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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.

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 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

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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 TiO_2 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 impact-related 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

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

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

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

where

$$m_2 = -5.7 \pm 0.5$$

is the typical slope of the impact-related trends ($\pm 1\sigma$). The impact-related 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.