THE FORMATION OF LUNAR SWIRLS: RESULTS FROM HAPKE'S RADIATIVE TRANSFER MODELING.

D. Liu[1] and L. Li[1], [1]Department of Earth Sciences, 723 W. Michigan Street, Indiana University-Purdue University, Indianapolis, IN, 46202, email: liudawe@imail.iu.edu and ll3@iupui.edu

Introduction: Lunar swirls are high albedo, optically immature regions on the Moon. They are coincident with regions possessing high magnetic field strength, but not associated with distinct topography [1-3]. Elucidating the origin of lunar swirls is essential to understanding the formation of lunar surface magnetic field and the relative importance of solar wind and micrometeoroid bombardment on space weathering [1]. Several hypotheses are proposed to explain the origin of lunar swirls. One hypothesis states that the formation of lunar swirls is attributed to comet impacts by which the dark fine top lunar regolith is stripped off and fresh unweathered soils are exposed [4]. Another is the dust transport model which considers the formation of lunar swirls as preferential accumulation of fine dust grains enriched in feldspathic materials [5]. The third hypothesis is the solar wind deflection by magnetic anomalies meaning that solar wind ions are deflected away from the on-swirl surface and focused onto off-swirl surface, resulting in high albedo, immature lunar soils for the on-swirl surface [6]. This last hypothesis is strongly supported by the observations that on-swirl spectra show partial reddening with little darkening due to retarded weathering, while off-swirl spectra exhibit only darkening with little or no reddening because of accelerated space weathering [2, 3]. The dark and flat off-swirl spectra can be explained by the production of larger submicroscopic iron (SMFe), implying off-swirl regions should have a higher mass fraction of larger SMFe and possible smaller SMFe than on-swirl regions [2-3].

In this study, Hapke's radiative transfer model described in [7] was applied to estimate the mass fraction of smaller and larger SMFe in on- and off-swirl regions. We aimed to test whether off-swirl regions are indeed enriched in both larger and smaller SMFe relative to on-swirl regions and whether the solar wind deflection is a valid hypothesis for addressing the formation of lunar swirls.

Data and Preprocessing: The study site is Reiner Gamma (Fig. 1a) located in the western Oceanus Procellarum (7.5^0N, 302.5^0E). The sub-image of M3G20090210T033052 M^3 Level 2 reflectance data covering the central portion of Reiner Gamma was first smoothed for noise reduction and the spectral bands between 540 nm and 2497 nm were retained for further correction. These bands were then corrected by multiplying the spectral bands with the coefficients, which were derived by dividing the lab measured 62231 reflectance spectrum by corresponding spectrum in M^3 data at each wavelength.

Method: *Lucey* and *Riner* (2011) [7] proposed a new model to account for the reddening and darkening effects of smaller SMFe (<50 nm) and darkening effects of larger SMFe (>50 nm) on the absorption of lunar soils:

$$\alpha = \frac{4\pi n_h k_h}{\lambda} + \frac{36\pi z M_c \rho_h}{\lambda \rho_{Fe}} + \frac{3 q_a M_i \rho_h}{d_{Fe} \rho_{Fe}}, \quad (1)$$

where M_c and M_i are the mass fraction of smaller and larger SMFe in lunar soils, respectively. Definitions and values for other parameters can be found in [8]. The first term on the right of Eq.1 represents the absorption of host lunar soil particles. The second and third term on the right of Eq.1 represent the absorption by smaller and larger SMFe, respectively. Combining Eq.1 with other equations in Hapke's model, *Liu* and *Li* (2012) [8] demonstrated the efficiency of this new model in accounting for space weathering effects.

Estimating mass fraction of smaller and larger SMFe for on- and off-swirl regions requires calculating k_h in Eq.1, which represents the absorption due to unweathered host lunar soil particles. According to the solar wind deflection model, k_h should be the same for

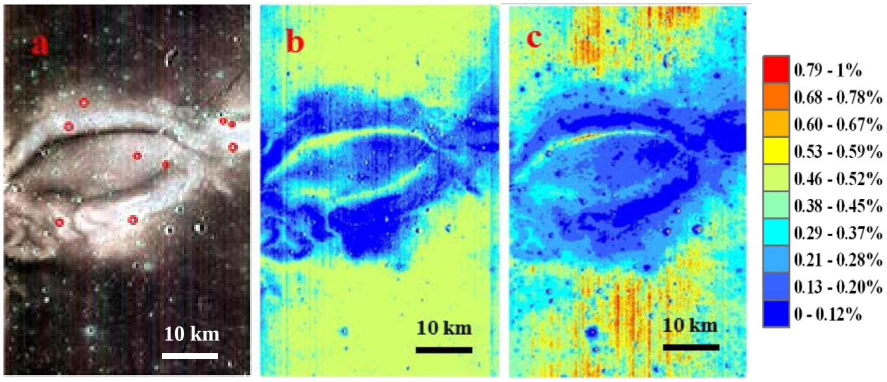

Figure 1. M^3 false color composite and derived mass fraction of SMFe for Reiner Gamma (7.5^0N, 302.5^0E). (a) The color composite (: R=950 nm, G=750 nm, B=540 nm), where red circles represent fresh craters in on-swirl regions. (b) Smaller SMFe. (c) Larger SMFe.

both on- and off-swirl host soils because the spectral difference between on- and off-swirl regions is mainly controlled by varying mass fraction of SMFe rather than compositional differences in host soil particles. To derive k_h of unweathered soils, spectra of the craters represented by the red circles in Fig. 1a were extracted by following the method of [2]. These fresh crater spectra possibly represent newly exposed materials containing little or no SMFe, and their spectra are mainly determined by the composition of unweathered host soils. The average spectrum of the selected fresh craters was fitted with Hapke's model (using Eq.1 in this work and Eqs.1-7 in [9]) by adjusting k_h only and assuming the mass fraction of both smaller and larger SMFe as zero. The k_h spectrum was derived when the difference between averaged image spectrum and fitting spectrum was minimized. After this step, a similar procedure was repeated to fit the spectrum of each pixel in the image by varying the mass fraction of smaller and larger SMFe and applying derived k_h for unweathered host lunar soils.

Results and Discussion: Shown in Figs. 1b and 1c are the mass fraction of smaller and larger SMFe in Reiner Gamma. Off-swirl regions evidently have higher mass fractions of smaller and larger SMFe than on-swirl regions. Dark lanes are clearly delineated in both figures with abundant SMFe due to weak magnetic field strength and less solar wind shielding in these regions. There is a good agreement between image and fitting spectra for on- and off-swirl soils and fresh craters (Fig. 2). The average RMSE between image and fitting spectra for the whole image is about 0.007. These results suggest that spectral differences between on- and off-swirl regions result from different mass fractions of smaller and larger SMFe. Off-swirl regions are indeed enriched in both larger and smaller SMFe as postulated by [2-3]. Due to the shielding effect of magnetic field, fewer solar wind ions, especially H^+ could penetrate into on-swirl regions and thus fewer Fe^{2+} could be reduced and sputtered to form smaller SMFe. For the shielded on-swirl surface the formation of large SMFe would be limited during impact melting because of a less availability of smaller SMFe in lunar soils [1]. In contrast, implanted H^+ can be deflected onto off-swirl regions resulting in off-swirl soils with H^+ saturation. When micrometeoroids impacts occur on the surface and provide enough energy, the regional abundant H^+ facilitates the reduction of Fe^{2+} by impact events, allowing a greater generation of smaller SMFe and OH^- [2-3]. This process also enhances the possibility of building up of larger SMFe via coalescence of abundant smaller SMFe.

Examining the 2.82 μm absorption of M^3 data for on- and off-swirl regions has demonstrated the enrichment of OH^- in off-swirl regions [3]. Other recent studies also favored the solar wind deflection model. For example, Christiansen Feature (CF) derived from Diviner data for Reiner Gamma is found to shift toward shorter wavelengths for the on-swirl relative to off-swirl regions [10]. This small absorption shift was explained by retard space weathering rather than changing the content of plagioclase, which otherwise supports for the dust transport hypothesis. In addition, little temperature anomaly indicated similar particle size across Reiner Gamma region and that the comet impact model may not be valid [10].

Conclusions and Future work: The results from this study show that the off-swirl surface has higher mass fraction of both smaller and larger SMFe than the on-swirl surface as the result of increased solar wind flux of the off-swirl surface. The results imply that the solar wind deflection model is appropriate to account for the formation of lunar swirls. Moreover, this study indicates that solar wind ion implantation could be the major agent of space weathering instead of micrometeoroid impacts. Otherwise, the mass fraction difference of SMFe between on- and off-swirl surfaces would be absent. The future work will be focused on analyzing more lunar swirls and testing the comet impact and dust transport models.

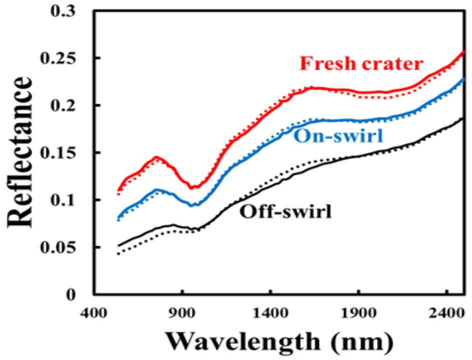

Figure 2. Comparison between fitted and measured spectral. Dotted line are fitted spectral, solid line are measured spectra.

References: [1] Blewett, D. T. et al. (2011) *JGR*, 116, E2. [2] Kramer, G. Y. et al. (2011a) *JGR*, 116, E04008. [3] Kramer, G. Y. et al. (2011b) *JGR*, 116, E00G18. [4] Schultz, P. H. and L. J. Srnka (1980) *Nature*, 284, 22-26. [5] Garrick-Bethel I. et al. (2011) *Icarus*, 212, 480-492. [6] Hood L. L. and Schubert, G. (1980) *Science*, 208, 49-51. [7] Lucey, P. G., and M. A. Riner (2011) *Icarus*, 212, 451-462. [8] Liu, D., and L. Li (2012) *LPS XLIII*, Abstract #2011. [9] Li, S., and L. Li (2011) *JGR*, 116, E09001. [10] Glotch, T. D. et al. (2012) *LPS XLIII*, Abstract #1951.