

A legacy of lunar water through SOFIA

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Background
Unprecedented detection of molecular water (H₂O) on the sunlit lunar surface has been made by SOFIA (Honniball et al., 2020).
Raised many new questions about the behavior, formation, and storage of water on the Moon.
Prior to this, it was suggested that water may be responsible for diurnal variations observed in the 3 μm hydration band and the UV water ice band ratio (Sounine et al., 2009).

Water on the Moon
Data obtained by SOFIA in 2018 show a strong 6 μm emission feature.
- Water is located at the Clavius crater region at high southern latitudes.
First unambiguous detection of H₂O on the sunlit Moon.
All spectra exhibit this 6 μm emission feature and 90% of spectra exceed 2σ significance relative to the background noise.

Source of lunar water
Now that water has been definitively detected on the sunlit lunar surface and through the SOFIA Legacy program we can begin to characterize the distribution of water, its source, retention, and loss.
Potential origins
- Solar wind hydrogen reacting with the lunar surface to form OH and potentially H₂O
- From pre-existing OH during a micrometeorite impact
- Re-cracked in with meteorites.

Indigenous water
Water indigenous to the Moon may reside in lunar igneous rocks or volcanic deposits.
The discovery of water in volcanic glass bead samples by Saut et al. (2008) indicate that parts of the lunar mantle are wet, while the bulk mantle is dry.
- Background abundance of water about 1 ppm water equivalent hydrogen (Ritonde et al., 2015).

New method to detect water on the sunlit Moon
To definitively show the presence of water on the sunlit lunar surface a new method was developed.
H₂O features a fundamental bending mode at 6 μm.
- New method to uniquely detect H₂O on the Moon
- No confusion with OH

Rare minerals
In addition to sensitivity to water, the 5-8 μm region also contains spectral features sensitive to the silicate mineralogy of the Moon.
The Christiansen feature (CF), a spectral phenomenon, is an emissivity maximum and the peak wavelength position is diagnostic of the silica polymerization of lunar minerals.
Tutorial on the 1-0 μm characteristics

ABSTRACT REFERENCES CONTACT AUTHOR PRINT GET POSTER

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BACKGROUND

Unprecedented detection of molecular water (H_2O) on the sunlit lunar surface has been made by SOFIA [Honniball et al., 2020]

Raised many new questions about the behavior, formation, and storage of water on the Moon

Prior to this, it was suggested that water may be responsible for diurnal variations observed in the $3\ \mu\text{m}$ hydration band and the UV water ice band ratio [Sunshine et al., 2008; Hendrix et al., 2019]

However, the $3\ \mu\text{m}$ and UV band ratio do not distinguish between water and hydroxyl (OH)

- OH attached to cations can mimic H_2O by broadening the $3\ \mu\text{m}$ band
- Variations in the UV water ice band ratio may be due to H_2O , but the same effect could be caused by OH
- OH can vary in abundance without migration, as solar wind hydrogen diffuses through lunar soil

Currently the $3\ \mu\text{m}$ band and UV water ice ratio cannot definitively determine the presence of water

WATER ON THE MOON

Data obtained by SOFIA in 2018 show a strong 6 μm emission feature

- Water is located at the Clavius crater region at high southern latitudes

First unambiguous detection of H₂O on the sunlit Moon

All spectra exhibit this 6 μm emission feature and 98% of spectra exceed 2σ significance relative to the background noise

To estimate the abundance of water we derived an empirical relationship between band depth in reflectance and absolute abundance of H₂O

$$M_{\text{water}} = 9,394D_{\text{band}}^2 + 9,594D_{\text{band}}$$

M_{water} is the abundance of H₂O (in ppm) and D_{band} is the depth of the 6 μm band. Abundances range from about 100 to 400 ppm H₂O

Poston et al. 2015 modeled that only 3 ppm of H₂O can reside on the surface of grains

- Chemisorbed water is unlikely to be a substantial portion of our signal
- Water detected by SOFIA likely resides within impact glass

Latitudinal trend of SOFIA water abundances is opposite of what we expect

- Due to Tycho crater ejecta at lower latitudes
- Likely not a global phenomenon

SOURCE OF LUNAR WATER

Now that water has been definitively detected on the sunlit lunar surface and through the SOFIA Legacy program we can begin to characterize the distribution of water, its source, retention, and loss.

Potential origins

- Solar wind hydrogen reacting with the lunar surface to form OH and potentially H₂O
- From pre-existing OH during a micrometeorite impact
- Be carried in with meteorites
- Indigenous to the lunar interior

Potential storage

- Chemisorbed on the surface of grains
- Trapped in impact glasses
- Within the structure of igneous minerals
- Quenched within volcanic glass beads

Where water resides provides evidence towards where the water originated and, therefore, which source dominates on the Moon

- SOFIA can determine the locations where water is stored

Water residing on the surface of grains

- Can originate from solar wind and micrometeorite impact
- Observations with SOFIA should reveal hourly diurnal variations of water

Water residing within impact glasses

- Can originate from pre-existing OH and impactor water
- If pre-existing OH, observations should reveal a distribution that mimics the solar wind flux
- If impactor water, observations should reveal a roughly uniform global distribution
- In both cases glass-trapped water will show no diurnal variation

INDIGENOUS WATER

Water indigenous to the Moon may reside in lunar igneous rocks or volcanic deposits

The discovery of water in volcanic glass bead samples by Saal et al. (2008) indicate that parts of the lunar mantle are wet, while the bulk mantle is dry

- Background abundance of water about 1 ppm water equivalent hydrogen (Albarede et al., 2015).

The origin of the wet portions of the mantle is likely due to a late addition of cometary or carbonaceous chondrite water

- Must be very poorly mixed to account for the wide variation in abundances

Remote measurements of pyroclastic deposits from M³ suggest total water (OH + H₂O) is a few hundred ppm H₂O i (Milliken and Li, 2017).

Other water rich anomalies have been identified in small locations that may reflect the presence of water-bearing igneous rocks (Klima and Petro, 2017). Either location could contain molecular water as opposed to hydroxyl.

With SOFIA we can determine if volcanic features contain water and therefore determine the water as indigenous to the Moon

NEW METHOD TO DETECT WATER ON THE SUNLIT MOON

To definitively show the presence of water on the sunlit lunar surface a new method was developed

H₂O features a fundamental bending mode at 6 μm

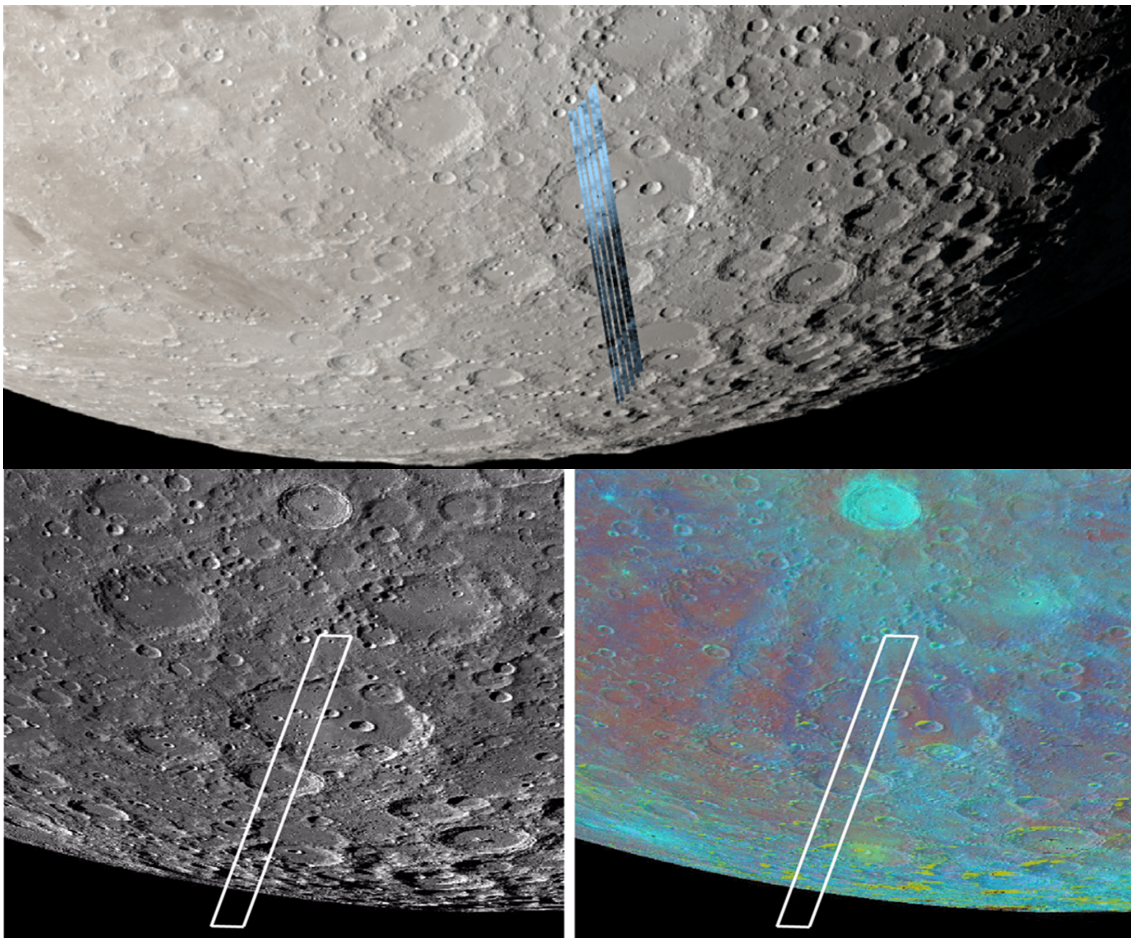
- New method to uniquely detect H₂O on the Moon
- No confusion with OH

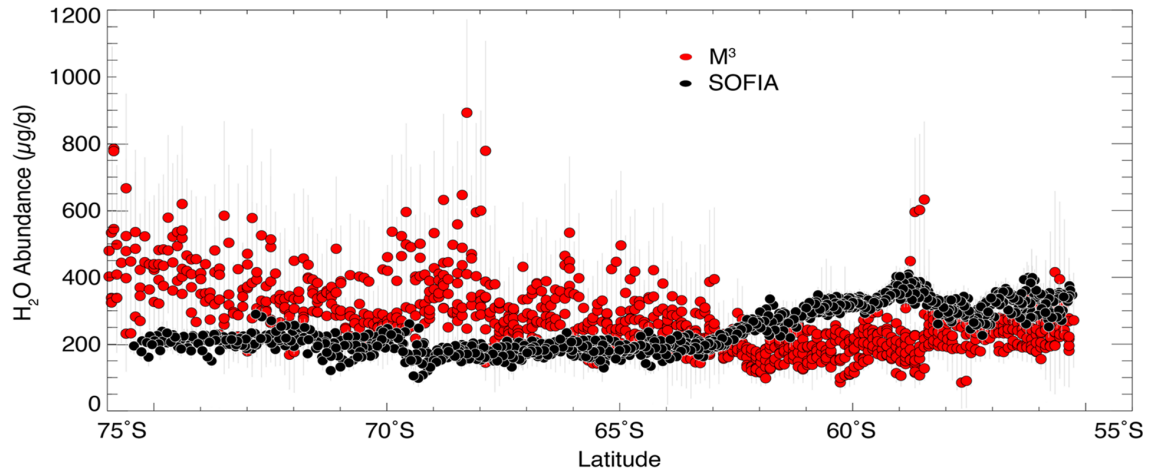
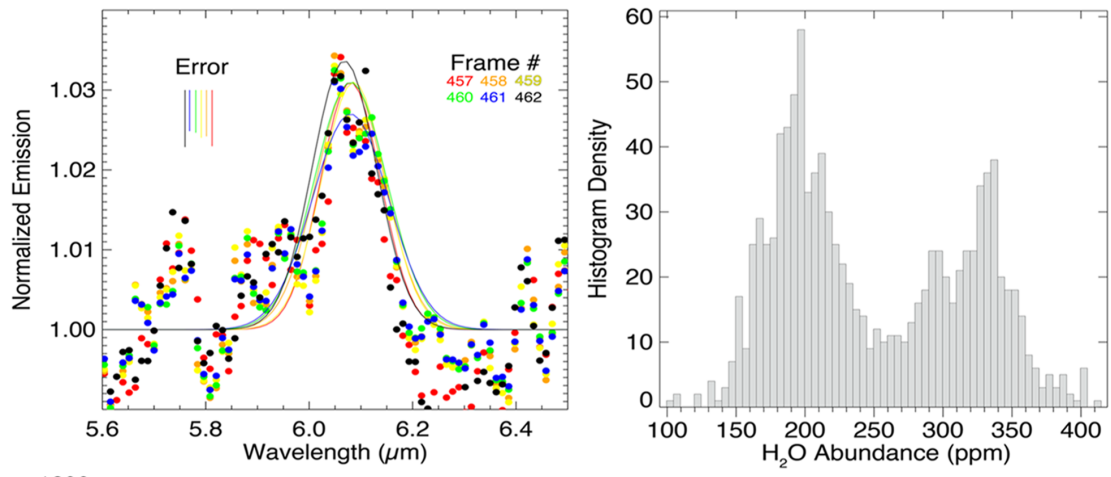
Difficulties of 6 μm observations

- Inaccessible from the ground
- Lacking in existing or planned lunar spacecraft

The unique capabilities provided by Stratospheric Observatory For Infrared Astronomy (SOFIA) allowed for the initial first detection of H₂O on the sunlit Moon

- Operational altitude of 45,000'
- Low telluric atmospheric water vapor





RARE MINERALS

In addition to sensitivity to water, the 5-8 μm region also contains spectral features sensitive to the silicate mineralogy of the Moon

The Christiansen feature (CF), a spectral phenomenon, is an emissivity maximum and the peak wavelength position is diagnostic of the silica polymerization of lunar minerals

Diviner on the LRO characterizes the CF using 3 broad spectral bands

- Glotch et al. (2010) identified highly silicic features pointing to sustained igneous processes
- However, Diviner is not capable of identifying what form of silica minerals are present

Higher spectral resolution and wavelengths below 7.8 μm are required to determine the specific type of mineral present

- SOFIA is uniquely capable of providing the observations needed to classify the specific silicic minerals

The silicic mineralogy and water content may be related

- Water and thorium have been associated with the silicic minerals (Haggerty et al., 2006)

An indicator of surface exposed lunar mantle is olivine

- Prominent spectral features in the 5-8 μm region
- SOFIA data can provide unique new data on the distribution of olivine

ABSTRACT

Through its unique instrument suite and operational altitude, the Stratospheric Observatory For Infrared Astronomy (SOFIA) has allowed for molecular water on the sunlit Moon to be detected for the first time. The discovery of water on the sunlit Moon is of high importance for planetary and lunar science. At this time SOFIA is the only observatory capable of detecting and mapping the 6 μm molecular water band on the lunar surface using the FORCAST instrument. Initial detections of water on the Moon with SOFIA were made at high southern latitudes in one region. Using FORCAST on SOFIA we are proposing a Legacy campaign to map water on the sunlit Moon. Maps of water across the Moon at multiple lunar times of day, latitudes, and over a range of compositions will allow us to fully characterize the behavior and processes of molecular water on the Moon. We will characterize the mobility of water and determine its correlation with solar wind intensity and other parameters that may indicate its formation mechanisms. Through SOFIA we will advance our understand of water formation, storage, and retention on the lunar surface and extend this to other airless bodies. Maps created through the Legacy program will inform scientists on the availability of molecular water as a resource and how to extract the water (based its residence location) and may be used for landing site selection during the Artemis program.

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