MOLECULAR WATER ON THE ILLUMINATED LUNAR SURFACE: DETECTION OF THE 6 \textmu{}m H-O-H FUNDAMENTAL WITH THE SOFIA AIRBORNE OBSERVATORY. C. I. Honniball1,2*, (cih@higp.hawaii.edu), P. G. Lucey1, S. Li1, S. Shenoy2, T. M. Orlando3, C. A. Hibbitts4, D. M. Hurley4, W. M. Farrell5, 1HIGP, University of Hawai‘i at Mānoa, Honolulu, HI, 2Space Science Institute, Boulder, CO, 3School of Chemistry and Biochemistry, School of Physics and Center for Space Technology and Research, Georgia Institute of Technology, Atlanta, GA, 4APL, Johns Hopkins University, Laurel, MD, 5NASA Goddard Space Flight Center, Greenbelt, MD

Introduction: Hydration on the lunar surface was first reported in 2009 by three spacecraft [1-3] manifested as a strong absorption at 3 \textmu{}m. The 3 \textmu{}m absorption is caused by the symmetric and asymmetric stretching of the O-H bond [4], which can be produced by both hydroxyl (OH) attached to metal cations, and by molecular water (H$_2$O).

When "water" is discussed regarding data at 3 \textmu{}m, the true meaning is OH, that may include H$_2$O but does not require H$_2$O. Currently there are no methods available to distinguish H$_2$O from OH bound to other cations or to quantify the ratio of H$_2$O to OH. Further, at 3 \textmu{}m, lunar radiance is a mixture of reflected and emitted radiance, complicating its interpretation and resulting in controversy regarding the abundance and distribution of OH or H$_2$O [e.g. 5,6].

There has been a study that suggests the detection of H$_2$O on the Moon using a far UV (FUV) water ice ratio from LRO LAMP [7]. On the illuminated Moon, the FUV water ice ratio shows a diurnal signature near lunar noon. Hendrix et al. [7] suggested the diurnal variation could be due to H$_2$O migrating if it spectrally behaves like water ice in the FUV. However, there is currently no data on the behavior of H$_2$O in the FUV and the possibility that the FUV signal is due to OH abundance variations cannot be ruled out.

To confirm or deny the presence of H$_2$O on the Moon, new techniques are needed to detect it. Fortunately, H$_2$O expresses a fundamental vibration at ~6 \textmu{}m, the H-O-H bend, that can only be produced by H$_2$O and is absent in other OH-bearing compounds [8-15]. Also advantageous is that at lunar temperatures at 6 \textmu{}m, the signal observed is emission with essentially no contribution from reflectance. Until recently, no observations of the Moon at 6 \textmu{}m had been conducted and no current or planned lunar spacecraft or ground-based telescopes are able to conduct 6 \textmu{}m observations of the Moon.

In this work, we present the first spectral observations of the Moon at 6 \textmu{}m using the NASA/DLR Stratospheric Observatory For Infrared Astronomy (SOFIA) an airborne 2.5 m telescope used for infrared and submillimeter astronomy [16].

SOFIA Lunar Observations: On August 30th, 2018 we conducted the first observations of the Moon at 6 \textmu{}m with SOFIA. We used the Faint Object infra-Red CAmera for the SOFIA Telescope (FORCAST) spectrograph providing a wavelength coverage of 5 to 8 \textmu{}m at a spectral resolution of R=200 (30 nm).

We observed two locations on the Moon, the Sulpicius Gallus and Clavius regions. Sulpicius Gallus is located near the equator and was chosen to represent a location with little to no H$_2$O because it experiences high maximum surface temperatures and its basaltic glass composition is hydrophobic [17,18]. Clavius is a location at high southern latitudes and is known to have a high abundance of hydration in 3 \textmu{}m data acquire with the Moon Mineralogy Mapper (M3) [6] and thus the presence of H$_2$O was possible. At each location, 6 frames of data were acquired with integration times of ~4 seconds. Observations of the two locations were conducted within 10 minutes at an altitude of about 43K feet. The SOFIA Project supplies fully calibrated flux data from 5 to 8 \textmu{}m as spectral images due to the Moon filling the entire slit of FORCAST.

Estimating Abundance of H$_2$O: Previous studies show that the absorption strength of the 6 \textmu{}m band correlates with the absolute content of H$_2$O [9,11,19]. To estimate the abundance of H$_2$O in the remote sensing data of the Moon we derived an empirical relationship between the 6 \textmu{}m band depth in reflectance and the absolute abundance of H$_2$O from water-bearing glasses formerly used to estimate the abundance of hydration at 3 \textmu{}m [6].

To apply this calibration we convert the provided flux data to radiance and convert the emission spectra to reflectance via Kirchoff’s law using an emissivity of

![Figure 1: Emission spectra of the Clavius region with the maximum (red) and minimum H$_2$O abundance.](image)
Water on the Moon: Data of the Clavius crater and surrounding region reveal a 1-3% 6 μm emission band that we attribute to molecular water on the Moon (Fig. 1). All spectra acquired at the Clavius region exhibit a 6 μm emission band.

To unambiguously assign the observed 6 μm band to H$_2$O, we compared the position of the lunar 6 μm band to: literature values of the center position of the H-O-H bend in crystalline hydrates [20]; 6 μm bands of water-bearing glasses [6]; and meteorites with water adsorbed from the terrestrial environment [21]. We find the Moon, water-bearing glasses, and meteorite band centers fall within the reported band center range for the H-O-H bend in crystalline hydrates. Based on these comparisons, we are confident the 6 μm band on the Moon is due to H$_2$O. We are unaware of any other lunar material that may exhibit an isolated 6 μm band.

We estimate abundances of ~150 to 650 ppm H$_2$O in the high latitude Clavius region with an average of ~400 ppm H$_2$O (Fig. 2). The estimates are lower limits and have an error of ~14 ppm H$_2$O found by propagating the error provided by the SOFIA data reduction.

![Histogram density of H$_2$O abundances measured in the Clavius region.](image)

Figure 2: Histogram density of H$_2$O abundances measured in the Clavius region.

The abundance of surface chemisorbed water that should be permitted at the latitude and lunar time of day of our observations is only about 3 ppm H$_2$O [22], over 100 times less than the abundance observed. This implies that most of the detected H$_2$O does not reside on the grain surfaces, but instead must reside within the interior of the lunar grains.

The interior water is likely resident within impact glasses [15]. Most lunar soil is a combination of 30 wt. % impact glass [23] and ~70 wt. % mineral fragments and most lunar minerals are nominally anhydrous and should have extremely low water contents [24]. If the detected interior water is confined to impact glass, then the abundance of water in the glasses ranges from 500 to 2100 ppm H$_2$O with an average of 1300 ppm H$_2$O. These abundances are consistent with retention of impactor water [15], or may be due to conversion of OH to H$_2$O in small impact events [25, 26].

In conclusion, we have detected molecular water on the illuminated lunar surface using the SOFIA FORCAST instrument. This is the first direct, unambiguous detection of H$_2$O on the Moon outside the permanent shadows at the lunar poles. We estimate that most of the observed water is stored within lunar impact glasses supporting the suggestion that little to no H$_2$O is available to migrate diurnally at high latitudes.

Acknowledgments: Observations were made using SOFIA. SOFIA is jointly operated by USRA, under NASA contract NNA17BF53C, and DSI under DLR contract 50 OK 0901 to the University of Stuttgart. USRA SOFIA Grant 07-0061.

References: