CONTROLS ON THE PHOTOMETRIC PROPERTIES OF LUNAR SWIRLS IN COMPARISON TO FRESH CRATER EJECTA. Mallory J. Kinczyk[1], Brett W. Denevi[1], Aaron K. Boyd[2], Ryan N. Clegg-Watkins[3,4], Bruce W. Hapke[5], Megan R. Henriksen[2], Mark S. Robinson[2], and Hiroyuki Sato[2], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA. [2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA. [3]Department of Earth and Planetary Sciences, Washington University in St. Louis, St. Louis, MO 63130, USA. [4]Planetary Science Institute, Tucson, AZ 85719, USA. [5]Department of Geology and Planetary Sciences, University of Pittsburgh, Pittsburgh, PA 15260, USA.

Introduction: Lunar swirls, the sinuous high-reflectance surface features [e.g., 1,2] associated with crustal magnetic anomalies [3], are a fascinating intersection between many branches of lunar science (e.g., geology, spectroscopy, magnetism, surface–solar wind interactions, impact dynamics). Models for their formation include reduced or altered space weathering due to solar wind shielding [e.g., 3–7], scouring of the surface by cometary impacts to expose fresh material and/or compact the regolith [8,9], and compositional [10] or magnetic [11] sorting of the soil.

Photometric studies of lunar swirls have shown that swirls are more forward scattering (reflect relatively more light at high phase angles) than fresh crater ejecta [8,12–14]. These photometric differences have been interpreted as indicating a difference in roughness or compaction of the upper regolith [12–15]. However, thermal infrared observations from the Diviner Lunar Radiometer show that swirls do not show anomalous thermophysical behavior expected for such regolith properties [7]. Thus the question remains: what is the cause of the photometric differences between swirls and fresh crater ejecta? Here we examine new photometric observations from the Lunar Reconnaissance Orbiter Camera (LROC) [16] of swirls east of Firsov crater (Fig. 1).

Data: A series of LROC Narrow Angle Camera (NAC) images (M1189921872, M1189949993, M1189957023, M1189964054, and M1189985144) was acquired of the Firsov swirls on 26 June 2015 when the solar incidence angle was 52°. By slewing the spacecraft between +51 and -58°, phase angles of 2°, 38°, 57°, 75°, and 109° were achieved, providing an unprecedented photometric set for the investigation of lunar swirls at high resolution. A digital terrain model (DTM) was created from a subset of these images using the SOCET SET Toolkit [17]. The DTM was sampled at 5 m and it was controlled to Lunar Orbiter Laser Altimeter profiles of the region. The NAC images were orthorectified using the DTM and mapped to a common projection at a pixel scale of 140 cm. A complementary set of images was acquired of the eastern ejecta of King crater in order to serve as a comparison to the Firsov site; DTM production and image orthorectification are underway.

Results: The forward scattering nature of the swirls is confirmed for the Firsov region. In a color composite with 2°, 57°, and 109° phase images in red, green, and blue, the swirls are relatively blue (high I/F at 109° phase) compared to fresh craters (Fig. 1). At high resolution, many small, fresh craters can be observed at 2° phase (Fig. 2a), but their contrast is greatly reduced at 109° phase, while the swirl remains high in reflectance compared to the mature background (Fig. 2c). In fact, in some cases swirls and fresh crater ejecta reverse contrast: ejecta deposits that are higher in reflectance than swirls at low phase angles (Fig. 2d) are lower in reflectance than swirls at high phase angles (Fig. 2f). For the case in Fig. 2d–f, the ejecta of the fresh crater, which formed within a portion of the Firsov swirl, is slightly higher in reflectance (0.052) than mature material in the region (0.049) at 109° phase. This appears to hold generally for fresh craters that formed within the Firsov swirls: at high phase angles, they are either comparable to or lower in reflectance than the swirl surface, and are higher in reflectance than nearby mature material.

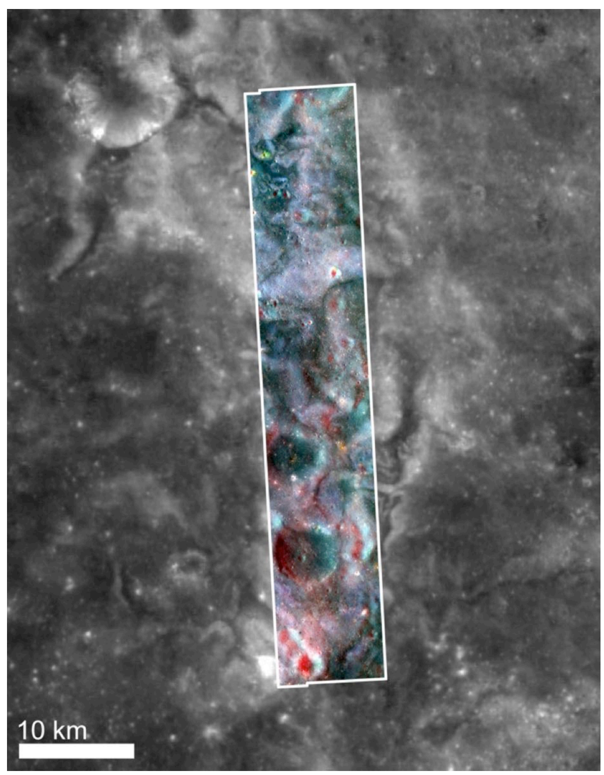

Fig. 1. The Firsov swirls. The extent of the NAC photometric sequence is outlined in white, NAC images at 2°, 57°, and 109° phase are shown in red, green, and blue, respectively. LROC Wide Angle Camera image at 643 nm provides background context. Scene centered at 4.34° N, 114.93° E.

Low-reflectance streaks are common on crater walls and in some crater ejecta in this region (Fig. 2), and they are comparable in reflectance to nearby mature material at all phase angles. While a comprehensive study has not yet been completed, similar features are not generally observed in other swirls or in other highland regions. The occurrence of these low-reflectance streaks is similar to those observed in impact craters that formed on pyroclastic deposits, though this site has not been noted as a location of pyroclastic volcanism. These dark streaks may be peculiar to the Firsov region, which has also been affected by relatively fresh ejecta from King crater, ~130 km to the east.

Discussion: Because observations suggest the thermophysical properties of lunar swirls are similar to mature soil [7], roughness and compaction differences with mature soil are unlikely to be the cause of the swirls' forward-scattering nature. Other properties also affect the phase function of a soil, including grain shape, internal scattering (caused by inclusions, defects, and boundaries inside particles), and albedo [18]. Sato et al. [19] suggest that complex agglutinate grains could have a large control on the scattering behavior of the lunar surface, and are dominantly backscattering, as opposed to transparent silicates, which are forward scattering. However, Sato et al. find that fresh impact craters are strongly backscattering and attribute this characteristic to the presence of optically thick clasts. The forward-scattering nature of the swirls could be the case where transparent silicates are exposed, without a large agglutinate population and without clasts that would reduce forward scattering [20]. Further modeling of the photometric properties of swirls and fresh craters in the Firsov region will aid in determining the controls on their scattering properties.

References: [1] Strom R.G. and Whitaker E.A. (1969) *Apollo 10 Photogr. Vis. Obs. NASA SP-232*, 20. [2] El-Baz F. (1972) *Apollo 16 Prelim Sci Rep NASA SP-315*, 29–93. [3] Hood L.L. and Schubert G. (1980) *Science*, *208*, 49. [4] Hood L.L. and Williams C.R. (1989) *LPSC 19*, 99. [5] Blewett D.T. et al. (2011) *JGR*, *116*, E02002. [6] Kramer G.Y. et al. (2011) *JGR*, *116*, E04008. [7] Glotch T.D. et al. (2015) *Nat. Commun.*, *6*, 6189. [8] Schultz P.H. and Srnka L.J. (1980) *Nature*, *284*, 22. [9] Bruck Syal M. and Schultz P.H. (2015) *Icarus*, *257*, 194. [10] Garrick-Bethell I. et al. (2011) *Icarus*, *212*, 480. [11] Pieters C.M. et al. (2014) *AGU Fall Meet.*, P11D–10. [12] Kaydash V. et al. (2009) *Icarus*, *202*, 393. [13] Pinet P.C. et al. (2000) *JGR*, *105*, 9457. [14] Kreslavsky M.A. and Shkuratov Y.G. (2003) *JGR*, *108*, 5015. [15] Starukhina L.V. and Shkuratov Y.G. (2004) *Icarus*, *167*, 136. [16] Robinson M.S. et al. (2010) *Space Sci. Rev.*, *150*, 81. [17] Henriksen M.R. et al. (2015) *Planet. Data Workshop, 2,* 7010. [18] McGuire A.F. and Hapke B.W. (1995) *Icarus*, *113*, 134. [19] Sato H. et al. (2014) *JGR*, *119*, 1775. [20] Denevi B.W. et al. (2016) *Icarus,* in press.

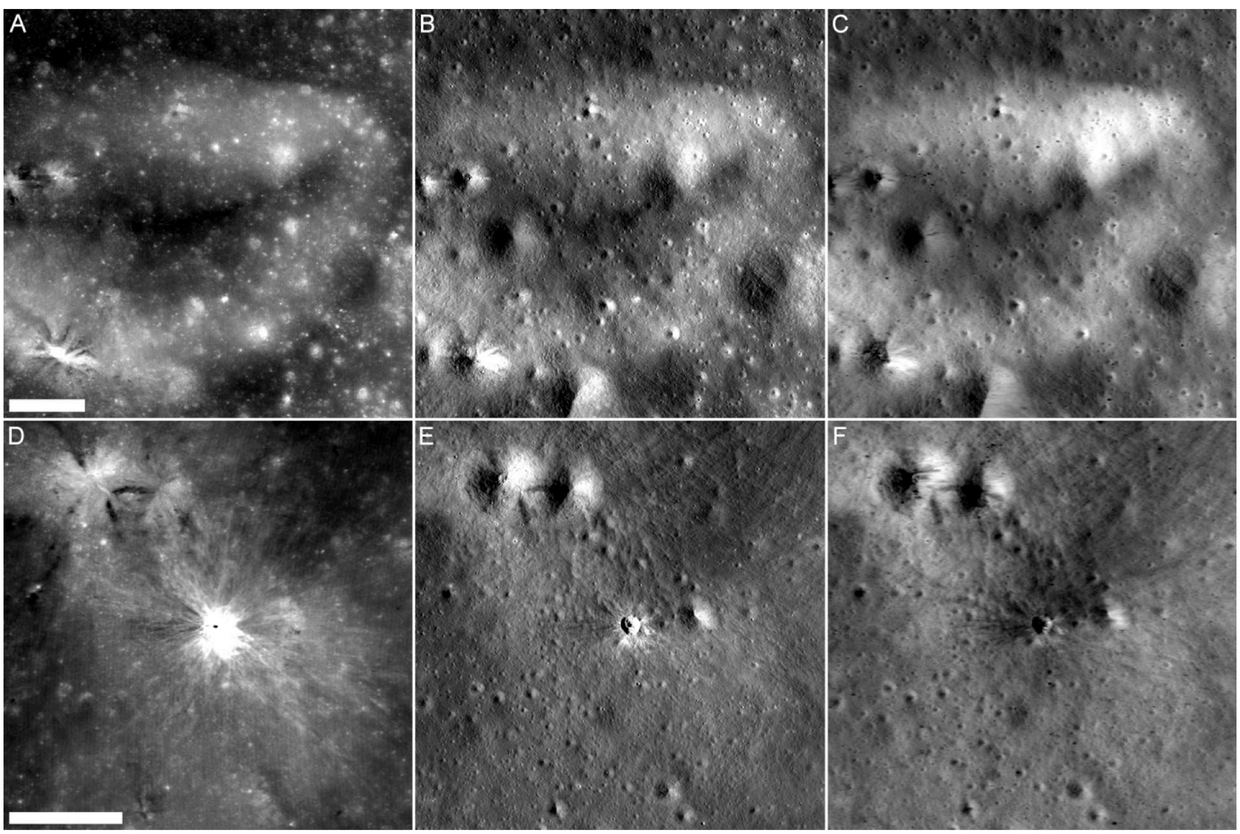

Fig. 2. Details from the NAC photometric sequence of the Firsov swirls. Left: 2° phase; center: 57° phase; right: 109° phase. A–C: Swirl and fresh craters. Fresh craters that are apparent at low phase are difficult to detect at high phase, while the swirl retains its contrast with mature material. D-F: A fresh crater formed within a swirl is lower reflectance than the swirl at high phase angles, but still higher in reflectance than nearby mature material. Each scale bar is 300 m.