ENHANCED HYDRATION AT CRATERS WITH CENTRAL PEAKS DETECTED BY GROUND-BASED OBSERVATIONS. C. I. Honniball[1], P. G. Lucey[2], N. E. Petro[1], S. Li[2], and K. E. Young[1], [1]NASA Goddard Space Flight Center, 8800 Greenbelt Rd., Greenbelt, MD, 20771 (casey.i.honniball@nasa.gov); [2] Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, HI.

Introduction: Within the last decade, the understanding of hydration on the lunar surface has undergone major transformation. The Moon is no longer presumed to be anhydrous with hydroxyl (OH^-) and water (H_2O) being widespread across the surface of the Moon [1-3]. The origin of hydration on the Moon is of high interest for understanding the evolution of the Moon as well as ongoing and dynamic processes. Hydration on the lunar surface can originate from several sources including the solar wind, meteorites, and the lunar interior.

Several 3 µm hydroxyl signatures, measured by the Moon Minerology Mapper (M^3) on Chandryaan-1 spacecraft, are associated with interior magmatic sources [1,4-6]. Locations with enhanced hydration directly associated to interior water and magmatic sources are pyroclastic deposits, silicic domes, and central peaks of some craters [1,4-6]. The observed hydration signatures in these areas are assumed to be derived from interior sources as there is a direct geologic association between the observed hydration and volcanic and impact features.

M^3 observations suffer from a limited spectral range at 3 µm which complicates the removal of thermal emission from the reflectance spectra and increases uncertainty in abundance estimates. Removal of the thermal component is vital to properly measure the strength of the 3 µm hydration band. Here, we present observations of Bullialdus and Aristarchus craters using the Spex infrared cross-dispersed spectrograph [7] at the NASA InfraRed Telescope Facility (IRTF) at Mauna Kea Observatory in Hawai'i. With the IRTF we can obtain lunar spectra from 1.67 to 4.2 µm of the entire Earth facing hemisphere at 1-2 km spatial resolution.

There are two goals of this project. The first is to confirm the enhanced hydration at Bullialdus central peak measured by M^3 [4,5] using IRTF observations and the strong thermal constraints provided by the longer wavelengths. The second is to identify other central peaks that may be enhanced in hydration that M^3 may not have detected due to thermal removal issues.

Data: On June 24th, 2018 and January 20th, 2019, observations of Bullialdus and Aristarchus craters were obtained (Figure 1), respectively, resulting in spatially resolved maps of portions of the craters, their central peaks, and the surrounding area. Data reduction and abundance estimates follow the methods described in Honniball et al. [3]. We have also collected data for maps of Tycho, Eratosthenes, and Copernicus and will investigate these in the near future.

One difference in the reduction of these data is the definition of the infrared continuum. Honniball et al. [3] used a linear continuum is fit to the data at 1.7 and 2.5 µm and extrapolated to longer wavelengths. However, for spectra with no obvious 3 µm band, we found that a linear continuum does not accurately estimate a zero abundance and provides negative abundances that range from -500 to -2000 ppm total water (OH + H_2O). In order to provide a better zero abundance estimate, we averaged several dry spectra for Bullialdus and Aristarchus observations and fit the average dry spectrum with a 3rd order polynomial. This new continuum is then scaled and tilted to fit all the spectra at 1.7 and 2.5 µm. This new method of defining a continuum provides a slightly better estimate of the zero abundance but still results in a few negative abundances around -280 ppm total water (OH + H_2O). Further work on the continuum of dry lunar spectra is needed to provide more accurate abundance estimates.

Results: Bullialdus central peak shows enhanced hydroxyl at 3 µm in IRTF data (Figure 1b). Abundance estimates at the central peak range from 100 to 360 ppm total water (OH + H_2O) with an average error of 12 ppm total water (OH + H_2O). Shadows on the east crater wall

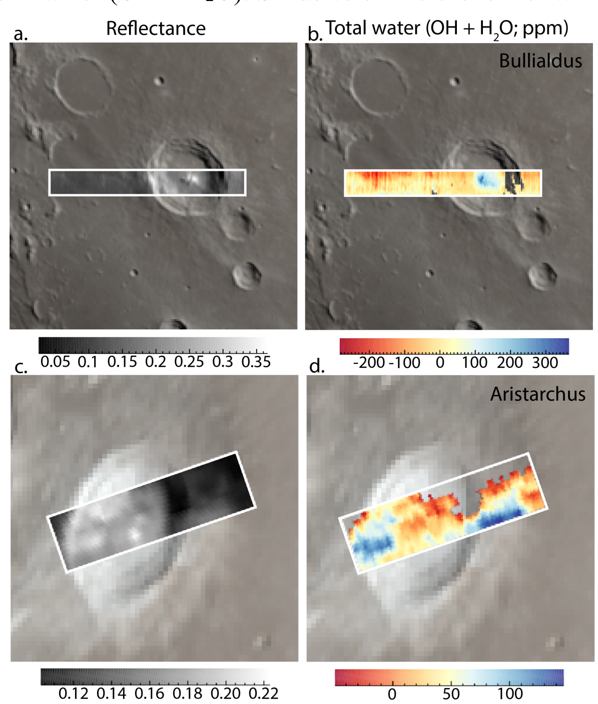

Figure 1: Reflectance map (a,c) and total water (OH + H_2O) maps (b,d) of Bullialdus (a,b) and Aristarchus (c,d) craters observed by the IRTF overlaid on an LRO image under the same lighting conditions as the IRTF observations. The white box represents the extent of the IRTF observations. Shadows are masked in b and d due to low signal-to-noise.

are low in signal and are masked out in Figure 1b. Compared to the surrounding material, the central peak of Bullialdus is the *only region* that shows hydration, similar to the results of Klima et al. [4] and Li and Milliken [1]. Negative abundance estimates shown in Figure 1b are due to the spectra featuring no detectable 3 µm band and the model continuum not accounting for a slight increase in reflectance relative to the shorter wavelength continuum in these types of spectra. Despite the slight negative abundance estimates it appears there is some spectral variation at 3 µm occurring in the mare surrounding Bullialdus crater.

Aristarchus crater does not show an enhancement in hydration at the central peak, only a slight hint of hydration (Figure 1d). There are, however, two locations that show enhanced hydration, the west crater wall and a portion of the eastern rim. The abundances of these two locations ranges from about 50 to 150 ppm total water (OH + H_2O). Outside the two enhanced areas at Aristarchus crater the remaining area appear "dry" (i.e., no 3 µm absorption) with some variations similar to what is seen in the mare region surrounding Bullialdus. Shadowed areas have been masked out.

Discussion: Bullialdus has been investigated previously by M^3 and has been shown to have an enhanced hydroxyl absorption band at 3 µm that is not consistent with purely surficial origins [1,4]. The conclusion was that the 3 µm band is likely due to a magmatic source below that was excavated during impact from depths of 6-9 km [4]. The 3 µm band at Bullialdus central peak measured by M^3 coincides with localized concentrations of thorium and norite [4], which suggest that Bullialdus impact excavated a mafic intrusion [9,10] further supporting the evidence of a magmatic source.

Our results of Bullialdus also reveal an enhanced 3 µm band at the central peak in agreement with the two M^3 studies. This lends confidence to the interpretation that the central peak is enhanced in hydroxyl and the band is not an artifact created by incomplete thermal removal in the M^3 data.

The abundances reported for Bullialdus central peak varies between studies. Klima et al. [4] report abundances up to 80 ppm total water (OH + H_2O) at the Bullialdus central peak. The data used in their study used the original thermal removal procedures for M^3. Li and Milliken [1] report abundances up to 250 ppm total water (OH + H_2O) using a new thermal removal correction to the M^3 data. Lastly, IRTF observations show abundances up to 360 ppm total water (OH + H_2O).

The differences in abundances between the three studies is likely due to different thermal removal procedures, different temperatures observed between the two instruments, and different definitions of a continuum. The wavelengths beyond 3 µm observed by the IRTF provides strong constraints on thermal models allowing for a more accurate removal of thermal emission and better estimates of the abundance. Our estimated abundances with the IRTF are more consistent with the estimates of Li and Milliken [1].

The abundance we measure with the IRTF in the central peak could represent the abundance present in the lunar interior. During the impact that formed Bullialdus much of the material in the crater and the crater ejecta may have been degassed due to the high temperatures encountered. However, the central peak of Bullialdus may not have experienced the high temperatures of impact [11] potentially preserving the internal abundance of hydroxyl in the magma source below.

Aristarchus crater was also investigated using M^3 data employing the thermal removal procedures of [6]. In their analysis the crater itself displays no hydration at the peak, the walls, or the ejecta. Our observations with the IRTF indicate abundances up to 150 ppm total water (OH + H_2O) based on observed variation in 3 µm band depth. The improved thermal constraint and continuum definition afforded by the IRTF wavelength range may allow us to detect weaker features than have been observed by M^3. The Aristarchus plateau features a large pyroclastic deposit; however, the portion of Aristarchus crater we observed does not contain pyroclastic material. The areas of enhanced hydration may be indicating the excavation of material from the magmatic source. An external source of hydration is unlikely due to the distribution of hydration in the crater.

Conclusions: The presence of enhanced hydration at Bullialdus central peak in IRTF observations lends confidence to M^3 observations using new thermal removal procedures. However, we do see discrepancies in the abundances measured by M^3 and the IRTF. The longer wavelengths of the IRTF observations provide strong thermal constraints and therefore better estimates of hydration. It is possible that IRTF data can be used to further develop the M^3 thermal removal procedure, but the methods used by Li and Milliken [1] are more appropriate than the original method to remove thermal emission.

Acknowledgments: NASA IRTF is operated by the University of Hawai‘i under contract NNH14CK55B. This work was support by NASA SSO program (#80NSSC18K0542) and C.I.H.'s appointment to the NPP at GSFC administered by USRA.

References: [1] Li S. and Milliken R. (2017) Sci Adv., 3, 8-11. [2] Honniball C. I. et al. (2020) Nat Ast, 10.1038/s41550-020-01222-x. [3] Honniball C. I. et al. (2020) GRL, 125, e2020JE006484. [4] Klima R. L. et al. (2013) Nat Geo, 6, 737-741. [5] Klima R. L. and Petro N. E. (2017) Phil. Trans. R. Soc. A 375: 20150391. [6] Milliken R. and Li S. (2017) Nat Geo, 10, 561-565. [7] Rayner D.W. et al. (2003), PASP, 115, 362. [8] Honniball C. I. (2019) University of Hawai‘i, PhD Dissertation. [9] Pieters, C. M. (1991) GRL, 18, 2129_2131. [10] Tompkins, S et al. (1994) Icarus 110, 261_274. [11] Young K. E. et al. (2016) LPSC 47, Abstract #1754.