LUNAR SWIRLS AS SEEN FROM SMART-1: VARIATIONS OF PHASE FUNCTION STEEPNESS.
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Introduction: Nature of lunar swirls, diffuse bright albedo features with no signs of topography, is still one of most intriguing problems in lunar science and would be a key to lunar surface evolution processes. We use images of swirl areas obtained in 2006 by the AMIE camera onboard SMART-1 spacecraft to access photometric properties of the lunar regolith. We map the steepness of phase function for these regions and analyze maps in terms of the regolith structure.

The steepness of lunar phase function as a tool for lunar photometry: The bidirectional reflectance R as a function of the photometric coordinates (phase angle α, photometric latitude β and longitude γ) can be presented in a factorized form: $R(\alpha,\beta,\gamma)= R_0\cdot F(\alpha,\beta,\gamma) = R_0\cdot f(\alpha)\cdot D(\alpha,\beta,\gamma)$, where $F(\alpha,\beta,\gamma)$ is the photometric function, R_0 is the reflectivity determined at normal geometry when α=0, $f(\alpha)$ is the phase function and $D(\alpha,\beta,\gamma)$ is the disk function (e.g. [1]). The phase function is responsible for the quick phase angle dependence of the brightness of lunar surface sites independently of there position on the Moon. The disk function describes the brightness distribution over the lunar surface at a given phase angle, which is related to the sphericity of the Moon. We use an approximation of $F(\alpha,\beta,\gamma)$ proposed by Akimov [2]:

$$F(\alpha,\beta,\gamma) = \exp(-\eta\alpha)\cos(\alpha/2)\times \times \frac{[\cos(\gamma-\alpha/2)]^{\nu\alpha+1} - [\sin(\alpha/2)]^{\nu\alpha+1}}{(1-[\sin(\alpha/2)]^{\nu\alpha+1})\cos\gamma}(\cos\beta)^{\nu\alpha} \qquad (1)$$

This formula contains only two adjustable parameters, the parameter of disk function ν and the steepness of phase function η. We apply this description to SMART-1 data for lunar swirls in order to estimate the η parameter distribution from the ratio of two images of the same region but obtained at different illumination/observation geometry [3]:

$$\eta = \frac{\ln\left(\dfrac{F(\alpha_1,\beta_1,\gamma_1)}{F(\alpha_2,\beta_2,\gamma_2)}\dfrac{D(\alpha_2,\beta_2,\gamma_2)}{D(\alpha_1,\beta_1,\gamma_1)}\right)}{\alpha_2-\alpha_1} \qquad (2)$$

AMIE data processing: Several lunar swirls were imaged in the regular tracking mode of SMART-1 in color and wideband spectral area of the AMIE micro-imager with a typical 100-200 m / pix resolution. We converted the raw counts of images to the values proportional to bidirectional reflectance under given observational geometry with the preliminary photometric calibration [4] which applies in-flight flat fields and temperature dependent dark frames. We also accounted for the exposure time and distance to the Sun at the time of frame acquisition. Since color filter images are partially spoiled by light scatter in adjacent wideband CCD area, we dealt only with the "blank" filter frames. Calculation of photometric angles for each image and spatial transformations of images obtained at different geometries to the Mercator projection were performed using the latest versions of AMIE SPICE kernels [4]. The local surface tilts (surface topography) disturb the values of β and γ, we neglect this effect applying our method to relatively flat areas only (mare, crater floors etc). Knowing the reflectance and photometric angles, we used the Eq. 2 to find the parameter η. The disk function parameter ν does not affect the spatial pattern of η affecting only the absolute values of η. Therefore we adopt $\nu = 0.3$ [3, 6].

Mare Marginis: Swirl in Mare Marginis covers mare areas and highland region north of crater Goddard. Numerous bright diffuse features of up to tens of kilometres size are best seen when superimposed on dark mare surface. We took a pair of AMIE images, 79/70 and 603/15 (indexed hereafter in the orbit/frame format). Fig. 1a presents the fragment of large-phase-angle image from the pair, centered at 86.7°E, 16.8°N. Swirl features are mostly seen in the upper part of the image above the 12 km sized crater Goddard B. The map of η (Fig. 1b) shows diffuse swirl details as distinctive photometric features with 20 % lower η values than neighboring mare and highland areas. Here brighter shades denote higher steepness of the phase function. Arrows point out most pronounced negative photometric anomalies that are anticorrelated with albedo. This example confirms the inverse correlation of steepness η with albedo that can be explained by weakening shadow-hiding effect due to growth of multiple scattering contribution with the increase of albedo.

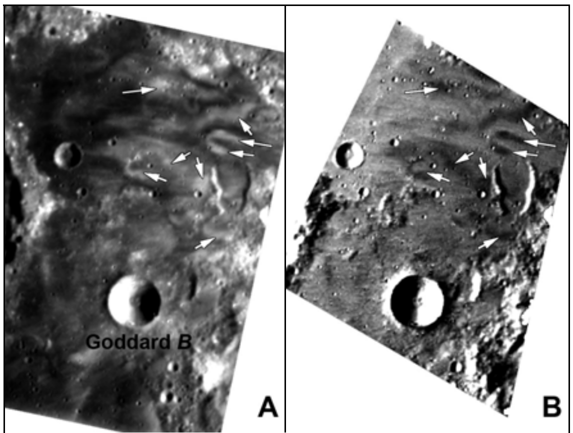

Fig. 1. Swirl in mare Marginis: (A) Reflectance at 60° phase, (B) The parameter of phase steepness obtained from phase angle ratio (9.4°/60°). Arrows denote swirl features seen as low-η details.

Mare Ingenii: The AMIE survey gives an opportunity to map the steepness of phase function at high phase angles for the farside Mare Ingenii swirl. We combined a pair of mages 142/40 and 2871/16 obtained at α=83° and 107°, respectively. The area imaged covers a portion of the crater Thomson M (165°E, 36°S) and shows a large oval-shaped swirl (35 km in size) as well as several small diffuse albedo details. Fig. 2a is a part of 107° frame, arrows show small swirl details surrounded with dark mare material. The η parameter map calculated from the phase ratio also reveals low values of steepness for bright albedo pattern formed by swirls (Fig. 2b). Nevertheless the distribution of η parameter is not perfectly anticorrelates with reflectance for mid-albedo swirl parts. The relative difference in the phase function steepness between swirl features and surrounding mare areas is 20-25 %.

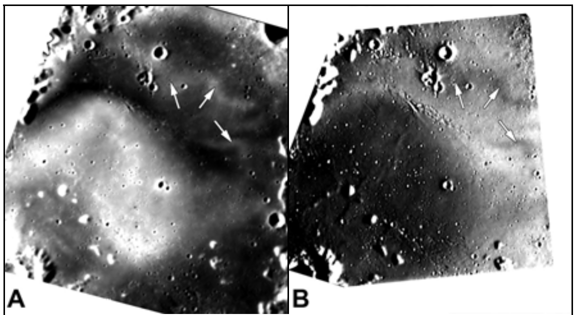

Fig. 2. Swirl in Mare Ingenii: (A) Reflectance image at 107° phase, (B) The parameter of phase steepness, obtained from the phase ratio (83°/107°). Big swirl albedo detail 35 km across shows itself as a low-η feature. Arrows denote small swirl features with lower phase function steepness.

Reiner-Gamma swirl (RGS): The RGS feature located at Procellarum is the most extensively studied swirl because of its good visibility over the dark mare surface. To make a phase-angle ratio image we took two images centered east of RGS core: 1781/41 and 1918/6. The 56° phase-angle reflectance image is presented in Fig. 3a. The η map obtained from the phase ratio (56°/98°) shown in Fig. 3b reveals two craters as positive photometric anomalies (pointed with black arrows). Those craters exhibit bright halos with high η values which not obey the general anticorrelation with albedo. A positive excess of phase function steepness for these craters could be explained by increasing regolith roughness that could be caused by producing a large number of boulders and blocks at the impact event. The most prominent negative photometric anomalies associated with bright swirl details are shown with white arrows in Fig. 3b. We note an obvious difference in swirl albedo pattern and η parameter pattern: a number of bright albedo features disappear in the steepness map. We also found that the absolute values of η within the negative anomaly spots are not correlated with reflectance. This fact also may prove a peculiarity of the millimeter-scale regolith structure in this region [3]. On the other hand, RGS parts photometrically identical to adjacent mare basalts would have the microstructure of upper regolith layer similar to mare surface.

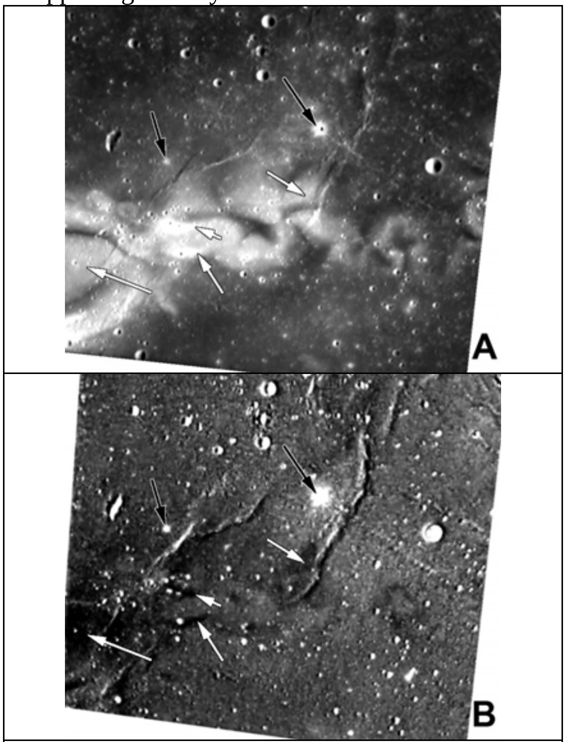

Fig. 3. Swirl Reiner Gamma: (A) Reflectance image at 56° phase, (B) The parameter of phase steepness, obtained from phase ratio (56°/98°). Black arrows denote positive negative anomalies; white arrows show most prominent low-η details.

Conclusions: SMART-1 photometric data on lunar swirls allow mapping variations of phase function steepness at a typical 100-200 m/pix resolution. Analysis of phase function steepness maps for swirls reveals the general anticorrelation of steepness with albedo that can be explained by the influence of the shadow-hiding effect and albedo on the steepness. Also we found the photometrically peculiar areas associated with both swirl details and proximal ejecta zones of small craters. The steepness is sensitive to the surface structure at scales larger than the characteristic light diffusion length (~1 mm for the lunar regolith). So these anomalies may prove the variations of the millimeter-scale regolith structure within swirls and demonstrate the increasing of a regolith mesoscale roughness for small craters ejecta.

Acknowledgement: This study was supported by CRDF grant UKP2-2897-KK-07.

References: [1] Hapke, B., (1993) Cambridge Univ. Press, 450 p. [2] Akimov L. (1979) *Sov. Astron.*, 23, 231. [3] Kreslavsky M., Shkuratov Y. (2003) *JGR* 108, 5015. [4] Grieger, B., (2007). ESA technical note S1-AMIE-SGS-TN-011. [5] Dougnac V., (2007) AMIE Sci. Meeting, Rome, 31 May -1 June. [6] Kaydash V., et al (2007) LPSC 38, Abstract # 1535.