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Far-Ultraviolet Characteristics of Lunar Swirls

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1. Introduction & Background

Lunar swirls are often described as bright sinuous regions of the Moon that appear to be relatively immature – i.e. less space-weathered than surrounding regions. Swirls are mysterious but seem to be linked to the interaction between the solar wind and the lunar magnetic anomalies (e.g., [1]). Commonly-studied swirls include Mare Ingenii (in a mare-highlands boundary region), Reiner Gamma (in a mare region), and Gerasimovich (in a highlands region). Swirls are known to be surface features: they have no expression at radar depths [2], exhibit no topography, and craters on swirls that penetrate the bright surface terrain reveal underlying dark material [3].

Using Clementine and Lunar Prospector data, it was found [4] that all swirls are associated with areas of magnetized crust, and that swirls exhibit spectral characteristics similar to immature material and generally have slightly lower FeO values compared with their surroundings.

Lunar swirls exhibit VNIR characteristics consistent with a reduced amount of space weathering compared to surrounding regions, which suggests a reduction in solar wind interaction at those locations. Nanophase iron, responsible for the spectral characteristics attributed to space weathering, is created by vaporization/deposition by micrometeorite impacts and sputtering/reduction by solar wind ions. On the swirls, the decreased proton flux (deflected by the magnetic anomalies) slows the spectral effects of space weathering (relative to nonswirl regions) by limiting the nanophase iron production to micrometeoroid impact vaporization/deposition (e.g., [5]). Analysis of Clementine spectra [6] of lunar swirls indicates that swirls are regions of retarded weathering, and that the production of larger-grained (>40 nm) nanophase iron dominates in these locations as a result of charged particle sorting by the magnetic field. In a study of M^3 data of the 2.82 μm feature indicative of OH abundance within and near swirls, [5] found that swirls are depleted in OH relative to their surroundings, consistent with the idea of a divergence of solar wind in these zones.

An electrostatic dust transport mechanism may be at play [7], where charged fine feldspathic dust is attracted into bright areas of swirls, and repelled from dark lanes within swirls. The authors point out that lunar swirls do not exhibit VNIR spectral trends typical of immature lunar soils, using Clementine data.

In the ultraviolet, lunar space weathering effects are the reverse of those at VNIR wavelengths: more weathered regions are bluer than less weathered regions [9], due to a weathering-related degradation of the UV absorption edge in iron-bearing silicates. Indeed, LROC color results of the Reiner Gamma swirl [10] show a low 321/415 nm ratio (i.e., steep UV slope), consistent with a lack of space weathering compared to the surrounding mature mare terrain. For the Gerasimovich swirl, located in low-iron (<5wt% FeO) highlands, regions within the swirl have higher 321/415nm ratio values than the mature background (consistent with the exposure of fresh plagioclase-rich soil). The 321/415nm ratio values for the Gerasimovich swirl are similar to those of the rays of Tycho, Jackson, and Necho [10].

In this work, we investigate the far-ultraviolet (FUV) characteristics of swirl regions to broaden the spectral coverage of these mysterious regions and further illuminate their possible origins.

As pointed out [7], lunar swirls could represent regions on the Moon where both solar wind and micrometeoroid bombardment are important: where solar wind bombardment produces nanophase iron (and the lack of this nanophase iron in swirl regions makes them visibly bright and UV dark) but maturation via micrometeoroid bombardment is important for producing glass-welded aggregates and fine-grained soils that can enhance weathering effects at VNIR wavelengths. It is also likely (e.g. [5]) that sputtering/vapor deposition, implanted solar wind hydrogen, and agglutination share responsibility for creating the range in nanophase iron particle sizes that produce the spectral effects of space weathering. The study of the shorter wavelengths probed by LAMP allows for further constraints to be placed on grain size and weathering effects.

2. LRO/LAMP Data

The Lunar Reconnaissance Orbiter (LRO) is currently in orbit at the Moon. The Lyman Alpha Mapping Project (LAMP) onboard LRO has been making measurements of the lunar nightside, dayside and atmosphere since September 2009. The LAMP instrument [11] is a photon-counting imaging spectrograph. The entire passband is 57–196 nm, in the far-UV (FUV) spectral region. For dayside measurements, the instrument is operated in "pinhole" mode, with the entrance aperture reduced by a factor of 736. The instrument was usually nadir-pointed in LRO's characteristic 50-km lunar orbit of the prime mission and provided ~500 m resolution. In LRO's extended mission the orbit has been modified to an elliptical frozen orbit that saves fuel and results in up to ~2 km resolution when at the North pole.

To determine the lunar FUV reflectance, we divide the LAMP data by the full-disk solar spectrum from SORCE SOLSTICE [12], taken for the day of each observation and convolved to agree with the LAMP resolution and line spread function. Past analyses of LAMP dayside data (e.g. [13]) have shown that spectral slopes in the 175-190 nm region are good indicators of weathering and composition.

2. LAMP Results

In general, we find that nearly all regions of the Moon are spectrally blue (i.e. increasing in albedo with decreasing wavelength) in the LAMP bandpass, due to the surface-scattering nature of the light interaction with the grains combined with the optical constants of the compositional materials. Mare regions are bluer than highlands regions due to their higher concentrations of opaques. Also, more weathered regions become spectrally bluer in the FUV due to the spectral contributions of nanophase iron [9], while less weathered regions are less spectrally blue, or are spectrally relatively red.

We find that swirls are spectrally red (i.e. less spectrally blue, see Fig. 1) compared to surrounding terrain, and appear to be less mature than other "immature" regions, consistent with a lack of weathering in these zones. Because UV wavelengths sense primarily the weather-produced rims on grains, this result is consistent with a lack of (weathering-produced) opaque rims, not consistent with micrometeoroid production of rims. The LAMP results are also consistent with accumulated fine-grained feldspathic material. Because weathering effects are expected to appear in the UV faster than in the VNIR [9], the lack of weathering effects in the FUV in the swirls regions tells us about timescales of processing.

References

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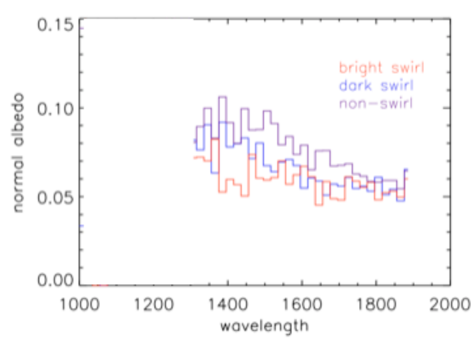

Figure 1. Sample LAMP spectra from the Reiner Gamma swirl bright region, dark region and off-swirl region. The visibly-bright swirl region is significantly less spectrally blue in the FUV than the dark swirl region and off-swirl region.