VARIATIONS IN THE DEPTH OF THE 3UM HYDRATION BAND DURING LUNAR ECLIPSE:IMPLICATIONS FOR THE HYPOTHESIS OF BALLISTIC MIGRATION OF WATER Abigail J. Flom[1], P.G. Lucey[1], C.I. Honniball[2], C.M. Ferrari-Wong[1], H. Kaluna[3], J.W. Head III[4] [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, 2500 Campus Rd, Honolulu, HI 96822 (aflom@hawaii.edu), [2] NASA Goddard Space Flight Center, Greenbelt, MD,[3] University of Hawaii at Hilo, Hilo HI 96720, [4] Brown University, Providence RI 02912

Introduction: Over the last decade, the behavior of volatiles on the lunar surface has become an important question in lunar science. This began with the discovery of the Moon-wide 3 μm band 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 H_2O (collectively referred to as hydration), which is supported by the discovery of hydroxyl with solar wind hydrogen in lunar agglutinate glasses [4] and the detection of an H_2O specific 6 um band [5]. Investigations of lunar hydration have important implications for understanding the conditions of the lunar surface environment as well as understanding volatiles on airless bodies throughout the Solar System.

Data in the 3 μm region is complicated by the presence of both emitted and reflected radiation, and there is debate about how to best correct for thermal emission in M^3 data, which does not contain any wavelengths beyond 3 μm to constrain thermal models for the data. Bandfield et al. [6] found a 3 μm feature across the Moon, but do not see differences with latitude or lunar time of day. On the other hand, Li et al. [7], Wohler et al. [8], and Honniball et al. [9] see strong strong differences with these parameters.

To deal with this thermal modeling problem, this work uses observations that are taken from the Mauna Kea Observatory using the SPeX infrared cross-dispersed spectrograph at the NASA InfraRed Telescope Facility (IRTF). A strong test of thermal corrections is their quality at longer wavelengths where thermal emission is increasingly dominant and this instrument collects data from 1.67 to 4.2 μm and the spectral range provides advantages over Moon Mineralogy Mapper data on the same region of the Moon. First, the complete 3 μm feature is covered allowing the whole absorption feature to be observed. Second, the spectrum extends out to longer wavelengths where the thermal emission dominates and a thermal model is better constrained. Third, we are able to take advantage of unique observing opportunities to observe thermal conditions not available in M^3 data such as conditions of partial lunar eclipse.

We obtained data of the Chang'E 5 site under thermal conditions not available in M3 data: a local time of 8:30 am and during local partial eclipse where illumination was only 40% of the fully illuminated site. These data provide a unique test of various models for the behavior of hydration on the Moon, and provide insight to the analysis of the Chang'e 5 samples. In this data set we noticed the unexpected development of a 3μm band as the eclipse progressed. In order to examine this phenomenon more closely, we additionally analyzed spectra taken at the subsolar point during the onset of partial eclipse that had higher time and temperature resolution than the Chang'E 5 site data set.

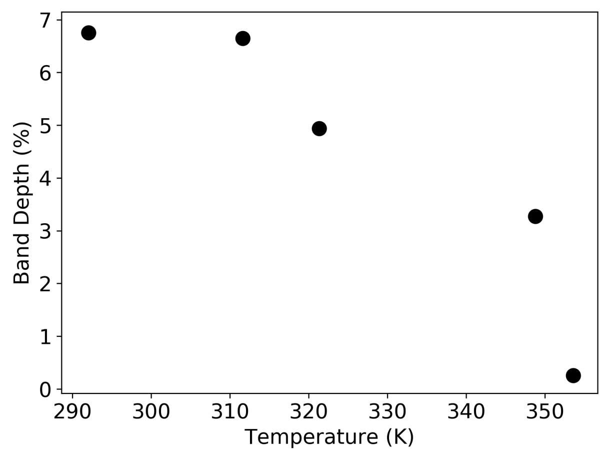

Figure 1: *Chang'E site 3 μm band depth versus temperature. The data points are the mean band depth versus the mean temperature of a map of the entire site. Data were collected during the onset of eclipse except for the 312K data point which was taken while exiting partial eclipse.*

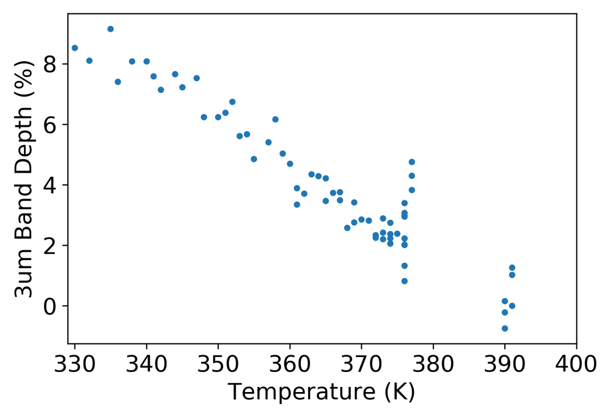

Figure 2: *Subsolar point 3 μm band depth versus temperature. These data were all taken during a near continuous collection as the subsolar point entered eclipse.*

Data: Observations of the area around and including the Chang'e 5 landing site (Figure 1) were obtained on November 30th, 2020 between 07:08 UT (full illumination) and 09:27 UT (Deepest Partial Eclipse) shortly before the landing of the spacecraft.

Observations of the subsolar point (Figure 2) were obtained on May 26th, 2021 between 09:00 UT (full illumination) to 9:04 UT then 9:16 UT to 10:00 UT (Deepest Partial Eclipse Observed). The gap in coverage was due to an issue with the telescope's dome that interrupted collection briefly to reset.

Methods: SPeX is a slit spectrograph, similar to M3. Maps of the landing site were created by scanning the spectrometer slit over the region as the detector array is read out. After the collection of each map, data were taken on the sky nearby the moon and a standard star was observed at an airmass similar to the Moon observations. Spectra were obtained from the image data using the SPEXTOOL software [10].

A solar-type star at an airmass similar to the Moon is observed and used to correct for atmospheric transmission as well as instrument response. These data relative to a solar type spectrum are then converted to radiance assuming a surface reflectance at non-thermal wavelengths, a solar flux model, and a photometric model.

The spectral effects of thermal emission from Solar System objects are not present in the spectrum of a solar type star, and the thermal emission is manifest in Moon/Star ratios by sharply rising flux toward the infrared depending on the lunar surface temperature. This thermal excess is fit at the longer wavelengths and when fitting the data with the thermal model surface roughness effects are taken into account [6]. The thermal emission was removed following the methods of Honniball et al. 2020 [9].

Results and Discussion: Under full illumination conditions, the Chang'e 5 site does not appear to have a 3 μm absorption band, which would indicate no hydration. However, the reflectance at 3 μm systematically decreases as the illumination and temperature decrease, leading to an increased 3 μm band depth (Figure 1). Interestingly the ratio band depth is at a level we would have expected to also be detectable at full illumination if it were present, which led us to investigate the possibility of the hydration band intensity changing during the eclipse.

The subsolar point data also has a systematic increase in 3 μm absorption band depth as the illumination and temperature decrease. This supports the results found at the Chang'E site and shows a band emerges even in the most extremely hot case. This data set is useful for evaluating models for the formation and transit of hydration on the lunar surface and the rapid increase in band depth on such a short timescale is a stronger constraint on the supply of water than diurnal variation in band depth.

There are two processes hypothesized for the variation in hydration band on the illuminated Moon with temperature: 1) that it reflects migrating water along temperature gradients [2] or, 2) that it is due to the temperature dependent formation of metastable hydroxyl [11], [12]. Each has challenges to explain these observations.

Migrating water requires that ballistic migration keeps up with the rapid passage of the Earth's shadow across the lunar surface, and there is enough water in the exosphere to adsorb to the cool surface. The duration of the measurement was about 2500 seconds, during which the relative band depth increased to a fractional depth of 0.08. Per Honniball et al. 2020, $17ppm$ corresponded a band depth of 0.04, so the abundance of water accumulated during the course of the eclipse was about $30ppm$. Assuming a basalt density of $3g/cc$, the abundance of water accumulated was about $100\mu g/cc$. The optical depth at $3\mu m$ is about $100\mu m$, so the total abundance of water accumulated on the sensed surface was about $3\mu g/cm^2$. Converting to molecules, assuming a molecular weight of $18g/mol$, there are $1.7x10^17$ molecules per cm^2 accumulated or $4*10^13/cm^2sec$ accumulated. Assuming arriving molecules are at a velocity of $1000m/s$, the exospheric density at the surface would have to be $4x10^8$ molecules per cm^3, 7 or 8 orders of magnitude above the LADEE constraint [13][14].

This appears to invalidate the hypothesis that time and temperature variations in the infrared 3um band are due to migrating molecular water as recently suggested by Hodges and Farrell (2022) [14] based on other arguments. The only viable remaining hypothesis for this band variation is that of temperature dependent metastable OH produced from diffusing solar wind hydrogen as proposed by Tucker et al. 2019 [12] .

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