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Latitudinal variation in spectral properties of the lunar maria and implications for space weathering



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ABSTRACT

Space weathering alters the optical properties of exposed surfaces over time, complicating the interpretation of spectroscopic observations of airless bodies like asteroids, Mercury, and the Moon. Solar wind and micrometeoroids are likely the dominant agents of space weathering, but their relative contributions are not yet well understood. Based primarily on Clementine mosaics, we report a previously unrecognized systematic latitudinal variation in the near-infrared spectral properties of the lunar maria and show that the characteristics of this latitudinal trend match those observed at 'lunar swirls', where magnetic fields alter local solar wind flux without affecting the flux of micrometeoroids. We show that the observed latitudinal color variations are not artifacts of phase angle effects and cannot be accounted for by compositional variation alone. We propose that reduced solar wind flux, which should occur both at swirls and toward higher latitudes, is the common mechanism behind these color variations. This model helps us quantify the distinct effects of solar wind and micrometeoroid weathering and could aid in interpreting the spectra of airless bodies throughout the Solar System.

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1. Introduction

'Space weathering' refers to the processes by which the optical properties of airless bodies change due to exposure to solar wind and micrometeoroid impacts. However, the difficulties of reproducing space-weathering conditions in the laboratory, or returning weathered samples to Earth, make it challenging to determine precisely how space weathering operates (Pieters et al., 2000, 2012; Hapke, 2001; Vernazza et al., 2009; Domingue et al., 2014). Remote sensing measurements, studies of lunar samples, and laboratory experiments have established that solar wind ion and micrometeoroid bombardment weaken spectral absorption features and cause the lunar surface to darken and redden (increase in spectral continuum slope in the visible and near-infrared) with time. These changes appear to be due to some combination of the formation of impact glasses and agglutinates (Adams and McCord, 1971), the regolith's disintegration into increasingly finer soils (Pieters et al., 1993), and the accumulation of nanophase iron (Hapke, 2001; Sasaki et al., 2001; Noble et al., 2007). Larger impacts also expose fresh material, which then gradually matures until the reflectance

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http://dx.doi.org/10.1016/j.icarus.2015.08.004 0019-1035/© 2015 Elsevier Inc. All rights reserved. spectrum reaches a steady state, which we call 'equilibrium color' for simplicity.

The equilibrium color varies considerably across the lunar surface, due primarily to differences in mineralogy. This is most obvious in the dichotomy between the bright, anorthositic highlands and the darker basaltic maria. However, as we will argue, the presence of 'lunar swirls' suggests that equilibrium color may also be influenced by the *flux* of weathering agents, rather than just their total accumulation (see Sections 3.1 and 4). If this is the case, then equilibrium color may also vary with latitude. Both solar wind and micrometeoroids originate primarily from within the ecliptic plane, which is inclined from the Moon's equator by just 1.5°. Hence maximum flux of these weathering agents occurs near the equator, with flux decreasing as incidence angle increases toward the poles.

This paper's central observation is that, when we examine imagery from across the lunar surface, we find that the equilibrium color does vary systematically with latitude. In Section 3.2, we show that this latitudinal color trend persists across a range of distinct compositions and that it is not an artifact of phase angle biases in the Clementine mosaics. Interestingly, the spectral properties of the latitudinal color trend match the characteristic color variation found at lunar swirls. In Section 3.1, we quantify the characteristics of the swirl-related color variation and, in Section 3.2, we show that it is statistically equivalent to the





observed latitudinal color trends, with a transition toward higher latitudes being attended by the same color change that occurs toward brighter parts of swirls. Finally, in Section 4, we argue that the best candidate for a common mechanism behind these color variations is altered solar wind flux. We present a qualitative model illustrating how this hypothesis comports with the observations and we discuss the possible implications with respect to the interpretation of spectral data, particularly at high latitudes.

2. Data sources

In this study, we use mosaics based on imagery from the 750 nm and 950 nm channels of the Clementine UVVIS (ultraviolet–visible) experiment (Nozette et al., 1994; Eliason et al., 1999), available from the USGS (www.mapaplanet.org). As a point of comparison, we also examine 1064 nm reflectance from the Lunar Orbiter Laser Altimeter (LOLA) experiment on board the Lunar Reconnaissance Orbiter (LRO) (Lucey et al., 2014). In discussing the observed trends in the Moon's spectral properties, we may use the word 'color' in a general sense to refer to combinations of albedo and the ratio between 950 nm and 750 nm reflectance (e.g., as a proxy for continuum slope).

Parts of our analysis require isolating portions of the lunar surface according to composition and/or topographic roughness. For composition, we use results from the Lunar Prospector Gamma Ray Spectrometer (Lawrence et al., 2002; Prettyman et al., 2006), specifically in order to identify FeO and TiO₂ content in the regolith. The topographic roughness metric we use is the interquartile range of the along-profile second derivative of elevation, at 1.8-km baseline (Kreslavsky et al., 2013), derived from Lunar Orbiter Laser Altimeter (LOLA) data. The latter is used to distinguish between the smooth maria and the rougher highlands.

3. Analysis

Before discussing the observed latitudinal color variation, we revisit the characteristic color signature observed at swirls, developing a new parameterization that will allow for a quantitative comparison between swirls and the newly observed latitudinal trends.

3.1. Color variation at lunar swirls

Lunar swirls are enigmatic collections of sinuous bright markings, often interposed with narrow dark lanes, that are co-located with many of the Moon's crustal magnetic anomalies (Fig. 1A). The bright parts of swirls superficially resemble optically immature surfaces such as fresh impact craters (Lucey et al., 2000b; Wilcox et al., 2005; Blewett et al., 2011). However, it has been shown (Garrick-Bethell et al., 2011) that swirls exhibit spectral trends that are distinct from those associated with impactrelated brightening (Lucey et al., 2000b). The two trends can be distinguished from one another, using Clementine UVVIS (ultraviolet-visible) mosaics (Nozette et al., 1994; Eliason et al., 1999), by plotting 750 nm reflectance against the 950 nm/750 nm reflectance ratio (Blewett et al., 2011; Garrick-Bethell et al., 2011), the former representing albedo and the latter serving as a proxy for both the near-infrared continuum slope and the 1 µm absorption feature found in iron-bearing silicate minerals. Both the swirl- and impact-related color variations involve changes in both albedo and the 950 nm/750 nm band ratio, but the impact-related variation is accompanied by a proportionally greater change in the 950 nm/750 nm band ratio (Fig. 1B), as originally reported by Garrick-Bethell et al. (2011).

In order to establish a quantitative basis for comparison with the latitudinal trends we discuss in Section 3.2, we parameterize the color variations that are characteristic of swirls, averaging over three different mare swirl areas: Reiner Gamma in western Oceanus Procellarum, Mare Ingenii on the farside, and Mare Marginis on the eastern limb. In each case, in the albedo versus band ratio diagrams, we found similar steep trends associated with the transition between impact craters and background soils, and shallower trends associated with the transition between dark and bright parts of swirls (Figs. 1B, 2B and 3B), in accord with Garrick-Bethell et al. (2011). The distinct color variations associated with impacts and swirls allow us to define parameters that clearly separate the two trends (Fig. 1C and D). The impact-related progression from bright craters to the more mature background soils can be characterized by an impact maturity parameter

$$\alpha = R_{750} - \left(\frac{R_{950}}{R_{750}}\right) \middle/ m_1 \tag{1}$$

where R_{750} and R_{950} are the Clementine 750 nm and 950 nm reflectances, respectively, and where

$$m_1 = -1.6 \pm 0.2$$

is the slope of the swirl-related trends $(\pm 1\sigma)$, averaged from the three separate mare swirl areas. The swirl-related trend slope is used in Eq. (1) so that impact maturity (α) is not affected by swirl-related color variations. Eq. (1) resembles previously developed optical maturity parameters (Lucey et al., 2000b; Wilcox et al., 2005) except that here, the goal is explicitly to isolate the impact-related color variation from that associated with swirls, and so the constants are different. Similarly, we can represent the swirl-related color variation, which we regard as distinct from optical maturity, as

$$\beta = R_{750} - \left(\frac{R_{950}}{R_{750}}\right) / m_2 \tag{2}$$

where

$$m_2 = -5.7 \pm 0.5$$

is the typical slope of the impact-related trends ($\pm 1\sigma$). The impactrelated trend slope is used in Eq. (2) so that β is not affected by impact-related color variations.

Although the α and β values vary according to local composition, the slopes of the impact- and swirl-related trends do not vary significantly across different mare regions. The values given here for m_1 and m_2 are therefore largely composition independent, at least within the maria. The α parameter is designed to have constant values along the swirl-related trends such that swirl features do not influence the value of α and so maps generated for the α parameter show impact features but not swirl features (Fig. 1C). Conversely, the β parameter is designed to have constant values along the impact-related trends such that maps of the β parameter highlight swirl features while muting impact features (Fig. 1D).

3.2. Latitudinal color variation

When we examine imagery from across the lunar surface, we find that the reflectance spectra vary systematically with latitude. The effect is not obvious when we examine the Moon as a whole, likely because the spectra are so strongly affected by composition, which varies considerably across the surface. However, when we account for variations in composition, the latitudinal trends emerge. As we will show, the latitudinal trends are especially pronounced within the maria, and may help to account for the unusually high albedo of Mare Frigoris—the highest latitude mare region.



Fig. 1. (A) 750 nm reflectance (albedo) at the Reiner Gamma swirl. (B) Spectral characteristics (albedo versus 950 nm/750 nm band ratio) of pixels sampled from the five rectangular boxes, with corresponding colors, in (A). The red point cloud corresponds to a representative background region whereas the dark blue point cloud corresponds to the brightest part of the swirl. Each of the point clouds displays a steep trend that follows the progression from fresh impact craters (lower right part of each point cloud); the dashed black line is a best fit through the red point cloud and, averaging over three separate mare swirl areas, has a slope of $m_2 = -5.7 \pm 0.5$. The black circles represent the steady state (equilibrium) colors reached with maximum optical maturity in each rectangle (since the majority of pixels are likely near saturation maturity, we take the median point in each cluster to represent the equilibrium color). The solid black line is a best fit through the red point cloud (D) are maps of the α and β parameters, defined according to Eqs. (1) and (2), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Color anomalies have been identified previously in polar regions (Yokota et al., 2011; Zuber et al., 2012) and latitudinal variation in space weathering has been considered previously (Yokota et al., 2011; Hendrix et al., 2012), however, this is the first observation of a broad systematic latitudinal color trend that is visible across the lunar maria. Moreover, the spectral characteristics of this trend match those found at lunar swirls (Section 3.1), suggesting a link between the two phenomena that may be helpful for understanding space weathering (see Section 4).

In addition to controlling for composition, below we examine the possible contributing effects of highland contamination in the maria and phase angle biases in the Clementine mosaics; we show that the observed latitudinal trends cannot be artifacts of such effects.

3.2.1. Effect of composition

Because surface color is strongly affected by composition, we separate the data into bins according to TiO_2 and FeO content (as measured by the Lunar Prospector Gamma Ray Spectrometer

[Lawrence et al., 2002; Prettyman et al., 2006]), and examine the spectral characteristics separately for each compositional bin. Fig. 4A shows, in the same parameter space we used to characterize swirls, that pixels sampled from higher latitudes tend to have higher albedo (750 nm reflectance) and lower 950 nm/750 nm band ratios, than those sampled from lower latitudes.

While Fig. 4A shows just one illustrative example, we examined all combinations of FeO and TiO₂ content using bins of 2 wt% width in FeO and 1 wt% width in TiO₂, set at half bin width increments (see Fig. 5 for additional examples). Because the latitudinal trend can only emerge if pixels are sampled from a wide range of latitudes, we discard compositional bins whose pixels do not reach latitudes of at least $\pm 50^{\circ}$ or do not span at least 50 total degrees of latitude. To ensure that slopes are estimated from robust samples only, we also discard bins whose pixels cover less than 0.25% of the lunar surface. Finally, to avoid artifacts in the Clementine mosaics that are related to severe illumination conditions at high latitudes, we also discard data within 20° of the poles. After applying these selection criteria, 59 compositional bins were 0.2

1.1 В 0.19 -33 1.05 -33.5 0.18 350nm-to-750nm Reflectance Ratio 0.17 Clementine 750nm Reflectar -34 Latitude (degrees N) 0.95 0.16 -34.5 -35 0.15 0.9 -35.5 0.14 0.85 -36 0.13 0.8 -36.5 0.12 0.75 -37 0.1 -37.5 0.1 0.7 162 163 166 167 0.1 0.12 0.14 0.16 0.18 0.2 165 Longitude (degrees E) 750nm Reflectance -32.5 0.84 -32.5 0.35 Б -33 0.83 -33 0.34 -33.5 0.82 -33.5 0.33 0.8 0.32 -atitude (degrees N) î -atitude (degrees -34.5 0.8 -34.5 0.31 Alpha Beta -35 0.79 -35 0.3 0.29 -35.5 0.78 -35.5 -36 0.28 0.77 -36 0.76 0.27 -36.5 -36.5 0.75 -37 0 26 -37 -37.5 0.74 -37.5 0.25 . 162 163 166 167 162 163 164 165 166 167 Longitude (degrees E) Longitude (degrees E)

Fig. 2. (A) 750 nm reflectance at the Ingenii swirl. (B) Spectral characteristics (albedo versus 950 nm/750 nm band ratio) of pixels sampled from the five rectangular boxes, with corresponding colors, in (A). For further details, refer to Fig. 1 legend. (C) and (D) are maps of the α and β parameters, defined according to Eqs. (1) and (2), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

retained for analysis. Fig. 4B shows a summary of all 59 latitudinal trend lines (gray lines) along with the swirl- and impact-related trends discussed in Section 3.1.

-32.5

The effect of iron content is apparent when the trend lines are color-coded by wt% FeO, as determined by the Lunar Prospector Gamma Ray Spectrometer (Lawrence et al., 2002) (Fig. 6). Lower iron regions (pale orange lines) tend to plot farther up and to the right in Fig. 6, in accord with Wilcox et al. (2005), whereas high iron regions (dark lines) plot farther down and to the left. This means that both α and β tend to be larger for low iron regions (in Section 3.2.5, we discuss the implications of this observation with respect to highland contamination in the lunar maria).

Although the latitudinal trend slopes are largely similar across different compositional bins, they become less consistent when iron content is very low, such as in the highlands. This is not surprising given that several studies suggest that the production of nanophase iron plays an important role in space weathering (Hapke, 2001; Sasaki et al., 2001; Noble et al., 2007). A paucity of iron in the highlands may prevent a clear appearance of the type of latitudinal trends we observe in the maria. In order to obtain as clear a signal as possible, we therefore focus our subsequent analysis on the maria.

3.2.2. Isolation of the maria

Because the latitudinal trends are most consistent within the maria, and because we are interested in comparing these trends with the spectral characteristics we analyzed for three marebased swirls (Section 3.1), we restrict the remainder of our analysis to the lunar maria.

As previously discussed, we use Lunar Prospector Gamma Ray Spectrometer (GRS) data to determine both iron and titanium content in the soils we examine. Unfortunately, in comparison to the Clementine data, the relatively coarse resolution of the GRS data (the effective footprint is roughly 45 km wide [Lawrence et al., 2002]) means that we cannot use GRS-based iron estimates to isolate the maria—choosing a conservatively high threshold for iron content would result in the exclusion of significant portions of the maria, while choosing a low threshold would result in the inclusion of highland pixels. Inclusion of low-iron highland pixels is undesired as it could artificially skew the spectral characteristics toward higher 750 nm reflectance and higher 950 nm/750 nm reflectance ratios (see Fig. 6 and Section 3.2.5).

We cannot isolate the maria based on iron estimates obtained from Clementine-based spectral techniques (e.g., Lucey et al., 2000a; Wilcox et al., 2005) because these techniques rely on the



Fig. 3. (A) 750 nm reflectance at the Marginis swirl. (B) Spectral characteristics (albedo versus 950 nm/750 nm band ratio) of pixels sampled from the five rectangular boxes, with corresponding colors, in (A). For further details, refer to Fig. 1 legend. (C) and (D) are maps of the α and β parameters, defined according to Eqs. (1) and (2), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

same parameter space we use in our own spectral analysis, namely 750 nm reflectance versus the 950 nm/750 nm reflectance ratio. Attempting to isolate the maria according to such spectral-based iron estimates would necessarily bias our results, artificially altering the slope of the best-fit latitudinal trends shown in Fig. 4.

To distinguish mare from highland terrain, we instead adopt an independent metric that characterizes topographic roughness at 1.8-km baseline (Kreslavsky et al., 2013) (see Section 2). A histogram of the topographic roughness (Fig. 7) shows a bimodal distribution, reflecting the dichotomy of kilometer-scale roughness between smoother maria and rougher highlands, with maria peaking at a roughness value of 2.3 m/km² and highland terrain peaking at a roughness value of approximately 19 m/km². We identify mare terrain as areas exhibiting roughness values below 5 m/km². After applying a de-speckling filter, designed to remove isolated features less than approximately 1° in diameter, we obtain a mask that we use to exclude non-mare pixels from our subsequent analysis. Fig. 8 illustrates the boundaries of our mare mask.

After excluding data from the lunar highlands, a clear latitudinal trend emerges in the Clementine 750 nm reflectance profile (Fig. 9A): mare surfaces are darkest near the equator and become increasingly bright toward higher latitudes, with the profile being approximately symmetric about the equator. This is a straightforward visualization of the latitudinal trend and allows for simple comparison with different datasets (e.g., reflectance from the Lunar Orbiter Laser Altimeter; see Section 3.2.6 and Fig. 9B), but in order to facilitate comparison with the swirl-related spectral trends, we now return to plots of 750 nm reflectance versus the 950 nm/750 nm reflectance ratio.

3.2.3. Comparison with swirl trends

After excluding the highlands, 28 of the original 59 compositional bins survive the selection criteria we described in Section 3.2.1. Fig. 10 illustrates not only that the latitudinal color trends persist across a range of different compositions, but also that these trends are remarkably similar to those associated with lunar swirls. That is, low latitude regions tend to have lower albedo and higher 950 nm/750 nm band ratios when compared with high latitude regions, and these changes occur in the ratio $m_3 = -1.5 \pm 0.3$, a slope that is indistinguishable from the swirl-related slope, $m_1 = -1.6 \pm 0.2$, at the one-sigma level (Fig. 11). Fig. 12 further demonstrates this result by showing that



Fig. 4. Color variation as a function of latitude for the full lunar surface, up to $\pm 70^{\circ}$ latitude (*cf.* Fig. 10, which is limited to the maria). (A) Spectral characteristics of pixels sampled from regions with between 15 and 17 wt% FeO and between 1 and 2 wt% TiO₂. Points are color-coded according to cosine latitude, illustrating that the optical characteristics of the surface vary systematically with latitude. Equatorial regions (red points) tend to have lower albedo and higher 950 nm/750 nm reflectance ratios than regions farther from the equator (blue points). The black trend line represents a least squares best fit through the data points. The solid black circle corresponds to the color predicted by the best-fit line at the equator and the white circle represents the color predicted at latitudes $\pm 70^{\circ}$. (B) Compilation of the 59 latitudinal trends we examined (gray lines), one for each compositional bin, compared with the trends discussed in Section 3.1: the solid red, green and blue lines represent the swirl-related color trends observed at Reiner Gamma, Ingenii, and Marginis, respectively; the dashed lines represent the impact-related color trends observed at each of those swirls. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a transition to higher latitudes is attended by the same type of color change that occurs toward brighter parts of swirls (Fig. 1D)—that is, increasing β .

3.2.4. Mare Frigoris

Mare Frigoris, spanning much of the near side at roughly 60°N, is the highest latitude and visibly brightest mare region, meaning that it makes a significant contribution to the latitudinal trend we observe (Fig. 12). The high β (high albedo and low 950 nm/750 nm band ratio) of Mare Frigoris could be attributed in part to its low FeO and TiO₂ content (Lucchitta, 1978; Pieters, 1978; Staid and Pieters, 2000). However, the FeO and TiO₂ abundances typical of Mare Frigoris (14 ± 2 wt% FeO; 0.9 ± 0.4 wt% TiO₂, see crosshairs in Fig. 13A) are also found in lower latitude mare regions, which, by comparison, appear darker and have higher 950 nm/750 nm band ratio of Mare Frigoris differ significantly from those of low-latitude maria of equal composition (Fig. 13B, see also lower left panel in Fig. 5).

Given that Mare Frigoris is apparently compositionally unexceptional, its spectral characteristics cannot be attributed merely to low FeO and TiO₂ content. While it remains possible that they are the result of anomalous surface contamination (see Section 3.2.5), our results suggest that the high albedo and low 950 nm/750 nm band ratio of Mare Frigoris are better understood as part of the broad latitudinal trend we observe across the lunar maria. Although Mare Frigoris accounts for an important component of the observed latitudinal trend, the analysis is not significantly affected by its removal (Fig. 14). After manually removing those mare pixels belonging to Mare Frigoris, five of the original 28 compositional bins must be excluded from analysis due to their reduced area and latitudinal span, leaving a total of 23 bins. After Mare Frigoris is removed, fewer high latitude pixels are included. Nevertheless, the latitudinal trends remain, and the estimated latitudinal trend slope is unaffected ($m_3 = -1.5 \pm 0.3$ with or without Mare Frigoris). Hence, anomalous spectral characteristics of Mare Frigoris alone cannot account for the latitudinal color trend, but the latitudinal color trend can account for the spectral characteristics observed at Mare Frigoris.

3.2.5. Highlands contamination

Diffusive contamination near mare/highland boundaries and contamination from major crater rays could be partly responsible for the latitudinal trends we observe if, by chance, such contamination occurs preferentially at higher latitudes, and if it produces the same relative changes in albedo and the 950 nm/750 nm band ratio. Here, we examine these factors and conclude that their contributions to the observed latitudinal trend are not significant.

Impact-induced diffusive mixing of highland and mare materials occurs near the mare/highland boundaries, and may be significant within 10-20 km of the boundary (Mustard et al., 1998). The edges of the maria may therefore be relatively bright compared with other mare regions of similar underlying composition. If the morphology of high latitude mare regions is such that their perimeter length to surface area ratios tend to be larger (e.g., Mare Frigoris is narrow compared with Mare Imbrium), the amount of highland contamination may be relatively greater at high latitudes, potentially contributing to the latitudinal color trends we observe. If true, this would imply that the color variation we observe for any given compositional bin (e.g., Fig. 4A) is, to some extent, a function of each pixel's distance from the nearest highlands, with pixels close to the highlands being brighter than pixels that are farther from the highlands, where contamination is weaker.

We test this hypothesis in two ways. First, we restrict our latitudinal color trend analysis to mare regions that are at least 50 km from the nearest highlands. Mustard et al. (1998) show that diffusive mare-highland mixing is significant only within <10 km of the mare-highland boundary and they find no evidence for mixing beyond 40 km from the boundary. We use the great-circle distance (in kilometers) from the center of each mare pixel to the center of its nearest highland neighbor pixel, where mare/highland surfaces are identified according to our topographic roughness metric (see Section 3.2.2). After excluding mare regions within 50 km of the nearest highlands, and again applying the selection criteria described in Section 3.2.1, only 13 compositional bins remain. The surface area coverage is considerably more limited than in our full-mare analysis (Fig. 10), but the resulting latitudinal trend slopes (-1.2 ± 0.3) are not significantly different (see

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Fig. 5. Latitudinal color variation across 12 distinct compositional bins. Equatorial regions (red points) tend to have lower albedo and higher 950 nm/750 nm reflectance ratios than regions farther from the equator (blue points). Each of the black trend lines represents the best-fit color variation between the equator (solid black circle) and latitudes of ±70° (white circle). Although only 12 are shown here, we examined 59 compositional bins in total (see Fig. 4B). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 15A and B and compare with Fig. 4). Note that the 50-km threshold we use here is also larger than the Lunar Prospector Gamma Ray Spectrometer footprint (\sim 45 km), potentially helping to improve the compositional accuracy of the bins.

As a further test, we once again plot 750 nm reflectance versus the 950 nm/750 nm reflectance ratio, except that in this case, we color-code points not by cosine latitude, but instead by each pixel's distance from the highlands, from 50 to 100 km (Fig. 15C). No significant color trend is obvious in Fig. 15C and a least squares best fit line through the data (black line) reveals only a slight tendency for pixels 50 km from the mare/highland boundary (white circle) to be brighter than pixels 100 km from the boundary (black circle). This is not to say that mare pixels are not typically brighter near mare/highland boundaries, only that (within a given compositional D.J. Hemingway et al./Icarus 261 (2015) 66-79



Fig. 6. Compilation of latitudinal trend lines for all 59 compositional bins, as in Fig. 48 but color-coded by iron content (Lawrence et al., 2002). Dark trend lines correspond to high iron bins while pale trend lines correspond to low iron bins. For comparison, the swirl- and impact-related trends are also shown: the solid red, green and blue lines represent the swirl-related color trends observed at Reiner Gamma, Ingenii, and Marginis, respectively; the dashed lines represent the impact-related color trends observed at each of those swirls. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 7. Histogram of topographic roughness with red line indicating the threshold below which we consider pixels to belong to the lunar maria; pixels above the threshold are discarded in our subsequent analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bin) this effect is relatively small compared to the effect of varying latitudes (Fig. 15A). While Fig. 15C shows just one illustrative example, we repeated this analysis for each of the 13 compositional bins described above. The resulting highland-distance trends do not resemble the latitudinal trends and, in some cases, even oppose them (Fig. 15D). Across the 13 bins, the highland-distance color trends are often poorly determined (large uncertainties), inconsistent (slopes are highly variable, with standard deviation ± 3.9), and generally weak (most of the trend lines are relatively short). For example, the average change in 750 nm reflectance between 50 km and 100 km away from the mare/highland boundary is 0.001 ± 0.004 , whereas the average change in 750 nm reflectance between the equator and latitudes of $\pm 70^{\circ}$ is



Fig. 8. Clementine 750 nm reflectance with red lines indicting the boundaries of the mare regions as identified by our topographic roughness criterion (regions with less than 5 m/km² roughness at 1.8-km baseline). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 9. (A) Clementine 750 nm reflectance profile across the lunar maria (as identified by surface roughness, see Fig. 8). (B) Profile of LOLA 1064 nm reflectance for the same region. In both profiles, reflectance tends to be lowest near the equator and higher toward higher northern and southern latitudes. The black lines and gray bands represent the mean and standard deviation at each latitude.

 0.05 ± 0.01 (ranges are 1σ). Although the effects of highland contamination cannot be said to make no contribution whatsoever, we conclude that they cannot be responsible for the stronger and more consistent latitudinal trends we observe (Figs. 4, 10, 14 and 15A and B).

Ray systems from major young impacts could also contribute to the high albedo of Mare Frigoris and other high latitude maria. However, ray systems similarly cross the low latitude mare regions and should have similar effects there. For example, rays from Copernicus, Aristarcus, and Kepler all extend across low latitude mare regions. The young crater Anaxagoras (~50 km in diameter) is the main contributor to contamination of Mare Frigoris but lies more than 300 km from its edge, at the closest point. Significant brightening associated with the similarly young, but larger, Copernicus crater (~100 km in diameter) is limited to within ~300 km, suggesting that Anaxagoras contamination is unlikely to dominate the spectra of Mare Frigoris. Moreover, although contamination from crater ray systems may affect the spectra of certain parts of the maria, there is no reason to expect such contamination to vary systematically with latitude in such a way as to create the latitudinal trends we report here. Werner and Medvedev (2010) found no concentration of rayed craters at high latitudes and, due to the present impact rate inhomogeneity (Le Feuvre and Wieczorek, 2011), we would actually expect less



Fig. 10. Summary of latitudinal trend lines (gray lines) for the 28 compositional bins that correspond to the maria. The solid red, green and blue lines represent the swirl-related color trends observed at Reiner Gamma, Ingenii, and Marginis, respectively. The dashed lines represent the impact-related color trends observed at each of those swirls. The latitudinal trends have slopes of -1.5 ± 0.3 , whereas the swirl-related trends have slopes of -1.6 ± 0.2 . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

contamination from young crater ejecta at high latitudes. Crater ray contamination could be substantially responsible for the trends we observe only if such contamination favors high latitudes by chance. Although we cannot rule out this possibility, we regard it as unlikely, especially given the symmetry of the latitudinal trends (Fig. 9) and the consistency of their slopes across a range of different compositions (Figs. 10, 14 and 15B).

Finally, even if highland contamination were to have a significant effect on the observed spectral characteristics, the effect would more likely involve an *increase* (rather than a decrease) in the 950 nm/750 nm reflectance ratio. As illustrated in Fig. 6, lowiron regions, such as the highlands, tend to plot farther up and to the right compared with high-iron regions, such as the maria, meaning that spectral trends due to highland contamination should have a positive slope, unlike the negative latitudinal trend slopes we observe ($m_1 = -1.5$).

3.2.6. Phase angle biases and LOLA reflectance

The Clementine spacecraft imaged the lunar surface over a range of phase angles (Sun-surface-spacecraft angle), from typically less than 25° at the equator, to as high as $\sim 100^{\circ}$ at high latitudes. The Clementine mosaics are photometrically normalized and calibrated such that they provide an estimate of reflectance reduced to standard illumination conditions (Eliason et al., 1999), but the imperfect calibration and imperfect knowledge of photometric behavior, leave small but systematic errors in the mosaics. In particular, the 950 nm reflectance mosaics exhibit artificially low reflectance values when based on imagery collected at relatively high phase angles (imperfections in the 750 nm reflectance mosaics are insignificant by comparison). This can be seen by comparing adjacent parts of the mosaic that are based on imagery collected at differing phase angles (Fig. 16). From Eq. (2), and bearing in mind that m_2 is negative, it follows that this has the effect of making relatively higher phase angle areas artificially low in β (and therefore appearing less like the bright parts and more like the dark parts of swirls). Because the high latitude Clementine data correspond to systematically higher phase angles, β therefore tends to be underestimated at high latitudes. This is the opposite of the trend we observe, indicating that the reported latitudinal effect on color must be even stronger than it appears in Figs. 4, 10 and 12.

The conclusion that phase angle biases are not the source of the observed latitudinal color variation is further supported by examination of an independent dataset obtained from the Lunar Orbiter Laser Altimeter (LOLA). LOLA was recently used to measure lunar surface reflectance at 1064 nm (Lucey et al., 2014). Because LOLA uses its own laser light source to illuminate the surface, reflectance estimates are obtained at a constant phase angle of nearly zero. Fig. 9B shows LOLA 1064 nm reflectance across the lunar maria, confirming that, independent of phase angle, higher latitude maria appear to exhibit higher reflectance, as seen in the Clementine data.



Fig. 11. Latitudinal trend slopes (crosshairs) compared with swirl trend (pale red band) and impact trend (pale green band) slopes (with $\pm 1\sigma$ variability illustrated by the width of each band). All 28 mare-based slope estimates (the same trends illustrated in Fig. 10) are shown versus the FeO bins (A) and the TiO₂ bins (B). In each case, the crosshairs show the width of the FeO or TiO₂ bin and the 1σ uncertainty on the estimated slope. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 12. Color variation as a function of latitude. (A) Map of β , computed according to Eq. (2), over the lunar maria (as identified by surface roughness, see Section 3.2.2). (B) Latitudinal profile of β across the lunar maria. The black line and gray band represent the mean and standard deviation at each latitude, averaged over all longitudes.



Fig. 13. (A) FeO and TiO₂ content (based on Lunar Prospector Gamma Ray Spectrometer data [Lawrence et al., 2002; Prettyman et al., 2006]) of Mare Frigoris (blue points) compared to other mare regions (red points). The black crosshairs illustrate the mean and standard deviation FeO and TiO₂ abundances for Mare Frigoris (14 ± 2 wt% FeO; 0.9 \pm 0.4 wt% TiO₂). (B) Pixels from Mare Frigoris (blue points) have higher albedo and lower band ratio than low latitude mare regions (red points, restricted to within $\pm 15^{\circ}$ of the equator) of equal composition (12-16 wt% FeO and 0.5–1.3 wt% TiO₂). The mean and standard deviation of each cluster is marked with crosshairs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 14. Comparison of latitudinal trends with and without pixels from Mare Frigoris. (A) Summary of all 28 mare-based latitudinal trend lines, including data from Mare Frigoris (same as Fig. 10). (B) Summary of the 23 mare-based latitudinal trend lines that remain after Mare Frigoris pixels are excluded. The mean slope differs by less than 0.04 between the two cases (much less than $1\sigma = 0.3$). In both cases, the swirl- and impact-related trends are shown for comparison as solid and dashed lines, respectively.



Fig. 15. Color variation of mare surfaces that are at least 50 km from the nearest highlands (compare with Fig. 4, which characterizes the entire lunar surface, and Fig. 10, which characterizes all of the maria). (A) Spectral characteristics of pixels sampled from regions with between 15 and 17 wt% FeO and between 1 and 2 wt% TiO₂. Points are color-coded according to cosine latitude, as in Fig. 4. (B) Compilation of latitudinal trends across the 13 compositional bins compared to the swirl- and impact-related trends (red, green, and blue lines). (C) Spectral characteristics of the same pixels as in (A), except that points are color-coded according to distance from the highlands: blue points correspond to locations that are 50 km from the mare/highland boundary whereas red points correspond to locations that are 100 km or more from the nearest highlands (pixels within 50 km of the nearest highlands are excluded). The black trend line represents a least squares best fit through the data points with the end points indicating the color predicted by the best-fit line at locations 50 km (white circle) and 100 km (black circle) from the mare/highland boundary. (D) Compilation of the 13 highland-distance trend lines) (ergy lines) compared to the swirl- and impact-related trends (red, green, and blue lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

The latitudinal color variation we observe is unlike the color trends associated with impacts but statistically equivalent to those observed at swirls (Figs. 10 and 11), suggesting a common mechanism. It has been proposed that the swirl-related color trend could be the result of magnetic and/or electric field-related alteration of the regolith microstructure (Pieters et al., 2014), electrostatic sorting of fine dust (Garrick-Bethell et al., 2011), or similar mixing of compositionally distinct materials (Blewett et al., 2011). However, it is not clear how such mechanisms could also produce the latitudinal color variation we report here. Instead, we propose that reduced solar wind flux is the most likely common mechanism behind the latitudinal and swirl-related color trends. Solar wind flux is reduced both with increasing latitude (due to the increasing incidence angle), and very likely at swirls, where strong magnetic fields may be partially shielding the surface from the impinging

solar wind (Hood and Schubert, 1980; Hood and Williams, 1989; Hemingway and Garrick-Bethell, 2012). Micrometeoroid flux, in contrast, varies with latitude but should be unaffected by magnetic fields (Richmond et al., 2003) and therefore cannot account for the color variations observed at swirls.

The observed latitudinal and swirl-related variations in spectral characteristics (i.e., those described by the β parameter) suggest a dependence on average flux rather than on the total accumulation of solar wind ions. A single grain saturates after only ~100,000 years (Hapke, 2001) such that even a surface shielded by as much as 90% would saturate after only ~1 myr. Consistent with this constraint, swirls often exhibit diffuse morphologies, with gradual transitions from the bright parts to darker background soils. In these regions, mean solar wind flux could vary smoothly between the bright parts of swirls and the darker background soils. Hence, if swirls are the result of locally altered solar wind weathering, their color must be controlled not by total accu-

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Fig. 16. Phase angle effects on 950 nm reflectance mosaics and derived β . Left panels show a low-latitude region in Mare Tranquillitatis. Right panels show a high-latitude region in Mare Frigoris. Top panels show the phase angle corresponding to the imagery collected across the regions. The middle panels show Clementine 950 nm reflectance, illustrating a bias toward lower reflectance values for imagery collected at relatively higher phase angles. The bottom panels show the derived parameter β , illustrating that the phase angle bias means that β is underestimated for higher phase angle imagery.

mulation of solar wind ions, but instead by some flux-dependent equilibrium—for instance between regolith gardening and solarwind-induced alteration of exposed grain surfaces.

These observations lead us to propose a new model of how space weathering operates for solar wind and micrometeoroids. Over length scales of a few kilometers, the surface exhibits considerable variability in α , owing to the appearance of fresh craters (low α) among the darker background soils (high α), whereas variability in β is low (Figs. 1B, 2B, 3B). Our interpretation is that the equilibrium β is reached so rapidly that we do not observe variability in its value over ~kilometer scales, whereas the evolution of α occurs gradually, as impact craters transition into mature soils over

longer timescales. We propose a model in which fresh impact craters begin with high albedo and low 950 nm/750 nm band ratios (the hypothetical "hyperfresh" point illustrated in Fig. 17, which should depend only on local mineralogy), then rapidly evolve to an equilibrium value of β (controlled by solar wind flux), and finally follow the steeper progression toward larger values of α , as they gradually mature toward the local equilibrium color. Both the rapid weathering to a solar wind flux-dependent β and the gradual weathering toward the local saturation level of α involve decreases in albedo and increases in the 950 nm/750 nm band ratio. However, the initial rapid weathering process (change in β) has a proportionally greater effect (by a factor of ~3.6) on albedo

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750nm Reflectance

Fig. 17. Inferred optical evolution process. For a given composition, all impact craters large enough to excavate fresh material should begin with the same characteristic color (the hypothetical "hyperfresh" point at right). In this model, following the impact event, the freshly exposed material experiences rapid weathering until it reaches an equilibrium value of β , controlled by solar wind flux. This rapid color change occurs primarily in albedo, but is accompanied by a small change in the 950 nm/750 nm band ratio. Subsequently, the crater material matures gradually (increases in α) until it reaches the local saturation maturity level of the surrounding, well-developed soils. This gradual maturation involves additional darkening, but is also accompanied by a proportionally greater band ratio increase than during the initial mode of rapid weathering.

(Fig. 17). In this model, the trends are parallel (see also Staid and Pieters, 2000; Wilcox et al., 2005), as the soil matures toward distinct solar wind flux-dependent equilibrium colors, rather than converging to a common point, contrary to expectations for a simple mixing process.

The differences in optical effects may reflect differences in the way solar wind and micrometeoroid bombardment affect lunar soils. For example, the darkening may be due primarily to the accumulation of nanophase reduced iron (Hapke, 2001; Noble et al., 2007) generated both by solar wind and micrometeorites, whereas the increased 950 nm/750 nm band ratio, which reflects both suppression of spectral features and increased continuum slope, may also be influenced by impact vitrification (Adams and McCord, 1971) and the soil's impact-induced disintegration into increasingly finer grains (Pieters et al., 1993), neither of which depend on solar wind.

In spite of the uncertainties regarding the precise mechanism for the observed latitudinal trends, our results help to quantify the effects of latitude-dependent space weathering, which may need to be accounted for when interpreting spectral measurements at different latitudes (Zuber et al., 2012; Cohen et al., 2014). The production and retention of hydroxyl (OH) groups, for instance, reportedly varies with latitude (Clark, 2009; Pieters et al., 2009; Sunshine et al., 2009; McCord et al., 2011; Hendrix et al., 2012) as well as at swirls (Kramer et al., 2011). The latitudinal variation in space weathering effects we report here may influence the interpretation of the spectral observations behind such findings.

Our results also suggest that it may be possible to use variations in surface color to quantify the reduction in solar wind flux at swirls. For example, the magnitude of color variation at the Reiner Gamma swirl is approximately equivalent to the color variation observed between the equator and 60° latitude, suggesting that this magnitude of color variation corresponds to a \sim 50% reduction in solar wind flux. This type of analysis, in conjunction with other methods, may in turn help in estimating the strength of surface fields at swirls and in making predictions that can eventually be tested with near-surface magnetic field and solar wind flux measurements.

5. Conclusions

Our analysis reveals a systematic latitudinal variation in the near-infrared spectral properties of the lunar surface, and in particular, across the maria. Specifically, low latitude mare regions tend to be darker and have higher 950 nm/750 nm reflectance ratios than high latitude mare regions, such as the noticeably bright Mare Frigoris. This latitudinal trend persists across a range of distinct compositions, confirming that it is not an artifact of the fact that regions with the highest iron and titanium content happen to be concentrated at low latitudes. Our analysis also shows that the trends are not significantly affected by contamination from the highlands, nor can they be artifacts of phase angle biases, as confirmed by our comparison with the constant phase angle LOLA reflectance data. Furthermore, the spectral characteristics of the latitudinal color trend are statistically equivalent to those observed at lunar swirls; higher latitude regions appear more like the bright parts of swirls. We propose that reduced solar wind flux, which should occur both at swirls and toward higher latitudes, is the common mechanism behind the observed color variations. We suggest a process by which freshly exposed materials initially experience rapid changes in color until reaching a solar wind flux-dependent equilibrium, followed by a more gradual period of optical maturation driven mainly by micrometeoroid impacts. If correct, this model could help quantify the distinct effects of solar wind versus micrometeoroid weathering and may be important for the interpretation of spectral observations made at different latitudes on the Moon and other airless bodies throughout the Solar System.

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