NEW DATA INTEGRATION TOWARDS SOLVING THE MYSTERY OF THE LUNAR SWIRLS

G. Kramer[1†], S. Besse[2], C. Neish[3], H. Tsunakawa[4], J. Haruyama[5], Y. Saito[6], T. Matsunaga[7], Y. Ogawa[8], M. Ohtake[5], Y. Futaana[9], M. Wieser[9], J. Bandfield[10], T. Glotch[11], E. Harnett[10], [1]Lunar Planet. Inst., Houston, TX [2]Univ. Maryland, College Park, MD, [3]Appl. Phys. Lab., Laurel, MD, [4]Dept. Earth & Planet. Sci. Tokyo Inst. Tech., Tokyo, Japan, [5]Inst. Space & Astronau. Sci., JAXA, Kanagawa, Japan, [6]Inst. Space Astronaut. Sci., Chuo, Japan, [7]Cent. Global Environ. Res., NIES/CGER, Ibaraki, Japan, [8]Univ. Aizu, Kukushima, Japan, [9]Swedish Inst. Space Phys., Kiruna, Sweden, [10]Univ. Washington, Seattle, WA, [11] Stonybrook Univ., Stonybrook, NY, [†]kramer@lpi.usra.edu

Introduction Lunar swirls are high albedo, curvilinear surface features, the origin of which has remained elusive ever since they were first characterized [1]. From the collection of measurements over the past 40 years, we know the swirls to be: 1) optically bright; 2) spectrally immature across the UV-VIS-NIR; 3) associated with magnetic anomalies (although swirls have not been detected at *all* magnetic anomalies).

There are 3 hypotheses for swirl formation: (1) fresh exposures from a recent comet impact [2]; (2) isolated regions where the magnetic fields have spared the surfaces from the effects of space weathering [3]; and (3) electromagnetic transport and accumulation of the finest fraction of the lunar soil [4]. We are beginning a reevaluation of the lunar swirls through the synthesis of new instrument data and the active collaboration of experts in the scientific fields from which these instruments derive. This effort is a significant advancement towards characterizing the swirls, testing the 3 hypotheses of swirl formation, and may help locate undiscovered swirls, such as those that may exist at other magnetic anomalies.

Kaguya (SELENE)

MAgnetic field and Plasma experiment - Lunar MAGnetometer (MAP-LMAG) The LMAG experiment has two main objectives concerning swirls: (1) mapping the magnetic anomaly of the Moon and (2) measuring electromagnetic and plasma environment around the Moon in cooperation with PACE (see below). The datasets of the nominal and extended missions cover about 95% and 85% of the lunar surface, respectively. Based on the high altitude dataset, which is available in the SELENE archives, initial global mapping at 100 km altitude has yielded full lunar coverage, and shows weak magnetic anomalies over almost the entire lunar crust, as well as strong spot-like or clustered ones [5]. Near-surface mapping over some swirls suggests that the strength of the horizontal magnetic component coincides with the high albedo part of the swirls [6].

MAgnetic field and Plasma experiment - Plasma energy Angle and Composition Experiment (MAP–PACE) The existence of mini-magnetospheres was suggested by [9] based on the magnetometer/electron reflectometer experiment on Lunar Prospector, which attributed observed heating of the solar wind electrons to the interaction between the solar wind and the lunar magnetic anomalies. However, the detailed mechanism of the interaction has been unclear mainly due to the lack of in-situ observed low energy ion data. This is how MAP-PACE observations of the low energy charged particles around the Moon can provide more information to solve the mystery of the swirls. If swirls are caused by the obstruction of the solar wind ion/electron collision on the lunar surface, Kaguya MAP-PACE ion data can be used to detect the reflected solar wind ions by magnetic anomalies that are reflected without impacting the lunar surface (such ions have been detected [cf. 7]). Kaguya MAP-PACE electron data can also be used as an electron reflectometer to detect magnetic anomalies on the lunar surface.

Lunar Imager/Spectrometer (LISM) One of the most powerful sensing instruments loaded on SELENE to investigate lunar swirl features is LISM, which consists of three specialized sub-instruments: the Multi-band Imager (MI), the Spectral Profiler (SP), and the Terrain Camera (TC) [8]. The MI is a multi-spectral imager with 4 visible color bands at 20 m spatial resolution and 5 color bands in the near-infrared (NIR) at 60 m spatial resolution. MI data can distinguish geological units in detail, and DTMs generated from MI data provide imoproved photometric information - a valuable commodity for analyzing swirls [10]. The SP is a line spectral profiler with a 400-m-wide footprint and 300 spectral bands in the visible to NIR ranges with 68 nm spectral resolution. SP data is sufficiently powerful to identify the lunar surfaces mineral composition. The TC is a high-resolution stereo camera with 10 m spatial resolution from a nominal altitude of 100 km. The stereo angle of 30° provides stereo pairs used to produce digital terrain models (DTMs) with a height resolution of 10 m or better. Detailed analysis of morphological features on and around lunar swirls and in conjunction with spectral profiles and magnetic field data will shed new light on the role of solar wind charged particles in optical maturation. Data from TC and the Lunar Reconnaissance Orbiter's (LRO) high resolution cameras can be used to test the comet impact theory using crater counting within the swirls and adjacent regions to date these features, and thus determine if the swirls are more cratered than surrounding regions. LISM successfully obtained 100% coverage of the Moon's surface, and most areas were observed several times with different solar elevation angles.

Chandrayaan-1

Sub-keV Atom Reflecting Analyzer (SARA) The Chandrayaan-1 Energetics Neutron Analyzer (CENA) sensor of SARA experiment is the first instrument that measures energetic neutral atoms (ENA) from a Moon orbit. By measuring surface-origin ENAs, which are generated by the interaction between the solar wind and the surface, CENA can monitor how much solar wind reaches the lunar surface [11]. In this way, SARA can test lunar swirl formation hypothesis (2) by relating the high-albedo swirls and surrounding regions to varying degrees of space weathering based on the solar wind flux. For example, initial analysis [12] showed that a strong magnetic anomaly reflects solar wind protons, and that the solar wind flux below the magnetic anomaly is lower by half. SARA also has a solar wind monitor sensor (SWIM), which is a miniatured electrostatic ion analyzer. By using SWIM data, [13] showed that the solar wind deflection occurs globally, especially in the lunar farside. This information also implies the reduction of the solar wind access to the lunar surface, which results in the change of the space weathering effect of the lunar surface.

Moon Mineralogy Mapper (M^3) M^3 mapped $\sim$95% of the lunar surface in 85 spectral channels between 450 and 3000 nm, and a spatial resolution that varied between 140 m/pixel at 100 km and 280 km at 200 km orbital alititude. Comparing spectra in fresh craters and surface soils in the swirls and adjacent regions expose the underlying pristine bedrock, allowing us to determine if this material is optically different from that of the swirls. This can also provide insight into the nature of the agents of space weathering, their effects on particular spectral features, and how these relate to the swirls. For instance, [14] showed that the swirls appear dark compared with inter-swirl and adjacent regions on a map that depicts the relative OH abundance (using the depth of the 2.82 μm absorption feature). The spatial location of the relative OH abundances are consistent with those from SARA [12]. The significantly low OH abundance on the swirls supports the hypothesis of [15] that the magnetic field is shielding the swirls from solar wind protons.

Lunar Reconnaissance Orbiter (LRO)

Mini-RF The Mini-RF synthetic aperture radar on LRO has provided a comprehensive set of X- (4.2 cm) and S-Band (12.6 cm) radar images of the lunar swirls, including the first radar observations of swirls on the farside of the Moon [16]. Swirls imaged with Mini-RF are indistinguishable from the surrounding regolith in both total radar backscatter and circular polarization ratio. This implies that average cm-scale roughness within the high-albedo portions of the swirls do not differ appreciably from the surroundings, and that the high optical reflectance of the swirls is related to a very thin surface phenomenon ($<$1 cm) not observable with X- or S-Band radar. Mini-RF observations cannot directly distinguish between the 3 swirl formation models because each of them predict erosion and deposition at only the finest scales ($<$100 μm), which is not distinguishable with X- or S-Band radar. However, radar is sensitive to composition, and higher titanium abundances in the lunar maria (in the form of the mineral ilmenite) are correlated with lower radar echo strength [17, 20]. The anomalous photometry of the swirl regions on calibrated UVVIS spectral data can mimic high wt% TiO_2 in the dark lanes in an opaque parameter image [18, 19]. Thus, when used in conjunction, Mini-RF and multi-spectral data can reveal more about than swirls than either data set alone.

Diviner The Diviner Radiometer is primarily a thermal infrared radiometer with 7 spectral channels: 3 spectral filters are near 8 μm and separate filters cover $\sim$13-23, 25-41, 50-100, and 100-400 μm [21]. The spatial sampling of Diviner is $\sim$200 by 400 m from a 50 km orbit and local time of the observations migrates across the full diurnal cycle throughout the primary LRO mission. The three 8 μm channels can be used to estimate the wavelength of the Christiansen feature, which is sensitive to the bulk silicate mineralogy of the surface. Initial results indicate that the Reiner Gamma Formation has a Christiansen feature position that is at a slightly shorter wavelength than the surrounding terrain consistent with a surface that has experienced less alteration due to space weathering [22]. There appears to be no difference in thermophysical properties within and outside Reiner Gamma indicating the surfaces have similar physical textures.

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