CORRELATING SWIRLS WITH PARTICLE TRACKING SIMULATIONS AT LUNAR MAGNETIC ANOMALIES IN SOUTH POLE-AITKEN BASIN AND MARE CRISIUM. R. Karimova[1], G. Y. Kramer[2], E. M. Harnett[3], [1]Department of Physics and Earth Sciences, Jacobs University Bremen, Campus Ring 1, 28759 Bremen, Germany, [2]Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058, [3]Deapartment of Earth and Space Sciences, University of Washington, 4000 15th Avenue NE, Seattle, WA 98195-1310.

Introduction: Lunar swirls are high albedo curvilinear features that do not follow local topography, and appear optically immature compared to their surroundings. They are located at the lunar magnetic anomalies, however not all anomalies have identified swirls [1] [2]. One of the theories that explain the origin of the swirls suggests that swirls are areas of retarded surface weathering due to shielding from the solar wind ions by the anomalous magnetic fields [1] [3].

The area for the study presented here covered the South Pole-Aitken basin (SPA) and Mare Crisium. Swirls were mapped using several multispectral datasets. The maps were correlated with particle tracking simulations to test the solar wind deflection hypothesis on the SPA anomaly. For Crisium the particle tracking simulations were used to constrain the best locations where swirls might occur and explore possible reasons for the lack of apparent swirls in the Mare Crisium magnetic anomaly.

Space weathering: The Moon is constantly bombarded by solar wind particles and micrometeorites due to the lack of an atmosphere and a global magnetic field. The process that causes physical and chemical changes in the regolith due to these influences is termed space weathering. Formation of nanophase iron ($npFe^0$) is one of the changes that results from space weathering. $NpFe^0$ is responsible for the changes in the optical properties of the regolith that has been exposed to space weathering, which includes decrease in overall reflectance, increase in spectral slope and reduced absorption band depths [4].

Magnetic anomalies and solar wind deflection model: The crustal magnetic anomalies on the Moon were first detected by Apollo 15 and 16. Observations have shown that solar wind particles could be deflected by these magnetic anomalies [5]. The efficiency of the magnetic field to deflect the solar wind depends on its strength and coherence. The coherence of the field defines how fast the magnetic field directions change over distance. A more dipole-like field would change less often with distance, and would be stronger at deflecting incoming solar wind [5].

Methods: The datasets used in the study were the Lunar Reconnaissance Orbiter Wide Angle Camera (LRO WAC) 643 nm normalized (no shadows) reflectance map, slope map derived from the LRO Global Lunar digital terrain model (WAC_GLD100) [6], and a false color band ratio map derived from LRO WAC reflectance map (415 nm was displayed as red, 321/415 nm ratio as green, and 260/415 nm as blue) [7]. The slope map was inverted (so high slopes appear bright and flat regions dark) and overlain on the normalized reflectance WAC map with 30% transparent slope map. This muted high reflectance due to topography in order to distinguish from high reflectance due to swirls. The false color map displayed the swirls in bright magenta/red with a good contrast from the surroundings. Optical maturity (OMAT), were derived from Kaguya Multiband Imager (MI) mosaics [8], to improve the identification of the swirls. After testing on the SPA region, the same datasets were used to search for swirls in Mare Crisium anomaly in combination with the particle tracking simulation results.

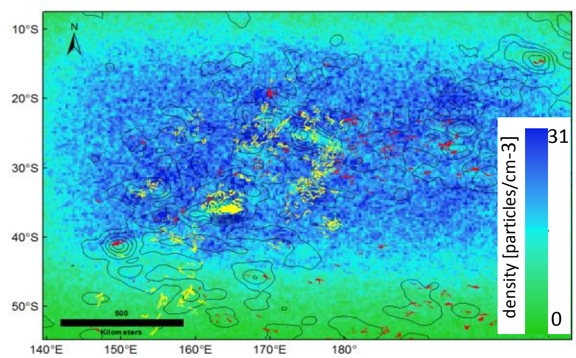

Figure 1: Proton density map for SPA. High values shown in blue and low values in green. Swirls mapped by [7] are shown in yellow. Magnetic field contour lines are in black.

Particle tracking: Models of the anomalous magnetic field used for the particle tracking simulations were obtained from http://www.planetary-mag.net [9]. The model used for particle tracking simulation is described in [10]. 400,000 non-interacting protons were launched on the magnetic anomaly of Mare Crisium, and 800,000 for SPA due to the larger extent of the area. Protons were chosen for the simulations because they are considered the primary reducing agents for the formation of $npFe^0$ [3] [5]. They were tracked until they impacted on the surface or left the simulation area due to deflection by the field. Density and flux maps generated from the simulation results were normalized to nominal solar wind densities at 1 AU of 5 particles/cm^3.

Results and discussion: *SPA:* South Pole-Aitken is the largest lunar basin located on the far side of the Moon. In addition to the large swirls in Mare Ingenii, and a number of smaller highland swirls between the Birkeland and Leeuwenhoek craters that have been mapped before [3][7] (yellow in Fig.1), new swirls (red in Fig.1) have been mapped extending to the north-east of Leeuwenhoek, and to the east to Orlov crater. Another smaller concentration was found further south around Bose crater (Fig.1).

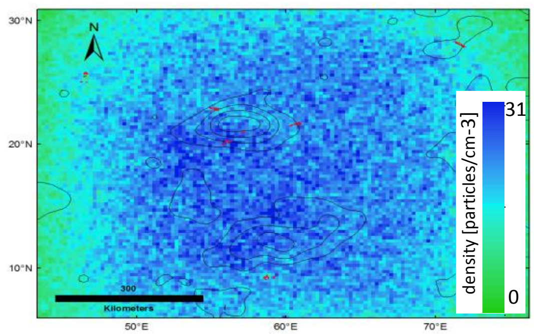

Figure 2: Proton density map of Mare Crisium. High values are shown in dark blue, low values in green. Magnetic field contours shown in black and potential swirls in red.

The SPA magnetic anomaly consists of multiple mini-anomalies, where particle tracking results showed significant proton deflection. Swirl locations coincided with these sites of low particle fluxes and densities very well (Fig.1), which indicates that they were shielded from the solar wind and are less weathered as a result. As in the previous study by [5] and [11], particle tracking could predict approximate swirl locations and not individual swirls, due to the coarseness of resolution of the available magnetic field measurements.

Crisium: Mare Crisium is one of the moderate magnetic anomalies (~5 nT at 40 km elevation) [2][8], and is notable for the lack of identified swirls. The region contains two locations where the field strengths reach local maximums- in the northern and southern regions of the mare. Particle tracking showed a weak deflection of particles only on the stronger northeastern part (Fig. 2).

Several potential small swirls of about 2-6 km were found on the northeastern rim of the mare, at the low particle density region (Fig. 2). However, all the signals are very faint, which does not allow one to conclusively define these features as swirls. This lack of prominent swirls could be explained by the particle tracking results, which show that the Crisium anomaly deflects significantly fewer particles and only in a small region compared to the strong anomalies in SPA. The reason for this could be the coherence of the magnetic field on Mare Crisium.

We generated slices of the magnetic field components (B_x, B_y, B_z) at different altitudes to infer the coherence of the Crisium anomaly. The B_z component slice at the surface (Fig. 3) shows that the northern anomaly has a strong -B_z and a weak +B_z components, while the southern part has a very weak -B_z. As a result, the weak +B_z in the north combines with the strong +B_z in the south creating a mostly radial magnetic field over the mare. The weak deflection observed at the northwestern rim of the mare occurs at the transition between the positive and strong negative B_z, where the field is tangential to the surface, and would be able to deflect incoming protons. The coarse resolution of the source magnetic data could also be averaging out finer scale features of the field, making it appear more coherent than it actually is [5].

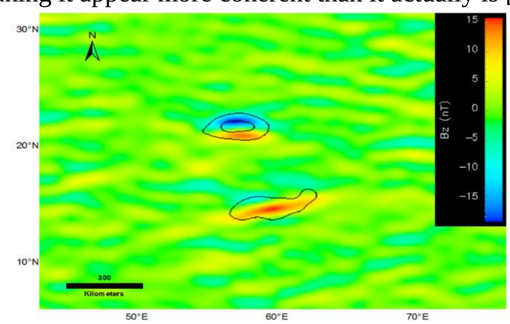

Figure 3: B_z component slice at the surface at Mare Crisium.

Conclusion: SPA swirls coincide with low particle flux and density cavities, supporting the solar wind deflection model. On the Crisium anomaly, particle simulation results showed only a weak deflection of protons around the northwestern rim of the mare, where faint, small candidate swirls have been mapped. The lack of strong particle deflection here can be explained by the structure of the magnetic anomaly, which suggested a radial magnetic field over the mare, with a small tangential part at the site where a weak deflection was observed. More investigation into the magnetic field structure is planned to confirm these structure inferences. Finer scale surface magnetic field measurements could provide better understanding why the Mare Crisium anomaly lacks obvious swirls.

References: [1] Hood & Williams (1989) *PLPSC* 19. [2] Blewett et al., (2011) *JGR* 116.E2. [3] Kramer et al., (2011) *JGR* 116.E4. [4] Pieters & Noble (2016) JGR 121, 1865–1884. [5] Harnett et al., (2016) *arXiv preprint arXiv:1605.05778*. [6] wms.lroc.asu.edu/lroc. [7] Denevi et al., (2016) *Icarus* 273: 53-67. [8] Lemelin et al., (2015) JGR, 120, 869–887 [9] Purucker & Nicholas (2010) *JGR* 115.E12. [10] Harnett & Winglee (2000) *JGR* 105.A11 24397-21007. [11] Tai Udovicic (2015) *31st LPI Summer Intern Conference* 31-33.