MOLECULAR WATER ON THE ILLUMINATED LUNAR SURFACE: DETECTION OF THE 6 µm H-O-H FUNDAMENTAL WITH THE SOFIA AIRBORNE OBSERVATORY.

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Introduction: Hydration on the lunar surface was first reported in 2009 by three spacecraft [1-3] manifested as a strong absorption at 3 µm. The 3 µm 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_2O).

When "water" is discussed regarding data at 3 µm, the true meaning is OH, that may include H_2O but does not require H_2O. Currently there are no methods available to distinguish H_2O from OH bound to other cations or to quantify the ratio of H_2O to OH. Further, at 3 µm, 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_2O [e.g. 5,6].

There has been a study that suggests the detection of H_2O 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_2O migrating if it spectrally behaves like water ice in the FUV. However, there is currently no data on the behavior of H_2O 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_2O on the Moon, new techniques are needed to detect it. Fortunately, H_2O expresses a fundamental vibration at ~6 µm, the H-O-H bend, that can only be produced by H_2O and is absent in other OH-bearing compounds [8-15]. Also advantageous is that at lunar temperatures at 6 µm, the signal observed is emission with essentially no contribution from reflectance. Until recently, no observations of the Moon at 6 µm had been conducted and no current or planned lunar spacecraft or ground-based telescopes are able to conduct 6 µm observations of the Moon.

In this work, we present the first spectral observations of the Moon at 6 µm 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 µm with SOFIA. We used the Faint Object infraRed CAmera for the SOFIA Telescope (FORCAST) spectrograph providing a wavelength coverage of 5 to 8 µm 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_2O 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 µm data acquire with the Moon Mineralogy Mapper (M^3) [6] and thus the presence of H_2O 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 µm as spectral images due to the Moon filling the entire slit of FORCAST.

Estimating Abundance of H_2O: Previous studies show that the absorption strength of the 6 µm band correlates with the absolute content of H_2O [9,11,19]. To estimate the abundance of H_2O in the remote sensing data of the Moon we derived an empirical relationship between the 6 µm band depth in reflectance and the absolute abundance of H_2O from water-bearing glasses formerly used to estimate the abundance of hydration at 3 µm [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

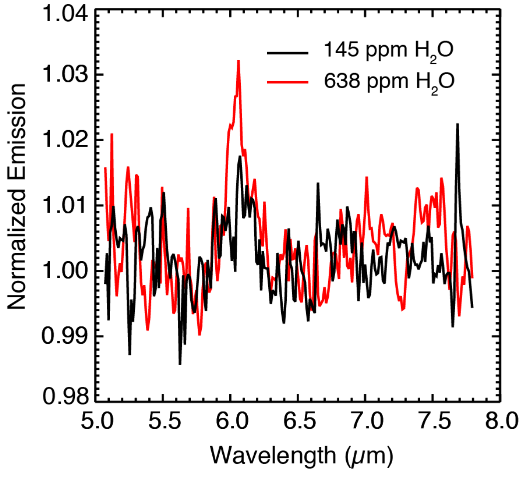

Figure 1: Emission spectra of the Clavius region with the maximum (red) and minimum H_2O abundance.

~0.3 at 5.6 μm based on the reflectance of mature lunar samples.

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_2O, 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_2O. We are unaware or any other lunar material that may exhibit an isolated 6 μm band.

We estimate abundances of ~150 to 650 ppm H_2O is present in the high latitude Clavius region with an average of ~400 ppm H_2O (Fig. 2). The estimates are lower limits and have an error of ~14 ppm H_2O found by propagating the error provided by the SOFIA data reduction.

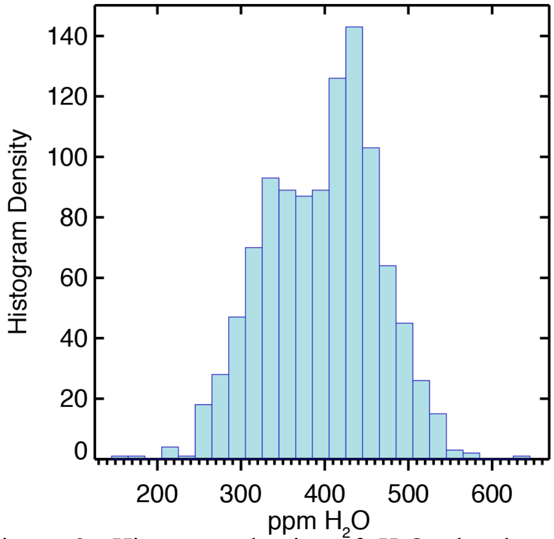

Figure 2: Histogram density of H_2O abundances measured in the Clavius region.

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_2O [22], over 100 times less than the abundance observed. This implies that most of the detected H_2O 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_2O with an average of 1300 ppm H_2O. These abundances are consistent with retention of impactor water [15], or may be due to conversion of OH to H_2O 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_2O 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_2O is available to migrate diurnally at high latitudes.

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