THE FORMATION OF LUNAR SWIRLS: PRELIMINARY RESULT FROM CHANG'E-1 IIM DATA D. W. Liu[1, 2], J. J. Liu[1, 2], H. B. Zhang[1, 2], W. L. Chen[1, 2], X. X. Zhang[1, 2], X. Y. Gao[1, 2], C. L. Li[1, 2], [1]National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing, China, [2]Key Laboratory of Lunar and Deep Space Exploration, Chinese Academy of Sciences, Beijing, China. Email: liudw@nao.cas.cn.

Introduction: Lunar swirls are bright curvilinear marking on the lunar surface. They are optically immature than the surrounding areas and coincident with regions possessing high magnetic field strength, but not associated with distinct topography [1-3]. Elucidating the origin of lunar swirls is central to understanding the relative importance of solar wind implantation and micrometeorite bombardment on space weathering, and the origin of lunar surface magnetic field [1]. One leading hypothesis for the formation of lunar swirls is solar wind deflection model. This model states that because of the deflection effect of lunar magnetic anomalies, a less amount of submicroscopic iron (SMFe) is generated in on-swirl regions due to a reduced solar wind flux, resulting in higher albedo of the lunar on-swirl regions than off-swirl regions to which solar wind ions are deflected to and a higher amount SMFe is accumulated [4].

In this study, an empirical approach described in [5] was applied to estimate mass fraction of SMFe in on- and off- swirl regions using Chang'E-1 IIM data. We aimed to test whether on-swirl regions are indeed deficient in mass fraction of SMFe relative to off-swirl regions and whether solar wind deflection model is a valid hypothesis for the formation of lunar swirls.

Study Areas and Dataset: Two lunar swirls including Reiner Gamma and Firsov were investigated in this study. Their geological settings, magnetic field strength, and locations are shown in Table 1. The sub-images of CE1_BMYK_IIM_SCI_N_20080622235347_20080623020131_2598_A and CE1_BMYK_IIM_SCI_N_20080707031219_20080707051934_2758_A Chang'E-1IIM Level 2C radiance data were used in this study. These two sub-images cover the central portion of Reiner Gamma and Firsov, and have been normalized to a standard geometry (i=g=30°, e=0°).

Table 1 lunar swirls investigated in this study

Swirls	Locations	Geological Setting	Magnetic Anomaly Strength (nT)
Reiner Gamma	7.5°N, 302.5°E	Mare	22 - Strong
Firsov	10.5°S, 16.5°E	Highland	11- Moderate

Method: Through conducting correlation analysis to the measured reflectance and mass fraction of SMFe of lunar soil samples from Lunar Soil Characterization Consortium (LSCC), *Liu and Li* (2015) [5] found that the ratio of 540 nm/810 nm single scattering albedo (SSA) of lunar soils is highly correlated with the mass fraction of SMFe and not strongly affected by the variation of particle size of lunar soils. A simple exponential function can be used to describe this correlation as indicated in Fig.1. This exponential function was used in this work to estimate the mass fraction of SMFe in on- and off-swirl regions.

The radiance data of the two sub-images were first converted to reflectance using equation: $R=(I/I_{std})*R_{std}$, where R_{std} is lab measured reflectance of lunar soil sample 62231, I_{std} is the corresponding radiance data of Apollo 16 landing site extracted from Chang'E-1 IIM 2C data, and I is the radiance data of sub-images covering the two swirl regions. Then, the reflectance data were converted to SSA using Hapke's radiative transfer model. The closest bands of Chang'E-1 IIM data to 540 nm and 810 nm used in the exponential function are 541 nm and 818 nm, respectively. However, 841 nm band of Chang'E-1 data was selected rather than 818 nm band because of its high noise. At last, the ratio of 541 nm SSA/841 nm SSA was used in the exponential function to estimate the mass fraction of SMFe in Reiner Gamma and Firsov.

Results and Discussion: Shown in Fig. 2b and Fig. 3b are the mass fraction of SMFe of Reiner Gamma and Firsov. Off-swirl regions evidently possess higher mass fraction of SMFe than on-swirl regions. The dark lanes enclosed within the sinuous bright markings are clearly delineated in both figures with abundant SMFe. The derived mass fraction of SMFe ranges from 0% to 0.37% consistent with the measured data of lunar soils (0~0.5%) [6]. In addition, the mass fraction of SMFe in Firsov is lower than that in Reiner Gamma, which can be accounted for by limited amount of Fe^{2+} to be reduced to SMFe in highland than in mare as a result of implanted solar wind H^+.

Off-swirl regions are indeed enriched in SMFe as postulated by the solar wind deflection model. Because of 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 SMFe. In contrast, implanted H^+ could be deflected onto off-swirl regions, resulting in

higher amount of SMFe accumulated in off-swirl regions than in on-swirl regions.

Implications and Conclusions: Results from this work imply that solar wind deflection model is a validate hypothesis for the formation of lunar swirls. Moreover, this study indicates that solar wind ion implantation could be the major mechanism of space weathering rather than micrometeoroid impacts. Otherwise, the mass fraction difference of SMFe between on- and off-swirl regions would be absent. Furthermore, the enrichment of SMFe in off-swirl regions has been confirmed by this work. The association of these regions to the observed enrichment of OH^-/H_2O in off-swirl regions [7] indicates the plausibility of reduction of Fe^{2+} to SMFe by impinging solar wind with the release of H_2O/OH^- in lunar soils. This gives rise to the possibility of using high mass fraction of SMFe to locate lunar surface areas with H_2O/OH^-.

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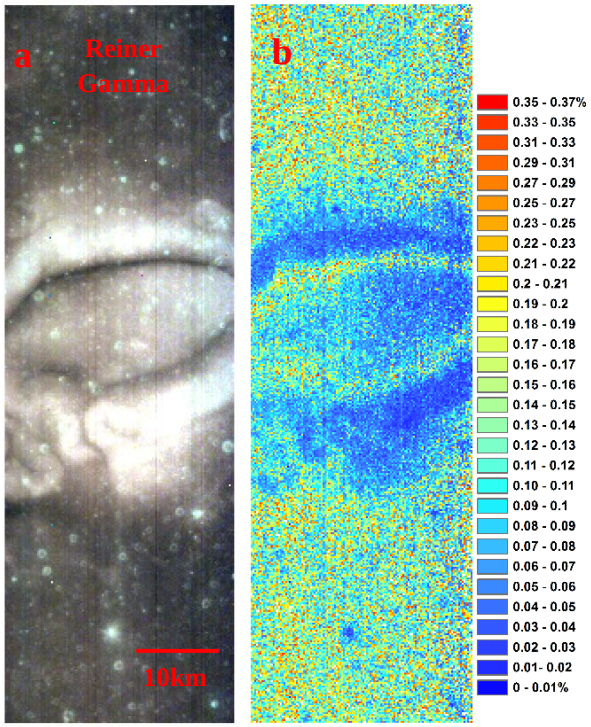

Figure 2. (a) Chang'E-1 IIM false color composite (R = 865 nm, G = 645 nm, B = 550 nm) for swirl Reiner Gamma. (b) Mass fraction of SMFe.

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] Hood L. L. and Schubert, G. (1980) *Science*, 208, 49-51. [5] Liu, D. and Li, L. (2015) *LPS XLVI*, #2560. [6] Morris, R. V. (1980) *LPS XI*, 1697-1712. [7] Pieters, C. M., and Garrick-Bethell, I. (2015), *LPS XLVI*, abstract #2120.

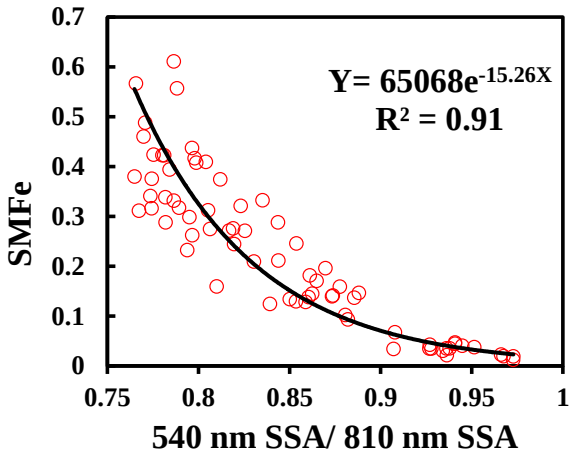

Figure 1. Correlation between the ratio of 540 nm SSA/810 nm SSA and SMFe for LSCC soil samples

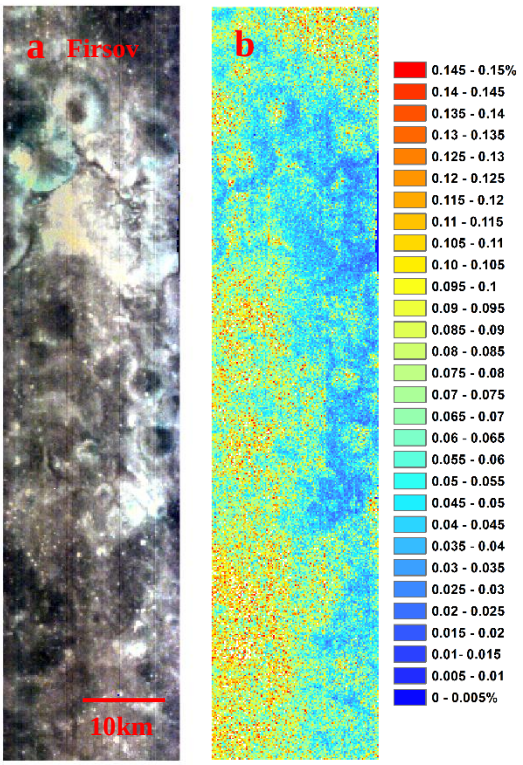

Figure 3. (a) Chang'E-1 IIM false color composite (R = 865 nm, G = 645 nm, B = 550 nm) for swirl Firsov. (b) Mass fraction of SMFe.