux for impactors of various sizes depending on the selenographic latitude and longitude is also predicted by observations and numerical calculations (Werner & Medvedev 2010; Le Feuvre & Wieczorek 2011; Wang & Zhou 2018). Hence, almost all of the impacts on the lunar surface, from large to small scales, show latitude dependence, and the grain size evolutionary pathway is probably affected by latitude effects.

This grain size evolutionary pathway seems to contain valuable information about the space environment such as the motion of space weathering agents. Interplanetary dust particles (IDPs) as a space weathering agent are divided into dust from comets and from asteroids. These two types of dust with different origins have different orbital properties such as relative velocity and eccentricity when they encounter the Earth–Moon system (Kortenkamp 2013; Yang & Ishiguro 2018). Therefore, the impact conditions of the two types of IDPs on the lunar surface are probably different. However, the detailed impact conditions, such as the flux, velocity, and location, are not well known. The grain size evolutionary pathway can hint at the properties of impactors and the factors having the greatest influence on space weathering on the Moon.

### 3.4. Size Distribution of Ejecta from the Crater Tycho

A fresh crater such as Tycho can be a good example for understanding the behavior of \( \Phi \) in an observation. Figure 5 shows the \( \Phi \) and \( \langle d \rangle \) distributions with distance from the center of Tycho. The blue and red symbols indicate the distributions of \( \Phi \) and \( \langle d \rangle \), respectively. The values on the figure represent averaged \( \Phi \) and \( \langle d \rangle \) values at various radial distances from the crater center. Figure 5 shows that \( \langle d \rangle \) tends to decrease depending on the increase of distance. \( \Phi \) also shows a decreasing trend depending on the increase of distance. \( \langle d \rangle \) is much larger inside the crater rim than outside of it. This phenomenon seems to be due to excavated fresh soils under the surface, mass wasting at the crater wall, and a higher rock abundance inside the crater. Bandfield et al. (2011) showed that the inside of the rim of Tycho has a higher rock abundance than the outside of the crater rim. In the ejecta blanket area, \( \langle d \rangle \) also shows a decreasing trend with increasing radial distance. Because a heavier particle requires more energy to be projected far from the impact, the grain size of impact crater ejecta is expected to decrease with increasing distance from the crater rim (Melosh 2011). Moreover, a decrease in the grain size of ejecta with increasing radial distance from the crater rim was observed by an in situ measurement of a terrestrial crater (Hörz et al. 1983).

\( \Phi \) is an indicator of the size distributions of lunar regolith having the same \( \langle d \rangle \). However, we can analyze the trend of \( \Phi \) according to the distance from the crater rim. In Figure 5, \( \Phi \)
shows interesting behavior. Only the area in which the distance range is from 1–2 radius has a significantly larger $\Phi$ value than other ejecta areas. This area does not have a distinctive FeO content compared with other ejecta areas (∼11 wt% for all areas of ejecta). This result implies that the initial grain size distribution of soil excavated by the impact probably varies with distance from the impact crater. Crater ejecta are emplaced ballistically around an impact crater (Melosh 2011). Thus, a large grain of ejecta travels a short distance. Despite the higher rock abundance on the inside of the rim, $\Phi$ is relatively small inside of the rim compared with that in the ejecta areas. The reason seems to be the difference in the $\langle d \rangle$ range between the inner and outer crater rim areas.

4. Conclusions

We analyzed both experimental and observational data on the lunar regolith. Laboratory experiments showed that $\Phi$ seems to be an indicator of the regolith size distribution when the average grain size is the same. When $\Phi$ is larger, the particles of the regolith are larger. As a result of analyses of observational data, we found that the regolith grain size evolves along a given pathway. Furthermore, we also found that the evolutionary pathway depends on both the FeO abundance and the selenographic latitude. The FeO dependence is considered to be the result of different resistances to comminution of the regolith material. These differences are thought to be caused by different impact conditions at a given latitude, because the meteoroid impact flux is much higher at low latitudes. Furthermore, by analyzing polarimetric observational data for the crater Tycho, we found that the $\langle d \rangle$ and $\Phi$ values of the ejecta decrease with increasing distance from the rim of the crater.

In this study, we conducted only a preliminary research of grain size evolution on the Moon, because the lunar regolith simulants do not suggest the same conditions as space observations do and are limited to the near side of the Moon. The Wide-Angle Polarimetric Camera (PolCam), an instrument on the Korea Pathfinder Lunar Orbiter, will begin its polarimetric observations from lunar orbit in 2021 January (Jeong et al. 2017). The PolCam will obtain polarimetric maps at a spatial resolution of ∼100 m. PolCam data are expected to provide detailed information about the grain size evolutionary pathway.

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Appendix

We present additional figures for four passbands ($U, B, V$, and $R$). Figures 6 and 7 correspond to Figures 3 and 4, respectively.
Figure 6. FeO dependence of the grain size evolutionary pathway for $U$, $B$, $V$, and $R$ bands; this figure corresponds to Figure 3 in Section 3.4.
Figure 7. Latitude dependence of the grain size evolutionary pathway for $U$, $B$, $V$, and $R$ bands; this figure corresponds to Figure 4 in Section 3.4.

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