

**A PROMINENT AND UBIQUITOUS OH/H<sub>2</sub>O FEATURE IN CORRECTED LUNAR SPECTRA.** J. L. Bandfield<sup>1</sup>, M. J. Poston<sup>2</sup>, R. L. Klima<sup>3</sup>, and C. S. Edwards<sup>4</sup>, <sup>1</sup>Space Science Institute (jbandfield@spacescience.org), <sup>2</sup>California Institute of Technology, <sup>3</sup>Applied Physics Laboratory, Johns Hopkins University, <sup>4</sup>Northern Arizona University.

**Introduction:** There is considerable interest in the spectral response of the lunar surface near 2.82 and 2.95  $\mu\text{m}$ , where OH and H<sub>2</sub>O have strong absorptions. Previous studies have identified these absorptions with variable strengths across the lunar surface [1–7]. The absorptions have been found to be most prominent at higher latitudes and at early and late local times (e.g., [1–2]), leading investigators to propose an environment where much of the OH/H<sub>2</sub>O migrates around the Moon on diurnal timescales (e.g., [1,4,8–10]).

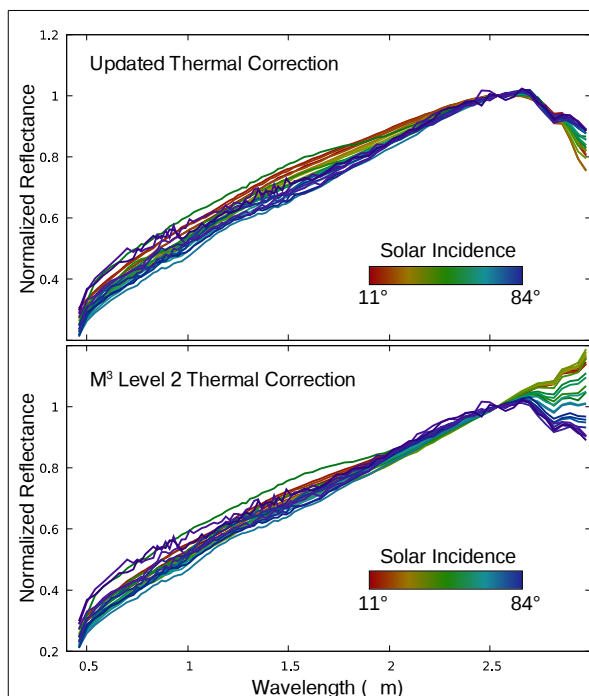
However, these studies are based on data that have significantly and variably underestimated lunar surface temperatures, resulting in inaccuracies that can substantially diminish or even entirely eliminate these spectral features. Recent work by *Li and Milliken* [7] and *Wöhler et al.* [11] have improved the accuracy of the lunar thermal corrections, but still appear to commonly underestimate temperatures. This prevents proper correction of data under many circumstances and inhibits comparison of surfaces with different illumination conditions.

We have developed a combined roughness and thermal emission model to predict the emitted radiance as a function of wavelength [12]. The modeled spectral radiance closely matches Lunar Reconnaissance Orbiter (LRO) Diviner Radiometer measurements over 8–300  $\mu\text{m}$  wavelengths.

The correction of M<sup>3</sup> data using the output of the roughness emission model is relatively straightforward. We assume that Kirchoff's Law applies ( $\epsilon = 1 - R$ ). In addition, the examples shown here assume a surface slope distribution of 20° RMS, similar to most lunar surfaces [12].

**Results:** The roughness model for the removal of thermal contributions from M<sup>3</sup> data has a dramatic effect on the resulting spectra (Fig. 2). At wavelengths greater than  $\sim 2.75$   $\mu\text{m}$ , the corrected reflectance spectra show a prominent negative slope with increasing wavelength. The relative depth of the feature varies by  $\sim 30\%$ , with a more prominent absorption at low angles of solar incidence. By comparison, the M<sup>3</sup> Level 2 thermally corrected data only show this slope at high angles of solar incidence (Fig. 1).

The modeled brightness temperatures are significantly higher than the M<sup>3</sup> Level 2 derived surface temperature, resulting in a much higher estimated thermal emission contribution and, consequently, lower reflectance values in the corrected data. The new correction has been validated using



**Figure 1.** M<sup>3</sup> thermally corrected spectra with variations in solar incidence. The updated data (top plot), corrected using a roughness emission model, shows a consistently strong 2.95  $\mu\text{m}$  absorption. This is in contrast to the M<sup>3</sup> Level 2 corrected data (bottom), which only shows a distinct 2.95  $\mu\text{m}$  absorption at high angles of solar incidence.

Diviner measurements collected over the same surfaces at similar solar incidence angles. The Diviner measurements closely match the model, with increasing brightness temperature at decreasing wavelengths. The brightness temperatures predicted by the roughness model at 2.95  $\mu\text{m}$  are higher than the Diviner measurements at moderate to high solar incidence angles, as should be the case for rough surfaces.

The newly corrected data have also been applied to different surface types to identify any spectral dependence on composition or degree of space weathering. In every case examined, regardless of surface type, the prominent 2.95  $\mu\text{m}$  absorption is present. However, similar to the spectra shown in Fig. 1, systematic differences in band strength are present.

For example, the central peak of Bullialdus Crater has a 2.95  $\mu\text{m}$  absorption similar to the crater floor. However, the central peak has a more prominent minor absorption present near 2.82  $\mu\text{m}$ , consistent with previous work [6] (Fig. 2). By contrast, the albedo

feature at Reiner Gamma shows a weaker 2.82  $\mu\text{m}$  absorption associated with higher albedo surfaces (consistent with [5]). The high albedo is also associated with a less prominent 2.95  $\mu\text{m}$  absorption (Fig. 2).

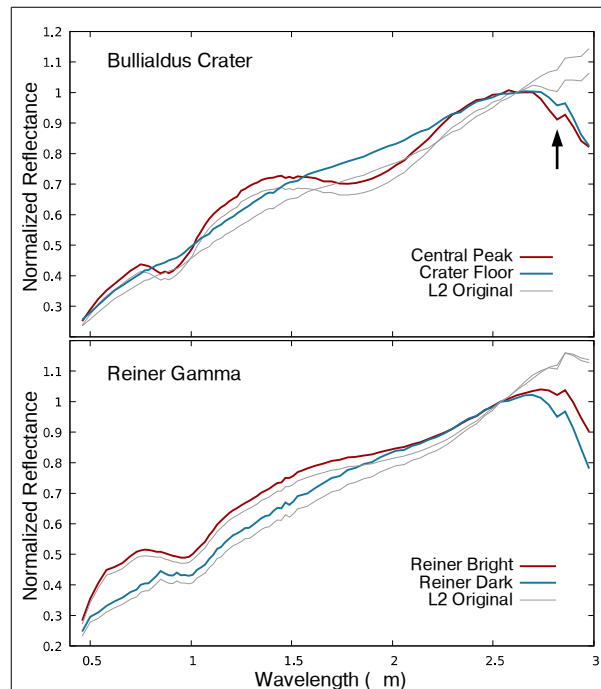
**Discussion:** Incorporation of the roughness emission model causes a dramatic change in the depth of the 2.95  $\mu\text{m}$  absorption in the  $M^3$  reflectance spectra. This absorption is prominent for all lunar surface types and at all latitudes and local times. The strength of the minor 2.82  $\mu\text{m}$  absorption is relatively unchanged with the updated correction. The dominance of the 2.95  $\mu\text{m}$  feature relative to the 2.82  $\mu\text{m}$  feature can be interpreted as  $\text{H}_2\text{O}$  being more abundant than OH at the lunar surface – a somewhat surprising result given that OH is expected to be more readily produced via solar wind implantation [4].

There is some variation in the depth of the 2.95  $\mu\text{m}$  feature, but it is opposite that of previous results [1, 11]. In this case, 2.95  $\mu\text{m}$  band depths are greater where solar incidence angles are low and surfaces are warm. On a qualitative level, this can be consistent with OH/ $\text{H}_2\text{O}$  formation on the lunar surface. However, given the extreme illumination and temperature variations for the spectra shown in Fig. 1, it is possible that these variations in band depth could be caused by environmental effects. For instance, the possibility of high vertical thermal gradients could negate the validity of Kirchoff's Law – something that all thermal corrections currently assume.

Spectra within bright and dark areas of Reiner Gamma can be more directly compared. In this case, the dark areas appear to have more prominent 2.82  $\mu\text{m}$  [5] and 2.95  $\mu\text{m}$  absorptions. This result is consistent with the hypothesis that strong magnetic anomalies shield the bright surfaces from the solar wind [e.g., 13], reducing the formation of OH and  $\text{H}_2\text{O}$  [5]. The anti-correlation of band depth with bright surfaces in Reiner Gamma suggests a solar wind source for these features.

Bullialdus Crater shows independently variable 2.82 and 2.95  $\mu\text{m}$  features. The association of a relatively prominent 2.82  $\mu\text{m}$  feature with the central peak in this case suggests that (in addition to a solar wind source) the variations in OH abundance are in part due to lunar petrology, as shown previously [6].

**Conclusions:** Properly accounting for lunar surface temperatures and roughness reveals an ubiquitous and prominent 2.95  $\mu\text{m}$  absorption (interpreted as  $\text{H}_2\text{O}$ ) in  $M^3$  data. Local and global variations in the strength of this band are present, but the variations are modest compared to the overall strength of the feature. The minor and much less prominent 2.82  $\mu\text{m}$  absorption (interpreted as OH) does not appear to be changed by the updated correction.



**Figure 2.**  $M^3$  thermally corrected spectra of Bullialdus Crater (top) and Reiner Gamma (bottom). Original  $M^3$  Level 2 data are shown in gray. The prominence of the 2.95  $\mu\text{m}$  absorption is similar between the Bullialdus Crater central peak and floor, despite variations in the minor 2.82  $\mu\text{m}$  feature (denoted by the arrow). By contrast, bright areas in Reiner Gamma have both shallower 2.82 and 2.95  $\mu\text{m}$  spectral features.

The presence of a strong 2.95  $\mu\text{m}$  feature for all major lunar surface types and the variations in strength associated with Reiner Gamma suggests a solar wind source for the 2.95  $\mu\text{m}$  feature. However, this does not preclude the possibility of variations in the 2.95  $\mu\text{m}$  absorption due to variations in petrology (such as magmatic water content) as well, though none have been identified to date.

**References:** [1] Pieters C.M. et al. (2009) *Science*, 56810.1126/science.1178658. [2] Sunshine J.M. et al. (2009) *Science*, 56510.1126/science.1179788. [3] Clark R.N. (2009) *Science*, 56210.1126/science.-1178105. [4] McCord T.B. et al. (2011) *JGR*, 10.1029/2010JE003711. [5] Kramer G.Y. et al. (2011) *JGR*, 10.1029/2010JE003729. [6] Klima R.L. et al. (2013) *Nat. Geo.*, 10.1038/ngeo1909. [7] Li S. and Milliken R.E. (2016) *JGR*, 10.1002/2016JE005035. [8] Dyar M.D. et al. (2010) *Icarus*, 10.1016/j.icarus.2010.02.014. [9] Hibbitts, C.A. et al. (2011) *Icarus*, 10.1016/j.icarus.-2011.02.015. [10] Poston M.J. (2013) *JGR*, 10.1029/2012JE004283. [11] Wöhler et al. (2016) *Icarus*, 10.1016/j.icarus.2016.12.026. [12] Bandfield J.L. et al. (2015) *Icarus*, 10.1016/j.icarus.2014.11.009. [13] Hood, L.L. Schubert, G. (1980) *Science* 208, 49–51.