Particle Size Evolution of the Lunar Regolith and a New Maturity Index. Minsup Jeong[1], Young-Jun Choi[1, 2], Sungsoo S. Kim[3], Il-Hoon Kim[3], Yu. G. Shkuratov[4], Hongu Yang[1], [1]Dept. of Lunar and Planetary Science, Korea Astronomy and Space Science Institute, [2]University of Science and Technology, Korea, [3]School of Space Research, Kyung Hee University, Korea, [4]Astronomical Institute of Kharkov V.N Karazin National University, Ukraine

Introduction: The surface of airless bodies exposed to space environments is gradually changed with time in both physical and chemical properties. This process is called space weathering. The agents of space weathering, that is, micro-meteoroid, solar wind particle, and high-energy particle, make multiple effects on the surface of airless bodies, simultaneously. As a result of space weathering, the reddening, darkening, and comminution of regolith have been occurred. Maturity index of lunar surface were established based on these phenomena. One of them is the optical maturity (OMAT) index which was proposed by Lucey et al. [1]. Grain size <*d*> is also one of the maturity indices for the lunar surface because <*d*> decrease with time by the micro-impact process. Correlations among <*d*>, albedo and maximum polarization degree of lunar surface was established by laboratory measurements and observations [2]. However, the main source of the micro impactor still unrevealed. Recent studies showed some important characteristic behaviors of the agent of weathering. Jeong et al. found latitude dependency of lunar regolith <*d*> [3]. Sim et al. [4] found that the optical properties vary systematically across the lunar surface depending on azimuth orientation of crater wall facets. The results above imply that the space weathering agents have something to do with the direction of incident to lunar surface. Here, we find new weathering properties that the lunar regolith size evolution track on single scattering power (SP) - <*d*> space. SP is defined by $I_{\perp} / I_{\parallel}$, where $I_{\perp}$ and $I_{\parallel}$ represent the perpendicular and parallel components of intensity.

Data: We have analyzed polarimetric and photometric data that were obtained by Jeong et al. [3]. The pixel scale of the data is 1.34 km at the center of lunar disk. The data were obtained in 5 pass-bands, which are U, B, V, R, and I whose effective wavelengths are 3738, 4435, 5586, 6763, and 8189 Å, respectively. In this study, we analyze only V band data. We note that we exclude the regions with the longitude range of $|\lambda| < 15°$ from this study due to the uncertainty.

Analyses: It is a well-known process that the decrease in regolith particle size on lunar surfaces with time is due to the comminution by a continual micro-impact. Thus, the smaller <*d*>, the more mature is regolith. However, it is relatively unknown how particles evolve in different conditions such as the latitude and composition of the surface.

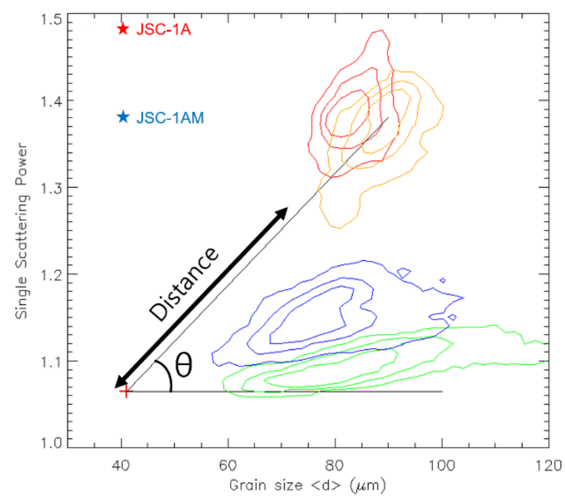

Figure 1. Distributions of grain size <d> vs. single scattering power SP for 4 different regions. Contours are for the 50th, 75th, 95th percentiles. Two star symbols indicate laboratory data

To understand the details of the regolith evolution, we define the single scattering power SP which is defined by a ratio between $I_{\perp}$ and $I_{\parallel}$. $I_{\perp}$ is mostly composed of a singly scattered light by a large particle and $I_{\parallel}$ is mostly composed of a multiply scattered light among small particles. Thus, the higher SP regolith, the more large particles contains. **Figure 1** shows that the correlation between <*d*> and SP. Here, two star symbols indicate data from laboratory experiments by Kim et al. [5]. The experiments were performed with sieved samples of JSC-1A. In the **fig. 1**, JSC-1A (red) refer to the unsieved JSC-1A, JSC-1AM (blue) refer to the sieved sample into the grain size range of 25 - 75 μm. This two samples, JSC-1A and JSC-1AM, have the similar average grain size <*d*> of 41 μm and 43 μm, respectively. However, SP values are significantly different between the two values. It seems that the difference of SP comes from the absence of large particles in JSC-1AM.

Results: Contour lines in **fig. 1** indicate 4 examples of lunar surface, which are Oceanus Procellarum (red), Mare Imbrium (orange), Crater Tycho (green), and a central north highland region (blue, location: 13E, 44N). Contours are for the 50th, 75th, and 95th percentiles. **Figure 1** shows two trends in <*d*> – SP space, which are the angle θ and distance *D* from origin (the red cross symbol; <*d*> = 41 μm and SP = 1.065). We have identified that θ has a specific value for each region of the lunar surface. **Figure 1** shows that maria (red and orange) and highlands (blue and green) are distinguishable on <*d*> – SP space. A mare region has a relatively larger SP than a highland. Hörz and Cintalla [6] performed impact experiments with stainless-steels at 1.4 km/s for several lunar materials which are SiO_2, Al_2O_3, FeO, MgO, CaO, Na_2O, and K_2O. According to the laboratory work, the average particle sizes decrease with the continuous impacts for all simulants. However, the amount of smaller particles (< 10 μm) in FeO and MgO simulant, which are abundant in mare regolith, are much less than Al_2O_3, Na_2O and K_2O simulants. Al_2O_3 is included in highland regolith twice more than mare regolith. It implies that a highland region produces smaller particles than a mare region, even in the same space weathering environments. Thus, the regolith of highland and mare are supposed to be evolved in different tracks on <*d*> – SP space. Here, we suggest D as a new maturity index. D seems to be a maturity index, which relatively reduces the influence of the composition of the regolith. D shows correlations with OMAT and <*d*>. The spearman's rank correlation ρ is 0.727 for <*d*> and 0.702 for OMAT.

Discussions: We have identified that θ has correlation with a selenographic latitude. **Figure 2** is the histograms of θ in maria (blue) and highlands (red) for 4 different latitude regions. **Figure 2** shows clearly the latitude dependency of θ in both of maria and highlands. The latitude dependency can give information about the distributions and motions of interplanetary dust particle (IDP) which is a main source of micro-impact on the lunar surface. Recently, Jeong et al. [3] and Hemingway et al. [7] found that the degrees of space weathering decreased with increasing selenographic latitude. They interpreted that the lower degrees of space weathering at higher latitude is due to the smaller flux of weathering agent at higher latitude. However, the latitude dependency of θ implies that there are other factors which have influenced the particle size evolution on the lunar surface. If the evolution of particle size is only affected by the flux of weathering agents, it will only differ by the time scale of D evolution on the same θ track. However, **fig. 2** shows the latitude dependencies not only D but also θ. A simple interpretation of this phenomenon is a difference of impact angle depending on latitude. The impact angle is an important factor for impact cratering process. The only vertical component of the impact velocity contributes to the cratering [8]. Moreover, the particle size of regolith becomes much smaller when impact with strong energy [6]. These may be an indication that the motions of space weathering agents are parallel directions to the ecliptic plane and the agents have a larger relative velocity with respect to the Moon. If relative velocity of the weathering agents is slow (similar with the Moon's escape velocity of 2.4 km/s), the particles near Hill sphere of the Moon have been affected by the gravity of the Moon. Thus, the slow particles are probably fallen down to the surface relatively randomly in direction. However, much faster particles relatively can overcome the Moon's gravity. Thus, the particles impact to the surface in the direction of their motions. In conclusion, the space weathering agent seems to be relatively fast and moving to parallel directions to the ecliptic plane.

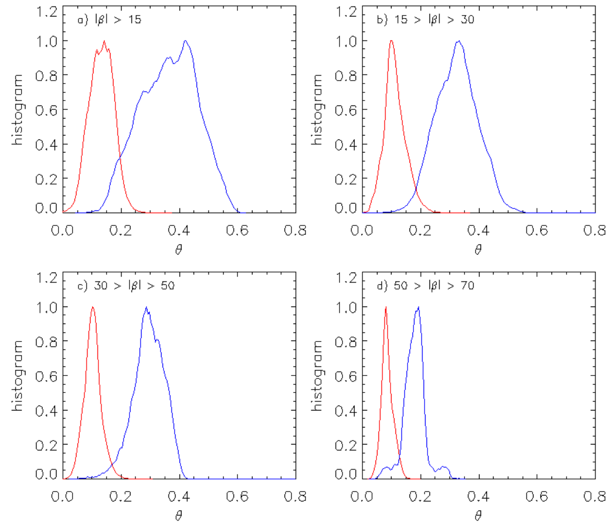

Figure 2 Histograms of θ in maria (blue) and highlands (red) for four different latitude regions.

Conclusions: To understand the regolith evolution on the lunar surface, we analyze a correlation between the single scattering power SP and grain size <*d*>. We developed a new maturity parameter D and found particle size evolution tracks on <*d*> – SP space.

References: [1] Lucey et al. (2000), JGR 105, E8 20,377-20,386; [2] Shkuratov and Opanasenko, (1992), Icarus 99, 486-484; [3] Jeong et al. (2015), ApjS, 221, 16; [4] Sim et al. (2017), GRL, 44, 11, 273-281; [5] Kim et al. (2017), ASR, 59, 1629-1635; [6] Hörz and Cintalla (1997), M&PS, 32, 179-209; [7] Hemingway et al. (2015), Icarus, 261, 66-79; [8] Chapman and McKinnon, (1986), In: Satellites, Univ. of Arizona Press, Tucson, pp. 492-580