Hydration Observations of Reiner Gamma Lunar Swirl in Partial Eclipse

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Introduction

A common view of the Moon as inherently dry abruptly changed when hydration was detected in lunar regolith; a Moon-wide 3 µm absorption band has been detected by multiple remote sensing instruments: EPOXI High Resolution Instrument, Cassini Visual and Infrared Mapping Spectrometer (VIMS), and the Moon Mineralogy Mapper (M3) [1, 2, 3]. This band signifies the presence of OH and possibly H2O (collectively referred to as total water or hydration), which is supported by the discovery of hydroxyl with solar wind hydrogen in lunar agglutinate glasses[4]. The study of this surface hydration and how it behaves on the Moon has important implications for understanding volatiles on airless bodies throughout the Solar System.

Lunar Swirls: A Natural Laboratory

An important hypothesis for the origin of lunar surface water is the chemical interaction of solar wind hydrogen with lunar surface oxygen [5] and key geologic features for the understanding of the origin of detected total water and the influence of solar wind are lunar swirls. Lunar swirls are bright albedo features on the lunar surface that have been linked to the presence of local magnetic fields [6, 7, 8]. A magnetic field could shield the surface from the solar wind, which is believed to decrease the amount of space weathering that the surface beneath it undergoes, causing that material to remain brighter than the surrounding material. Solar wind is also hypothesized to be the source of the observed water via hydrogen implantation onto exposed oxygen in fractured mineral surfaces. A swirl's unique ability to potentially show differences in the water band due to differences in solar wind intensity while keeping other parameters constant make it a natural laboratory for studying solar wind interaction.

This project focuses on the behavior of hydration in and around the Reiner Gamma swirl (figure 1). This feature has been examined in two previous studies using Moon Mineralogy Mapper (M3) data. The first study, by Kramer et al 2011, found that there was a greater band depth at 2.82 µm off swirls versus on swirls. The band depth difference in that study followed the swirl's bright albedo markings on the surface. In fact, it was suggested that swirls can be better identified with this hydration feature than with other methods [9]. However, a subseqeunt study performed by Li and Garrick-Bethell 2019 showed a weaker band depth that correlated with the presence of the magnetic field but did not follow the swirl's markings on the surface [10]. Using the same data set, these studies tell different stories about the behavior of lunar hydration at this swirl. Interpretation of data near 3µm is complicated by the presence of both reflected sunlight and thermal emitted light from the Moon's surface and experts disagree on how to separate the two [11,12,13]. In order to understand how hydration behaves at swirls, this work focuses on collecting data that better constrains thermal models and exploting the unique thermal and light conditions of lunar eclipses.

Thermal Correction in Eclipse

It is difficult to constrain the thermal model for M3 data because it is limited in its wavelength coverage (<3µm). A strong test of thermal corrections is their quality at longer wavelengths where thermal emission is increasingly dominant. To deal with this thermal modeling problem, this work uses observations that are taken at the Mauna Kea Observatory using the SPeX infrared cross-dispersed spectrograph at the NASA InfraRed Telescope Facility (IRTF). This instrument collects data from 1.67 to 4.2 µm and the spectral range provides several advantages over Moon Mineralogy Mapper data on the same region of the Moon. First, the complete 3µm feature is covered allowing the whole absorption feature to be observed. Second, the spectrum extends out to longer wavelengths where the thermal emission dominates, allowing for a more sensitive thermal correction. Third, observations can be taken at lunar times of day that are not available in data from M3, including the early morning, late afternoon, and during special observing conditions such as eclipse.

Observations during lunar eclipse provide an elegant solution to the thermal emission problem. When the observing target on the lunar surface is in partial eclipse, the solar illumination decreases and the temperatures on the surface drop. Lower temperatures mean that the thermal emission is pushed out to longer wavelengths, allowing measurements of purely the reflected component out to longer wavelengths. This essentially allows the thermal modelling problem to be sidestepped for data taken under these conditions. In addition, it provides a good test of thermal corrections applied to data taken the same night at full illumination.

Partial Eclipse

In partial eclipse the thermal emission is greatly reduced and the measured radiance (L) is dominated by the solar irradiance (I) multiplied by the surface's bidirectional reflectance (R_{bdr}).

$$L = R_{bdr} \cdot I / \pi$$

This allows the bidirectional reflectance to be calculated by simply rearranging the equation.

$$R_{bdr} = L / (I / \pi)$$

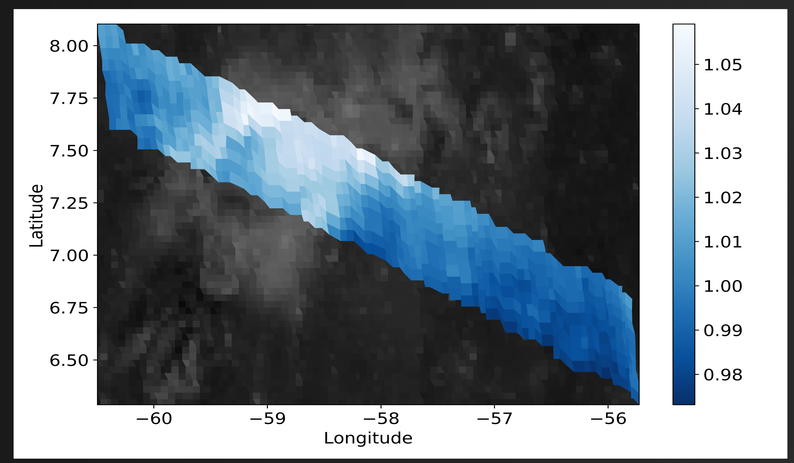

Figure 1: Band ratio map of 3 micrometers to the continuum (blue tones) overlaid on Map of Reiner Gamma at 1550 nm from Kaguya Multiband Imager (gray tones). Darker Blue represents a deeper absorption feature which indicates more hydration.

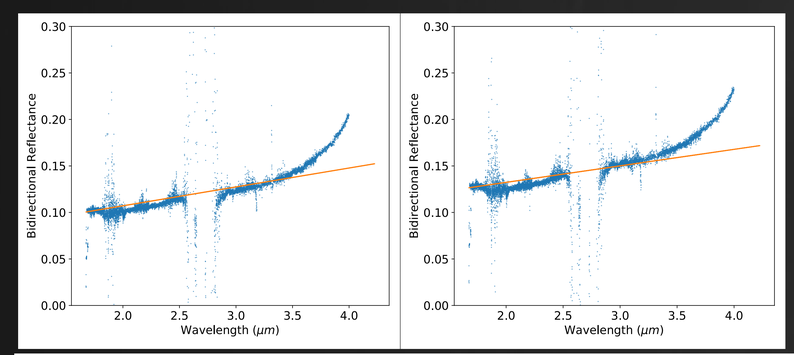

Figure 2: Bidirectional Reflectance (blue) of material in the surrounding maria (left) and on the swirl (right) plotted with the continuum (orange). At wavelengths beyond 3 µm there is some contamination from uncorrected thermal emission.

We collected data at Reiner Gamma as the swirl was coming out of the January 21, 2019 lunar eclipse. The slit was moved across the target and spectra were taken from 10 locations along the slit to create a hyperspectral map of the swirl. The ratio of the median reflectance between 2.9 and 3 µm and the continuum fit at shorter wavelengths was calculated in order to investigate the behavior of the 3 µm band and by extension lunar hydration (figure 1). The band ratio map shows a higher 3 µm band ratio on the swirl versus in the surrounding maria. Band ratio values from on the swirl have a ratio of above 1. This is likely due to the continuum in the 3 µm region being poorly approximated by a line (figure 2). These spectra show some uncorrected thermal emission at their longest wavelengths. However, models of spectra with decreased illumination like these show that this thermal emission is not affecting the 3 µm region (figure 3a). The spectra from the maria surrounding the swirl have a band depth of about 6% compared to the material on the swirl, which is consistent with solar wind being a source of lunar hydration. The decrease in hydration seems to follow the swirl pattern on the surface which is consistent with the results of Kramer et al 2011.

Full Illumination

In full illumination the measured radiance (L) is composed of the solar radiance(I/π) multiplied by the surface's bidirectional reflectance (Rbdr) and the surface's thermal emission (B(T)) multiplied by the emissivity of the surface (E).

$$L = R_{bdr} \cdot I / \pi + E \cdot B(T)$$

According the Kirchhoff's law of thermal radiation, the emissivity and the directional hemispherical reflectance (R_{dhr}) sum to unity ($1 = R_{dhr} + E$). Using Kirchhoff's law to input a substitution allows the equation to be rearranged for reflectance. Both types of reflectance are described by Hapke as functions of the incidence angle (i), the emission angle (e), the phase angle(ø), and the single scattering albdeo (ω) [14]. The viewing geometry angles are known parameters, so the function can be solved for single scattering albedo. This is done by writing this as a function equal to zero and then using the fsolve function in python's scipy package.

$$0 = R_{dhr}(\omega,i) - [\, L - B^*(T) \,] / [\, (I/\pi) \cdot R_{bdr}(\omega,i,e,ø) / R_{dhr}(\omega,i) - B^*(T) \,]$$

Thermal models that predict the surface's thermal radiance (B(T)) can then be input. The model that produces an output reflectance spectrum that follows the continuum and does not have concavity due to over or under corrected thermal emission at longer wavelengths is then chosen to correct the data (figure 3).

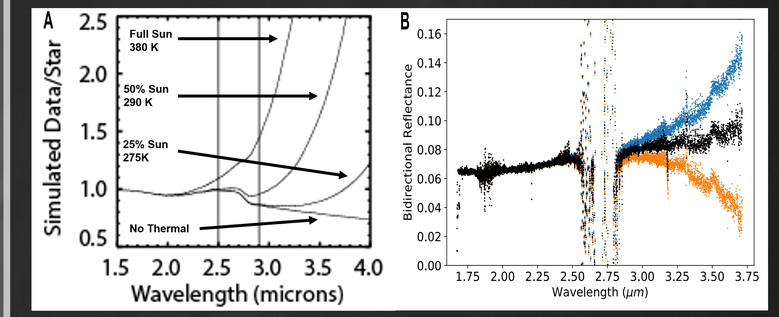

Figure 3: A. Model of reflectance spectrum with thermal component as illumination drops. 25% illumination is similar to the conditions in the eclipse. B. Reflectance spectrum with thermal component removed (black), Reflectance spectrum with undercorrected thermal component (blue), Reflectance spectrum with overcorrected thermal component (orange).

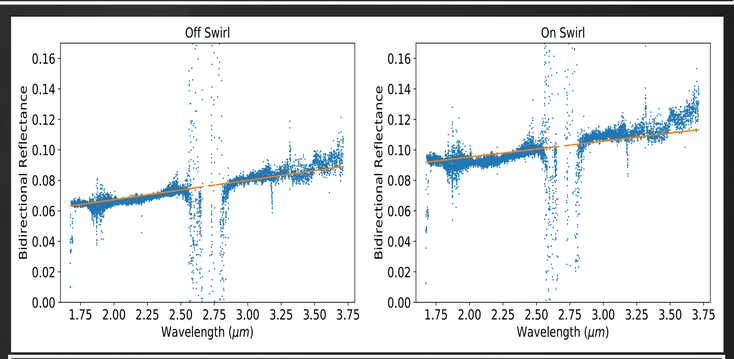

Figure 4: Bidirectional Reflectance (blue) of material on the swirl (right) and in the surrounding maria (left) plotted with the continuum (orange).

The thermally corrected spectra (figure 4) give similar results to the eclipse spectra (figure 2). At 3 µm, the on swirl reflectance is above the continuum while the surrounding maria reflectance is below the continuum. This indicates that this method of thermal correction is successfully solving for the reflectance spectrum that is not significationly contaminated by thermal emission at 3um.

References

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