DIURNAL VARIATIONS OF LUNAR SURFACE WATER FROM GROUNDBASED TELESCOPIC OBSERVATIONS.

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Introduction: Prior to 2008, the Moon was believed to be anhydrous. However, following new laboratory analysis of Apollo samples [1] and spacecraft observations [2-4], the Moon is now known to host both interior and surface water. Three spacecraft have observed a lunar 3 µm absorption band that is attributed to hydroxyl (OH) with a possible addition of molecular water (H_2O). The 3 µm band is a sum of OH and H_2O (termed "total water" in FTIR community [5]). The 3 µm band was observed at high latitudes and away from the subsolar point at low latitudes, in addition to varying in strength with lunar time of day (TOD) and local geology.

While measurements of the 3 µm band [2-4] were revolutionary, the returned spacecraft data have limitations. Cassini and Deep Impact data provided full wavelength coverage of the 3 µm band but are limited in spatial resolution, global coverage, and lunar TOD. The Moon Minerology Mapper (M^3) onboard the Chandryaan-1 spacecraft provided global coverage at high spatial resolution and several lunar TODs, however its spectral range ends at 3 µm, only covering the short wavelength region of the 3 µm band.

To bridge the gap between wavelength, global and temporal coverage, and lunar TOD we use the SPeX infrared cross-dispersed spectrograph [6] at the NASA InfraRed Telescope Facility (IRTF) at Mauna Kea Observatory. With the IRTF we are able to obtain lunar data from 1.67 to 4.2 µm of the entire earth facing hemisphere at 1-2 km resolution. The goal of this project is to determine if the 3 µm band exhibits a diurnal variation at TOD not observed by M^3.

Data: On November 21st, 2018 observations of the lunar surface along three chord lines were obtained, all within the Western hemisphere near the dawn terminator, (Fig. 1). The three chords were taken within 2 hours under photometric conditions. Each chord begins and ends off the Moon to collect adjacent sky measurements necessary for proper corrections for absorptions by the Earth's atmosphere. The three chords are named for a prominent lunar feature through which each passed (Hansteen Alpha, Kepler, and Copernicus). Hansteen Alpha was closest to the dawn terminator while Kepler and Copernicus are 20° and 24° E of the Hansteen Alpha, respectively.

Methods: Data are initially calibrated using the SPEXTOOL software [6]. Further processing is done using custom IDL routines. Groundbased observations must include corrections for absorptions by Earth's atmosphere. Observations of spectrally solar-like stars at similar atmospheric path lengths as the lunar observations are used to remove atmospheric
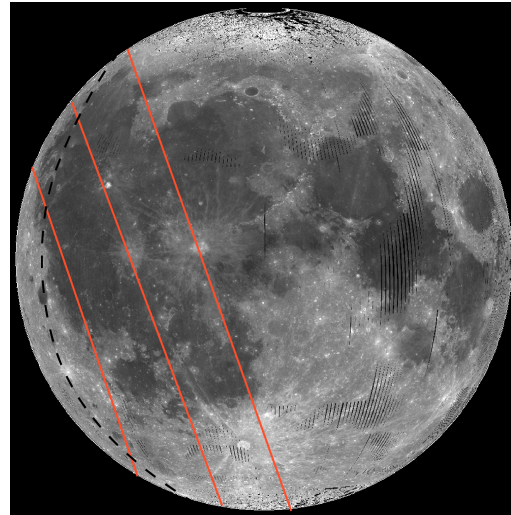

Figure 1: Orthographic map showing the three chord lines acquired on November 21st, 2018. From left to right are the Hansteen Alpha, Kepler, and Copernicus Chord. The dawn terminator is approximated by the dashes line.

absorptions. The initial calibrated data are ratios of lunar radiance to these solar analogs.

Lunar spectra longward of 3 µm are heavily affected by thermal radiation. Accurate removal of the thermal component is vital for proper investigation of the ~3 µm band and its spectral properties. Current thermal model experts, however, disagree on the removal of thermal radiation. Analysis of data from M^3 has led to strikingly different conclusions: Li et al. [7] and Wöhler et al. [8] see strong variations in the strength of the corrected 3 µm band indicating variations in the abundance of total water (OH + H_2O). However, Bandfield et al. [9] concluded that there is a strong feature but it does not varying with latitude or TOD. Unlike M^3 data, IRTF data out to 4 µm strongly constrains thermal models and therefore the behavior near 3 µm because at 4 µm almost all the measured flux is emitted and is much greater than at 3 µm.

For this work we follow the methodology used for asteroid thermal radiation removal [10-12]. Our thermal radiation model accounts for rough surfaces similar to Bandfield et al. [9]. Modeled thermal radiance is created using a range of surface roughness and temperatures between 200 to 400 K. Utilizing the long wavelengths beyond 3 µm we are able to constrain the modeled thermal component. After the removal of thermal emission the spectra are in continuum removed reflectance and can be used to assess spectral differences between OH and H_2O and for estimates of total water abundance (Fig. 2).
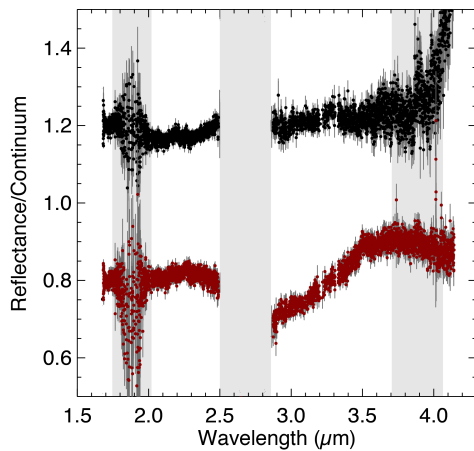
Figure 2: Reflectance spectra after thermal radiation removal. The bottom spectrum shows a step down from 2.4 to 2.9 μm indicating the presence of total water. The top is an example of a flat spectrum with no total water.

Estimating total water abundance is accomplished using the methods of described in Li (2016) [13,14].

Results: Figure 2 shows two examples of thermally corrected lunar IRTF data. The presence of total water in our spectra is indicated by a step between 2.5 and 2.9 μm. The data exhibit strong variations in band depth of the 3 μm absorption (Fig. 2). The depth of the band ranges from no step (top) to a strong 3 μm absorption (bottom). Many spectra show no absorption, like the top spectrum in Fig. 2, indicating no total water is present at the location the spectrum was acquired.

Maximum total water abundances less than 300 ppm calculated from the data are consistent with abundances observed by M[3] [7] for latitudes below 60° (Fig. 3). Minimum abundances are approximately zero. Along each observed chord there are strong variations in total water concentrations. The minimum water observed occurs at mid-northern latitudes and maxima for each chord occurs at mid southern latitudes.

Time of day variations are seen across constant latitude in Fig. 3. Abundance variations with TOD are approximately constant at latitudes around -20° but an increase in abundance can be seen near 0° latitude. The minimum detected total water varies with latitude and TOD and occurs at mid northern latitudes during mid-morning.

Discussion: Thermal emission within the spectra is strongly constrained by the data at longer wavelengths and removal of the thermal component does not remove or enhance the observed step. Thus, the observed TOD variation appears real and does not appear to be damped out by the removal of thermal emission when using methods commonly used on asteroid [12].

Maps produced by Li and Milliken [15] show the strongest total water variation along lines of constant latitude below 60° N and S. This variation is superimposed on the general increase in total water to
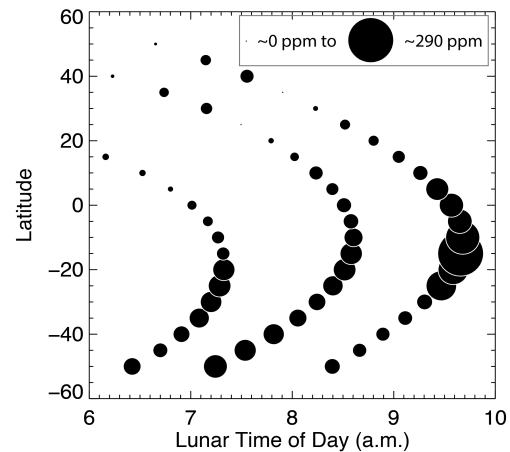

Figure 3: The three chords plotted as lunar TOD vs. Latitude with the Hansteen Alpha on the left, Kepler in the center and the Copernicus on the right. Symbol size is proportional to the abundance of total water.

high latitudes. Our observations show similar variations in the equatorial to mid-latitudes. To date, little work has been done at these low concentrations and latitudes. The low abundances appear not to controlled by simple combinations of latitude or TOD and we observe asymmetric trends about the equator indicating another controlling factor, possibly composition.

The same three chords have been observed on two different nights with different lunar TODs but have not yet been processed. After processing, these additional observations may provide insight on the effect of composition on total water concentration at these low abundances.

Conclusions: Groundbased observations of the lunar surface water allows us to address diurnal variations. The wavelength range of the IRTF allows us to constrain thermal models for accurate assessment of the 3 μm absorption band. Our observations show variations with TOD that appear real based on the presence of the 3 μm band. TOD variations are asymmetric about the equator but further investigation of data acquired at different TODs is needed to control for composition. Observed variations in total water abundance are consistent with those reported by Li and Milliken [15] at low abundances.

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