Understanding Space Weathering of Lunar Soils with a Polarized Perspective. Lingzhi Sun[1,2], Paul G. Lucey[1], Casey I. Honniball[1,2], Macey Sandford[1,2], Emily S. Costello[1,2], Liliane Burkhard[2], Reilly Brennan[3], Chiara Ferrari-Wong[1,2], [1]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, HI, USA, lzsun@higp.hawaii.edu; [2]Dept. of Earth Sciences, University of Hawaii at Mānoa, Honolulu, HI, USA; [3]Georgia Tech, Atlanta, GA, USA

Introduction: Polarization is a relatively little utilized remote sensing technique but contains unique information on the composition and physical state of planetary surfaces. Shkuratov and co-workers [1-3] have demonstrated the contribution of polarization to lunar studies using laboratory measurements of lunar samples and analogs, and telescopic observations of the Moon. Shkuratov and Opanasenko (1992) showed a relationship between polarization, albedo, grain opacity and grain size [1]. Recently, Jeong et al. (2016) reported extensive multispectral polarization telescopic observations, deriving hemispheric grain size distribution maps and drawing conclusions regarding the differential effects of space weathering on the mare and highlands [4]. Finally, The Korean Pathfinder Lunar Orbiter will carry POLCAM, a multispectral imaging polarimeter, to lunar polar orbit, which will provide unprecedented global and high resolution polarimetry measurements. Both [3] and [4] showed that multispectral polarization is sensitive to space weathering effects in a manner that is distinct from other methods of estimation of this effect such as OMAT [5].

Many space weathering effects occur at the surface of grains, in particular various types of vapor deposited rims. Polarization can be used to isolate the spectral properties of grain surfaces. The surfaces of lunar grains are polarizing perpendicular to the plane formed by the Sun, surface and observer, so an instrument with its polarizer oriented with respect to this axis will include polarized grain specular reflection as well as unpolarized light that has propagated through the interior of the grain. With the polarizer oriented parallel to the Sun-target-observer plane, the specular component is excluded, and the signal is dominated by light that has undergone depolarizing multiple scattering [6,7]. Thus, by subtracting the multiple scattered component obtained by observations at parallel geometry from the sum of specular and multiple scattering effects measured at perpendicular geometry, the spectral properties of the surface can be isolated, and this separation of the spectral effects of surface and interior scattering may provide new insight into space weathering.

The spectral polarization of lunar soils at near-IR wavelengths have barely been explored by former workers. In this study, we present polarized near-IR spectra of eight lunar soils, and study the revealed space weathering-related grain properties of lunar soils with radiative transfer theory [7].

Data: Our data is collected at 90-degree phase angle (Fig. 1), which is near the angle where the maximum positive polarization for lunar soil was observed by Shkuratov and coworkers [3]. We measured the polarized spectra for eight lunar soils, with widely varying FeO, TiO_2 and maturity (Is/FeO) [8]. The grain size of all the samples measured here is less than 150 microns.
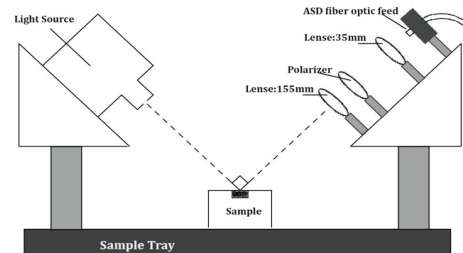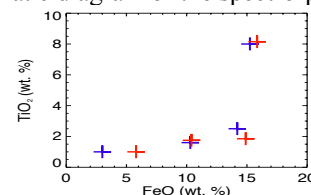

Fig. 1 Schematic diagram of the spectro-polarimeter.

Fig. 2 FeO and TiO_2 contents of measured samples. Blue and red crosses refer to immature and mature soils, respectively [8].

Radiative transfer modeling: In this work, we will mainly consider the linear polarization of lunar soils. When unpolarized light interacts with lunar soil, the observed light comes from two parts, one is the linearly polarized specular reflected light, and the other is the depolarized multiple scattered light. The specular reflected light only interacts with grain surfaces, which may contain space weathering information; the unpolarized light goes through multiple reflection and transmission, so it would carry the compositional information regarding interior of grains. The energy distribution for the perpendicular branch ($\perp$) and perpendicular branch (//) is shown below:

$$\omega\left[P(g)\right]_{\perp} = R_{\perp} + (\omega - S_e)/2 \qquad (1.1)$$

$$\omega\left[P(g)\right]_{\parallel} = R_{\parallel} + (\omega - S_e)/2 \qquad (1.2)$$

Where P(g) is the phase function, and $R_{\perp}$ and $R_{//}$ are Fresnel coefficients of specular reflection, and $\omega - S_e$ refers to the unpolarized part [7]. The radiative transfer equations we used here are listed below:

$$r_{\perp}(i,e,g) = K\frac{1}{4\pi}\frac{\mu_0}{\mu_0+\mu_e}\left\{\omega P(g)_{\perp} + \frac{\omega}{2}[H(\mu_0/k)H(\mu_e/k)-1]\right\} \quad (1.3)$$

$$r_{\parallel}(i,e,g) = K\frac{1}{4\pi}\frac{\mu_0}{\mu_0+\mu_e}\left\{\omega P(g)_{\parallel}+\frac{\omega}{2}[H(\mu_0/k)H(\mu_e/k)-1]\right\} \quad (1.4)$$

Where r is the reflectance and ω is the single scattering albedo [7], and K is the porosity of lunar regolith. The percent polarization is expressed as,

$$P = (r_{\perp} - r_{\parallel}/r_{\perp} + r_{\parallel})\times 100\% \quad (1.5)$$

If substitute r with Eq. 1.3 and 1.4, and substitute $\omega P(g)$ with Eq. 1.1 and 1.2, then the percent polarization can be expressed by the Fresnel coefficient and single scattering albedo. It is clear that the percent polarization is determined by the refractive index (real index n and imagery index k) and phase angle. Once percent polarization and phase angle are known, this method can be applied as a new approach to estimate the refractive index for minerals.

Results and discussions: The percent polarization of eight lunar soils are shown in Fig. 3a. It can be seen that the percent polarization of all the samples decreases with wavelength, consistent with the known dependence of polarization on albedo [3]. For the mature and high-Ti soil 10084, 97, their percent polarization can reach as high as 20% at 0.5 μm. We also observe negative polarization for the Apollo 16 sample 67711, 58, which consists of more than 90% plagioclase and is very bright and highly transparent, so most of the light has gone through multiple scattering within the sample and little is specularly reflected, thus enhancing the parallel branch and weakening the perpendicular branch.
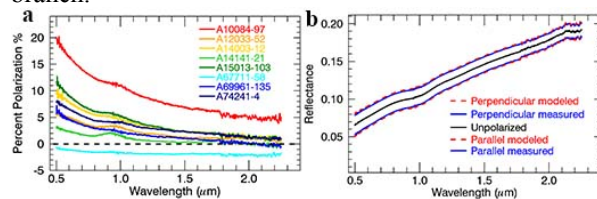

Fig. 3 a) percent polarization of eight lunar soils; b) measured and modeled polarized spectra for lunar soil 10084, 97.

Using the equations listed above, we successfully reproduced the polarized reflectance for 7 lunar soils (except 67711, Fig. 3b). In this model the real index of refraction n was varied as a function of wavelength to produce the best fit, so we are able to estimate n with polarized spectra (Fig. 4). In Fig. 4, we show the derived n for three pairs of soils that have similar FeO and TiO_2 content but different maturity, and mature soils are displayed in red, immature soils are displayed in blue, we also show the ratios of n of mature vs. immature soils in Fig. 4d. We find that compared to that of the immature soils, the real index n for mature soils is higher in value at visible and near-IR wavelengths, and the spectra of n show a redder slope for mature soils. This might due to the presence of space weather-

ing products on the rim of mature soil grains, for instance, vapor deposits and/or nanophase Fe. In previous studies, n has been assumed to be a constant for a lunar soil, even when estimating the degree of space weathering [9,10], but our result show that it not only varies with wavelength but also changes with space weathering.

The above model is useful and effective, but presently has two shortcomings to be overcome. First, it assumes the grain surfaces and interiors share the same optical properties, whereas space weathering causes significant changes in surface chemical and optical properties. Second, it does not predict negative polarization. In future work, we will emphasize modeling the difference between the perpendicular and parallel polarizations which should contain merely the surface optical properties, which are directly related to space weathering processes.
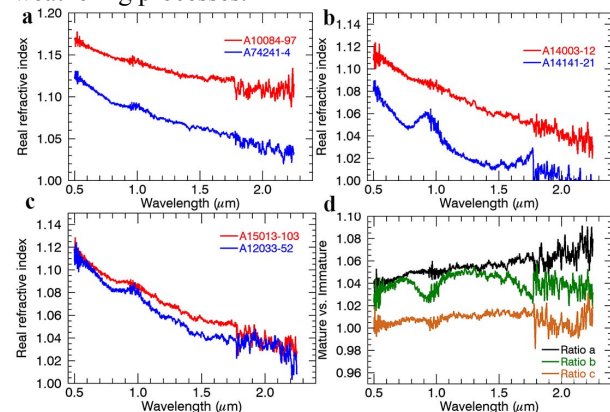

Fig. 4 a-c show three pairs of modeled real index n for mature and immature soils having similar compositions, d shows their ratios.

Conclusions: Using radiative transfer modeling, we successfully reproduced polarized spectra of lunar soils, and developed a new approach in estimating the real index n of refraction. We found that the spectra of n for lunar soils become redder and higher in value after space weathering. Polarization spectroscopy is less utilized in lunar science, but it can reveal properties of lunar grains, and provide a new perspective in understanding lunar space weathering.

References: [1] Shkuratov, Y. G. & Opanasenko, N. V. (1992), Icarus, 99, 468. [2] Shkuratov, Y. G. et al. (1992) Icarus, 95, 283. [3] Shkuratov, Y. G. et al. (2007), Icarus, 187(2), 406-416. [4] Jeong et al. (2015) ApJS, 221, 16. [5] Lucey et al. (2000), JGR, 105(E8):20377-20386. [6] Pellicori (1971), Appl Opt. 10(2). [7] Hapke B. (2012) Cambridge University Press, New York. [8] Lucey et al. (2018) 49th LPSC, 1718. [9] Lucey (1998), JGR, 103 (E1):1703-1713. [10] Hapke B. (2001), JGR, 106(E5): 10039-10073