# Lunar Surface Hydration:

# A View from Earth

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# New Earth-based data sets to investigate lunar water

Part 1: Ground-based observations of lunar surface hydration

- NASA InfraRed Telescope Facility (IRTF) in Hawaii
- Address the reality of lunar hydration variations
- Enhanced hydration at central peaks

Part 2: Detection of molecular water on the sunlit Moon

- NASA/DLR Stratospheric Observatory For Infrared Astronomy (SOFIA) – airborne
- Search for $H_2O$ on the lunar surface


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# View from Apollo: a dry Moon

Apollo samples show a depletion in volatile elements – Including H

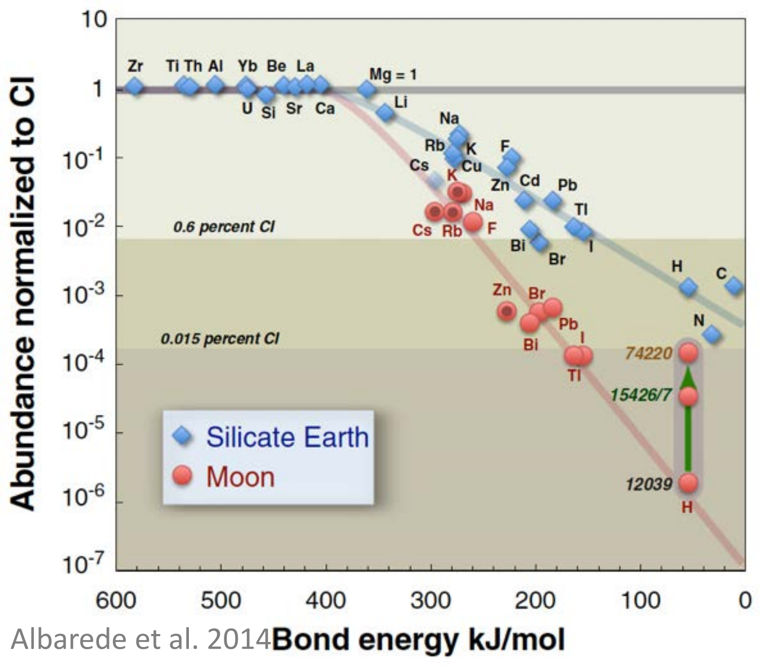
High water contents discovered in

- Lunar apatite [McCubbin et al., 2010]
- Pyroclastic glasses [Saal et al., 2008]
- Melt inclusions [Hauri et al., 2011]

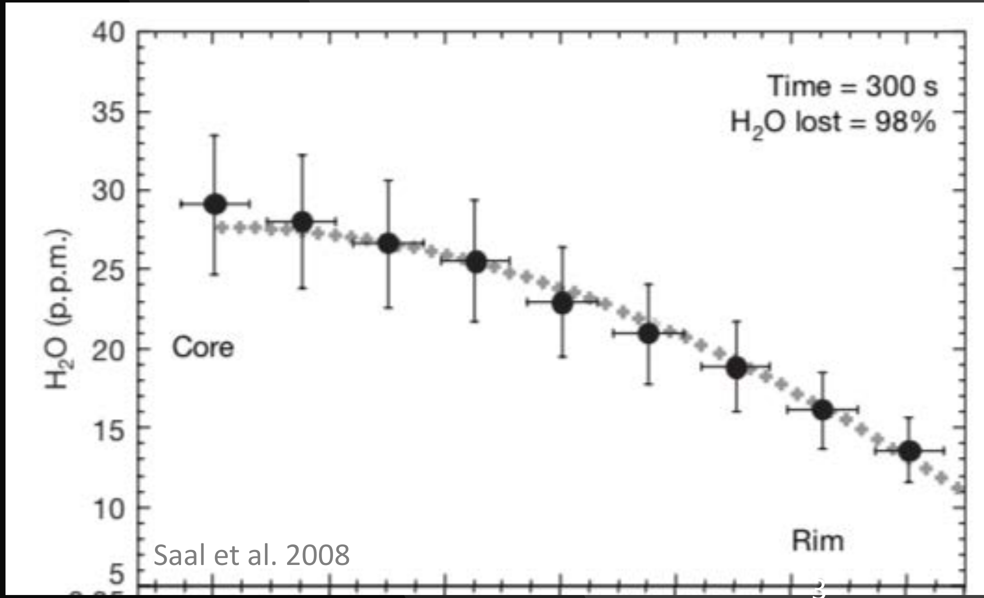
The lunar crust is largely composed of anorthosite

- 6 ppm $H_2O$ measured [Hui et al., 2013]
- Suggests a highly depleted lunar surface

Surface of the Moon is a blank slate for studying volatiles introduced after formation



Albarede et al. 2014



Saal et al. 2008

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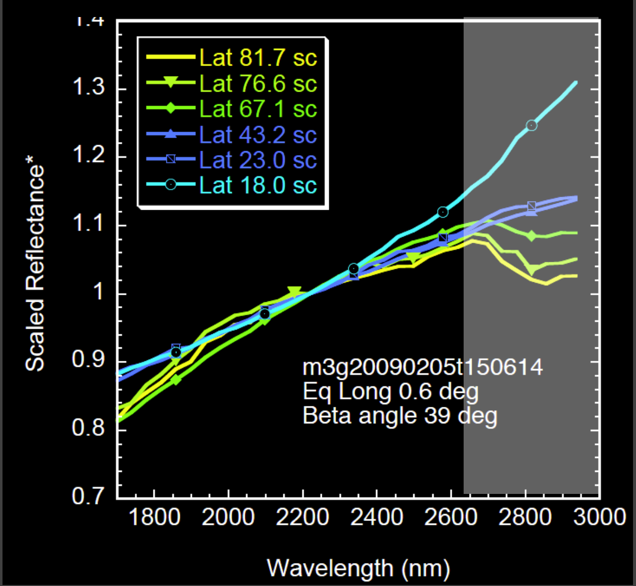
# Observations of lunar surface water

In 2009 spectrometers on 3 spacecraft detected a 3 µm absorption feature

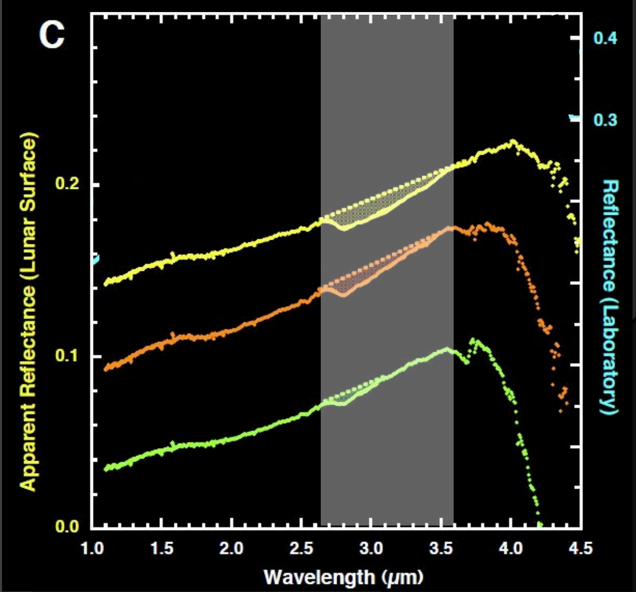
- Chandrayaan-1 – $M^3$ [Pieters et. al., 2009]
- Deep impact – HRI [Sunshine et. al., 2009]
- Cassini – VIMS [Clark, 2009]

Attributed to hydroxyl (OH) and/or molecular water ($H_2O$)

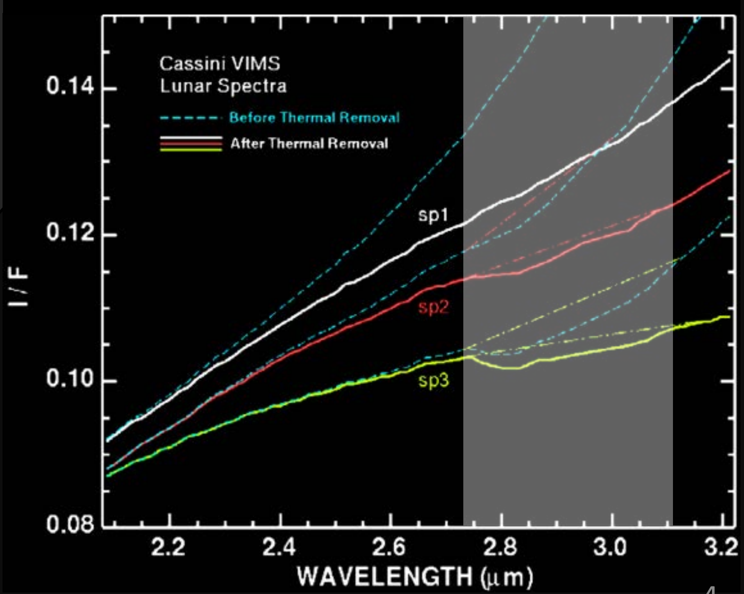
Chandrayaan-1 – $M^3$




Deep Impact – HRI




Cassini – VIMS

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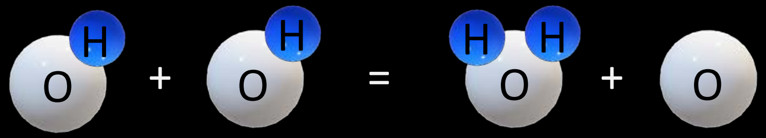
# Detection was unexpected

In 1966 experimental evidence emerged for proton-induced OH formation on lunar analog material [Zeller et al., 1966]

Later it was hypothesized that the formation of nanophase iron is caused by solar wind hydrogen producing $H_2O$ [Housley et al., 1974]

Recombinative desorption can convert OH to $H_2O$

- laboratory experiments suggest this conversion is inefficient due to relatively low temperatures [Jones et a. 2018]




Micrometeorite impact provides extremely high temperatures

- can cause efficient recombinative desorption
- may account for the spikes in water detected in the exosphere by LADEE during meteor streams [Benna *et al.* 2019]

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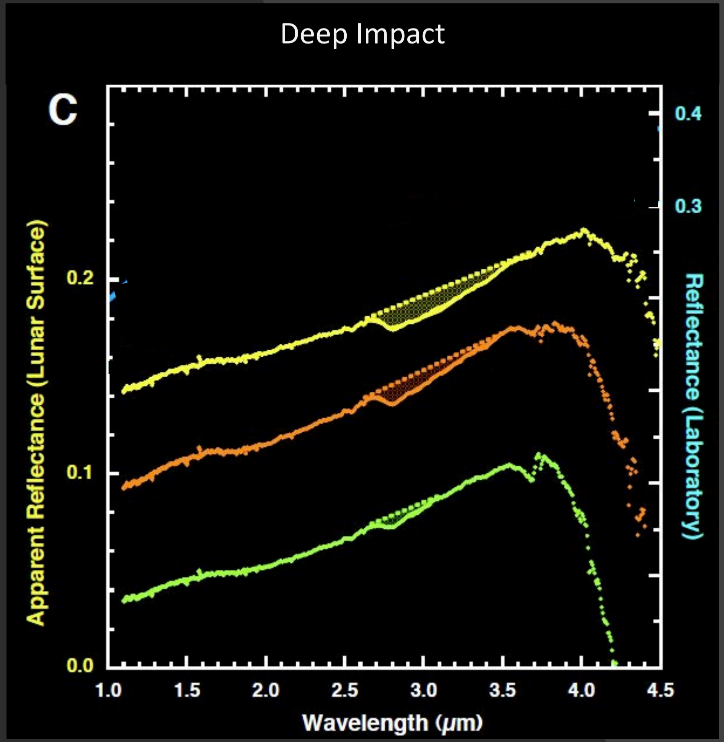
# Variations in the abundance of water

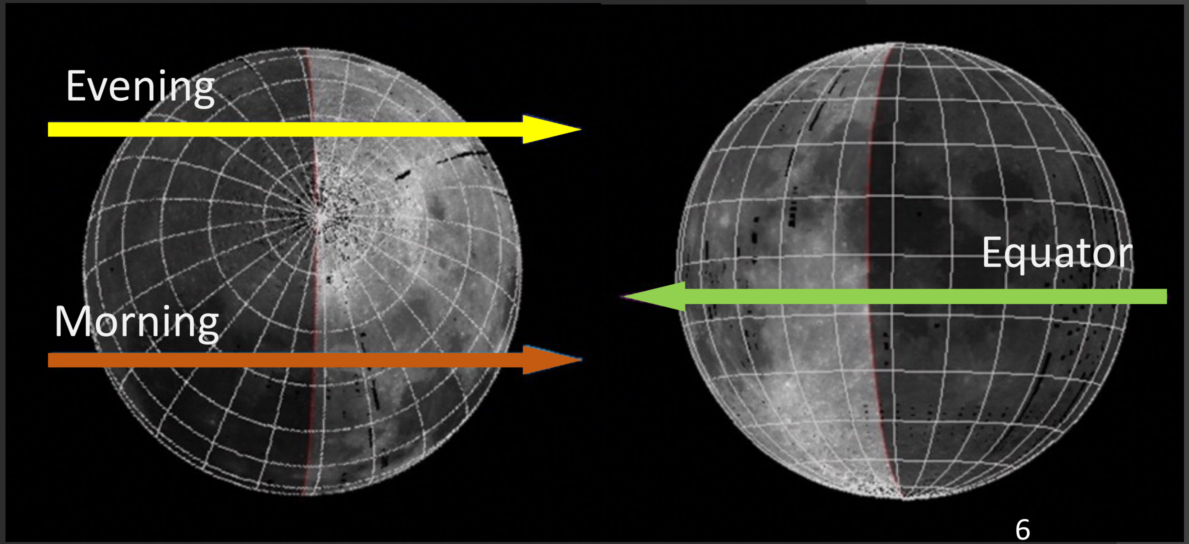
Spacecraft reflectance data show variations in band depth with lunar time of day

Could be caused by migration of:

- $H_2O$ [Sunshine et al., 2009 ]
- H temporarily binding with O to form OH [Tucker et al., 2017, Farrell et al., 2017, Starukhina 2006]

Band depth, however, is not always abundance

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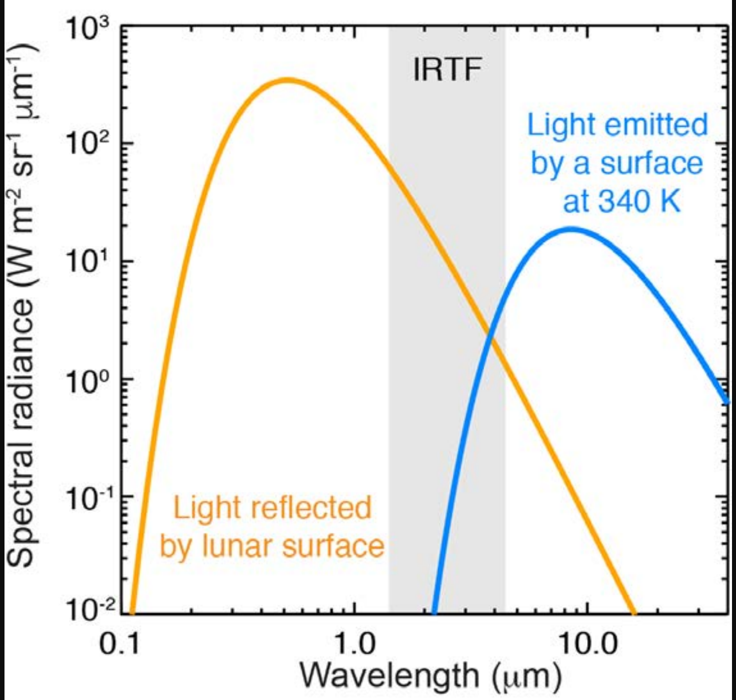


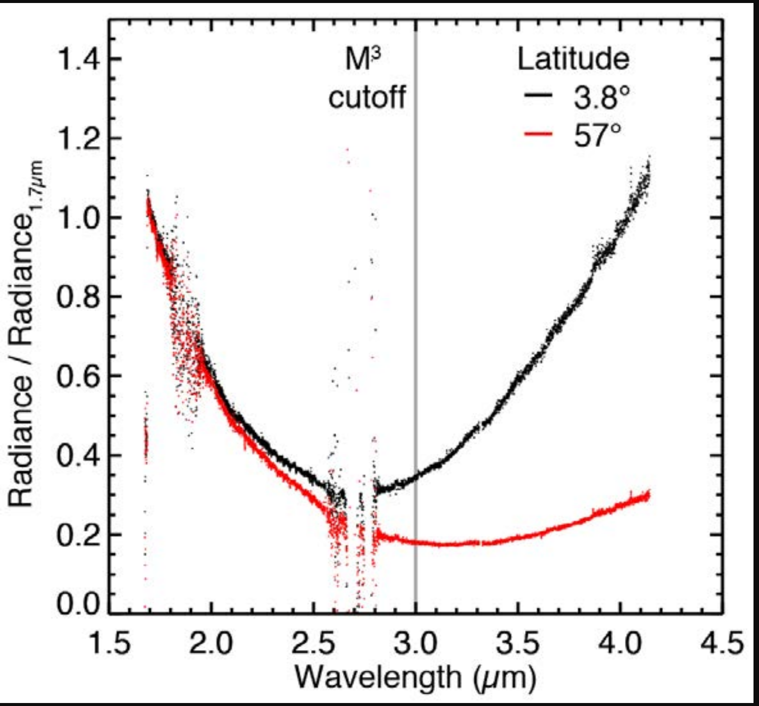


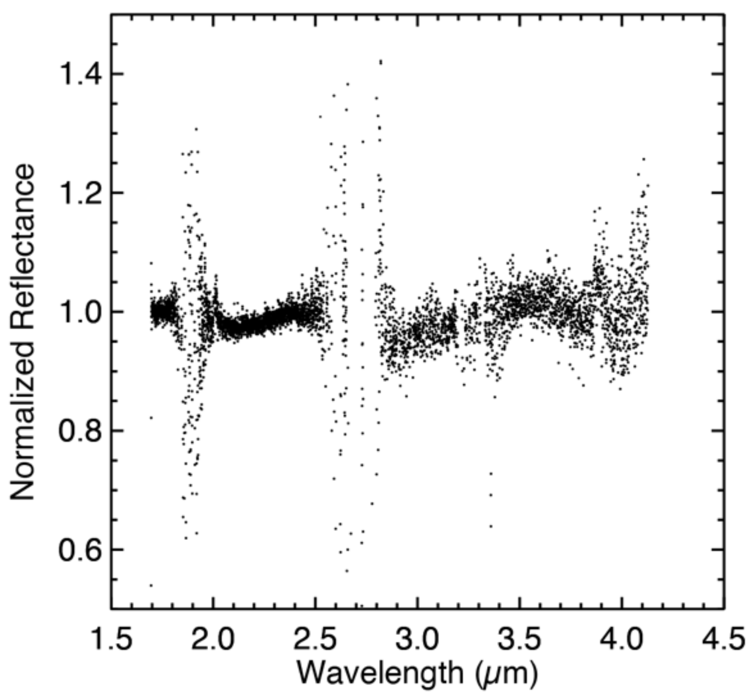


# Controversial thermal removal

3 μm region effected by the mixture of reflected and emitted light

Thermal component must be modeled and removed

- Thermal emission turns on around 2 microns
- Longer wavelengths heavily effected

Variations may not be due to migration but instead to thermal infill



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# Variation or No Variation?

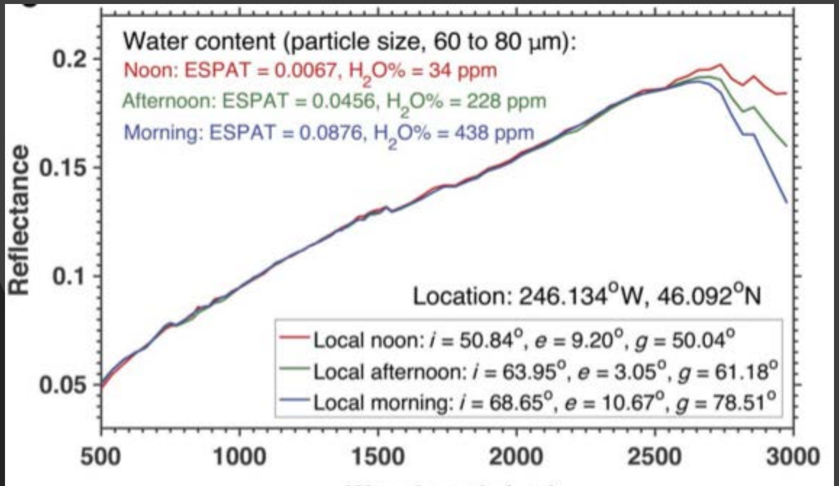
3 independent studies investigate diurnal variation in M[3] data - each coming to a different conclusion

1. Li and Milliken 2017: strong variations at low latitude, asymmetric between morning and evening, little variation at high latitude

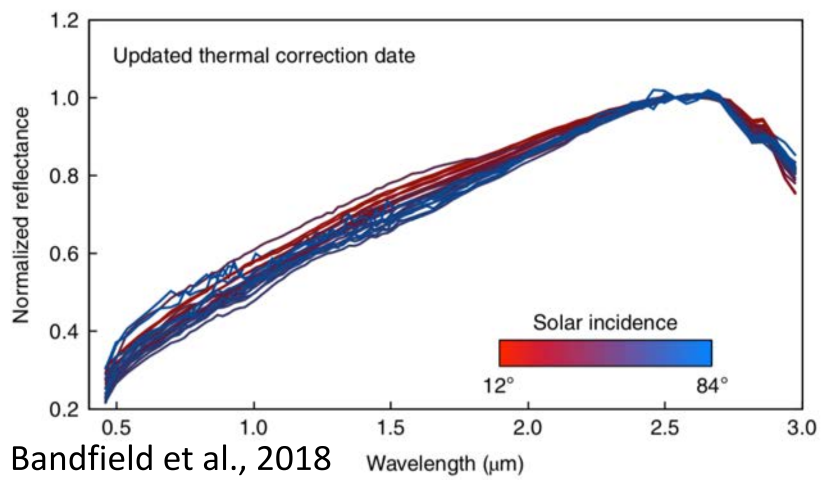
2. Wolher et al., 2017 and Grumpe et al., 2019: no variation below ~30°, strong symmetric variation above ~30°

3. Bandfield et al., 2018: no variation with time of day, temperature, or latitude, 3 µm band is always present

All use similar physics but subtly different assumptions regarding the photometric and subpixel temperature behavior




Li and Milliken 2017




Bandfield et al., 2018

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# Spacecraft data limitations

Thermal corrections with M³ data are ambiguous

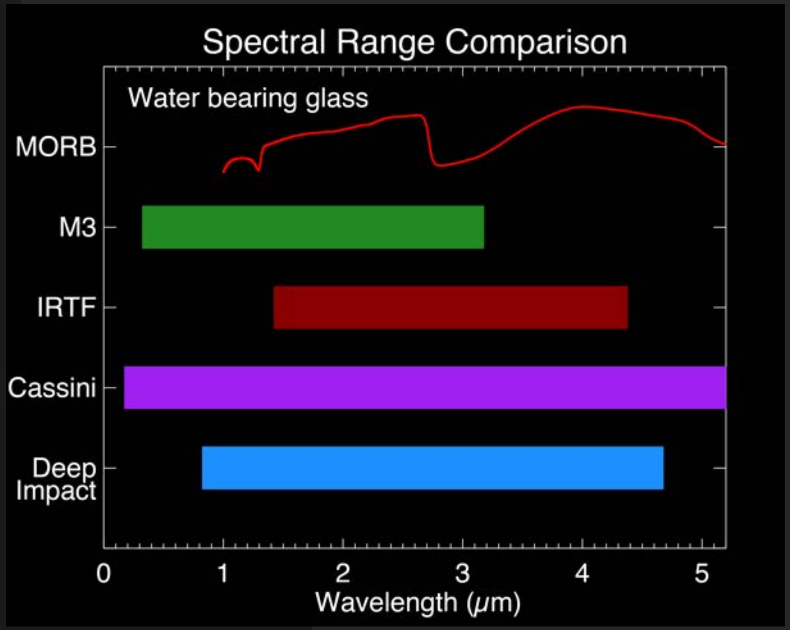
- 3 µm signal is both reflected and thermal emission
- thermal dominates at longer wavelengths

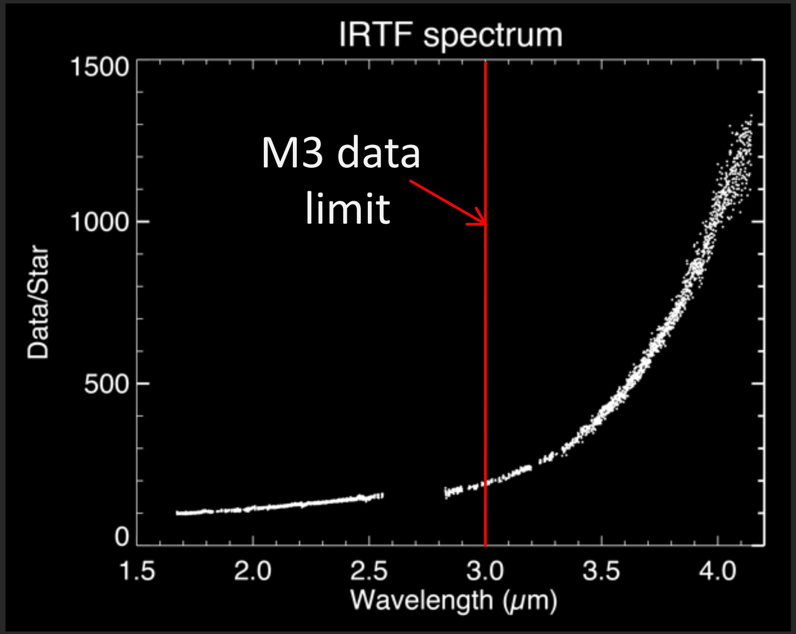
Accurate removal of thermal emission requires longer wavelengths beyond 3 µm

M³ is limited in spectral range

- ends at 3 µm, the center of the OH band

Cassini and Deep Impact have low spatial resolutions and limited lunar time of day coverage

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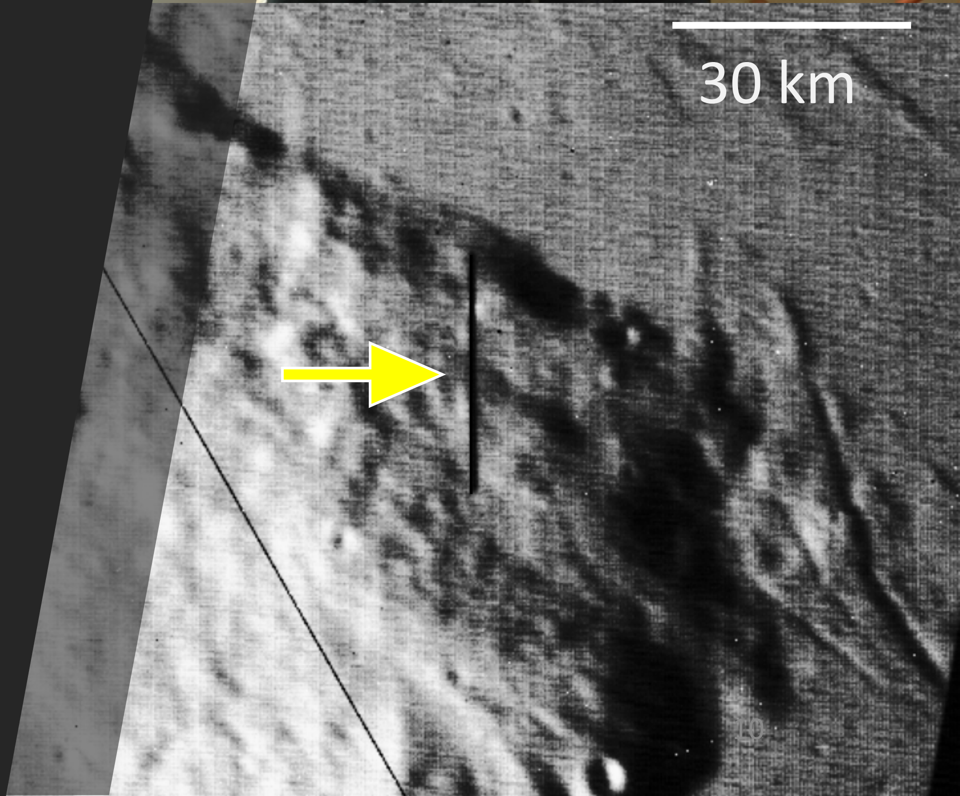
# New ground-based data for diurnal investigation

SPEX on the NASA InfraRed Telescope Facility (IRTF) on Mauna Kea

- High resolution cross dispersed spectrograph
- Access to the entire lunar nearside
- Access to all lunar times of day
- High spatial resolution of 1-2 km
- Covers 1.6 – 4.2 microns

The IRTF provides strong constraints on thermal emission and can address the reality of diurnal variation

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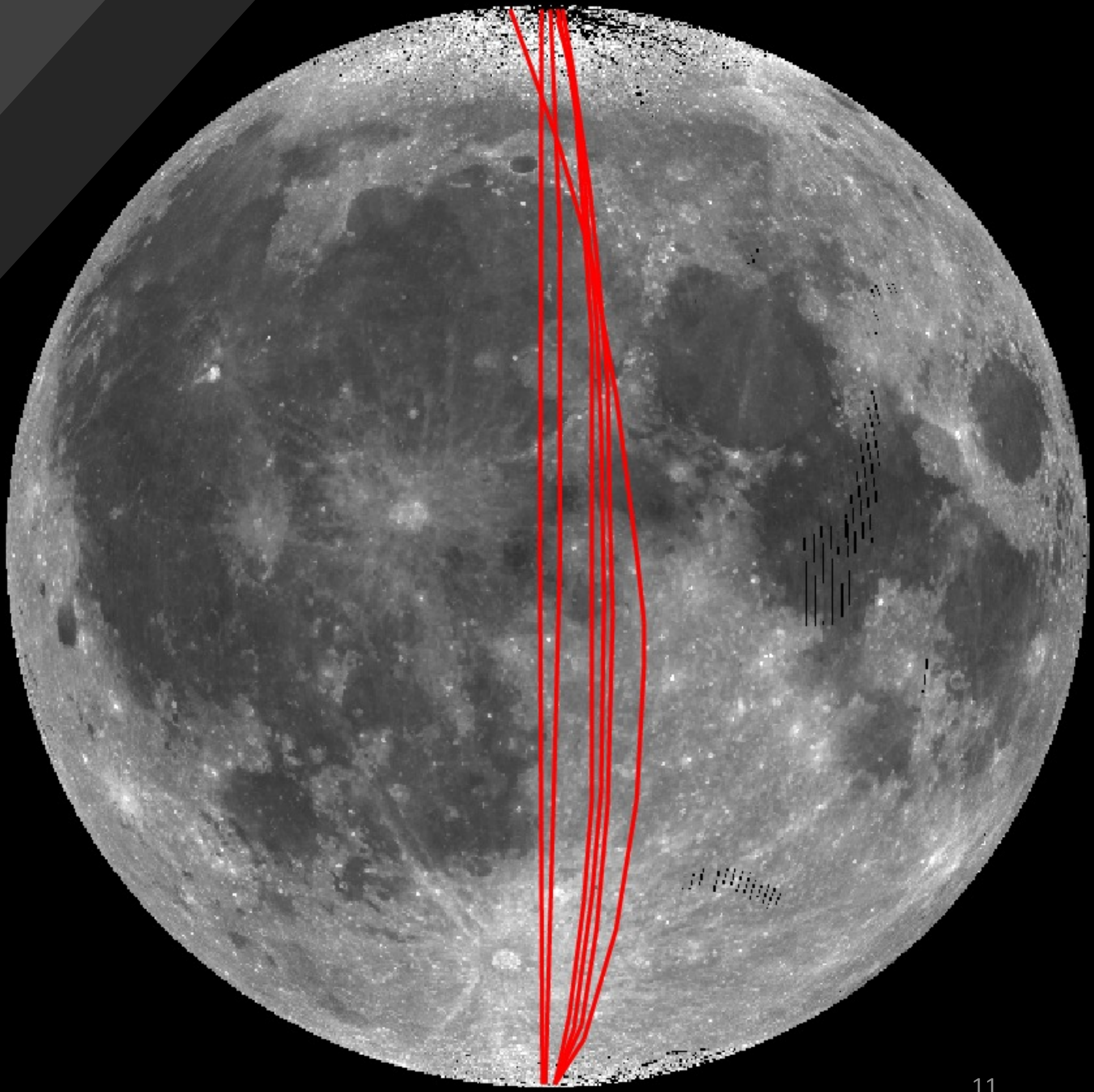
# Data collected with the IRTF

6 pole-to-pole chord profiles

Times of day covered
- 6 am to 12 pm
- 6 pm

Afternoon times
Coming soon



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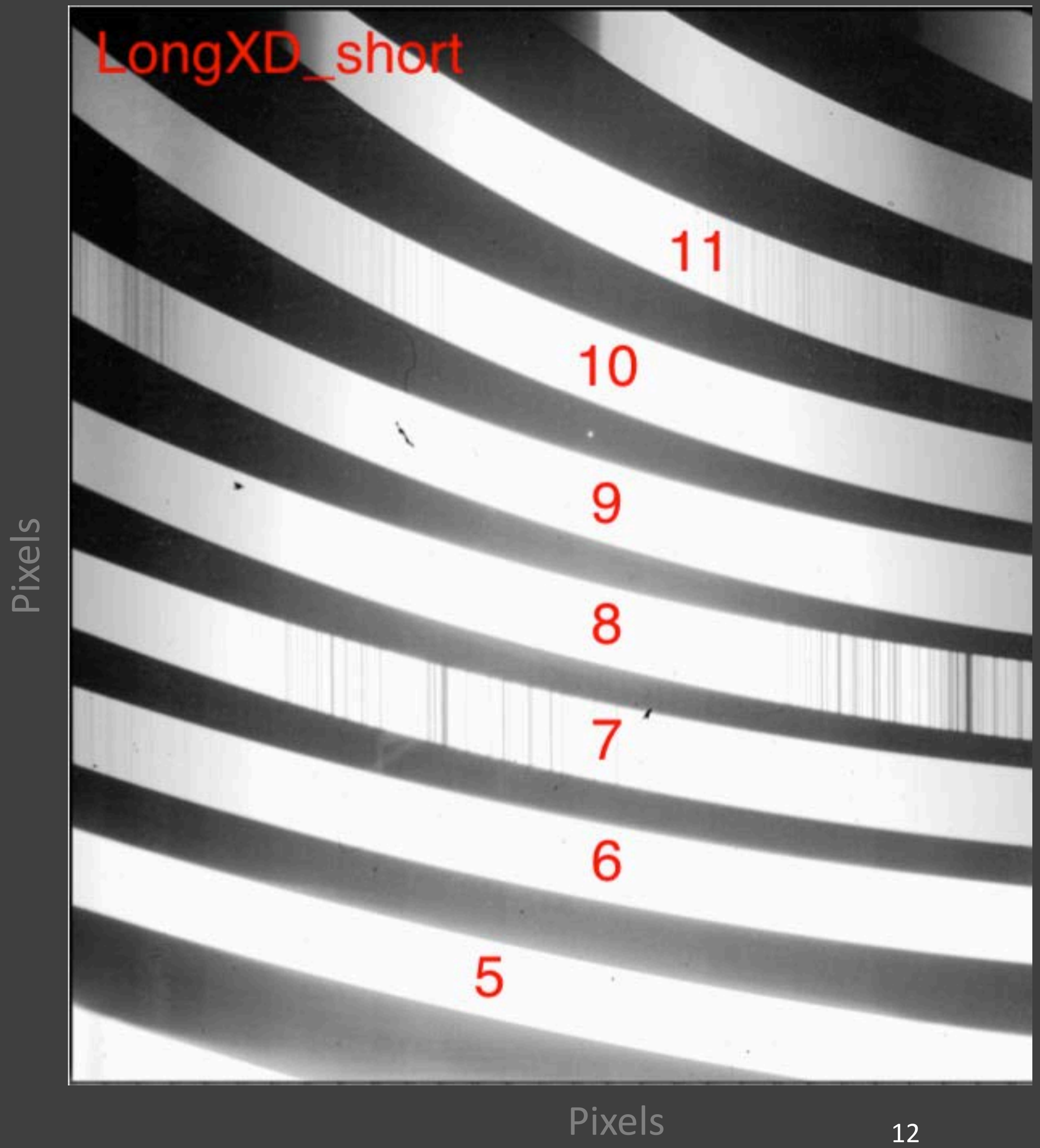
# Data calibration

Spextool: Spectral extraction tool

- IDL-based data reduction package written by Cushing, et al 2014 to reduce data obtained with Spex on the IRTF

1. normalized flat field images and wavelength calibration files
2. Non-linearity correction
3. Extract apertures positions
4. Background subtraction
5. Extract spectra and wavelength calibrate

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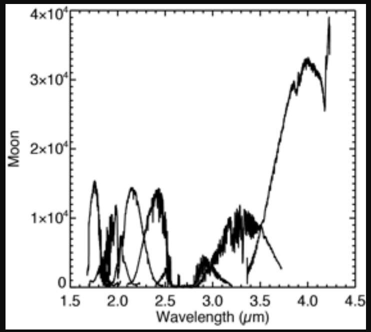
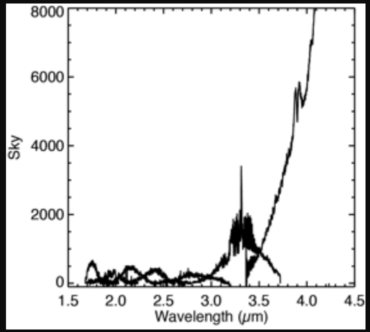
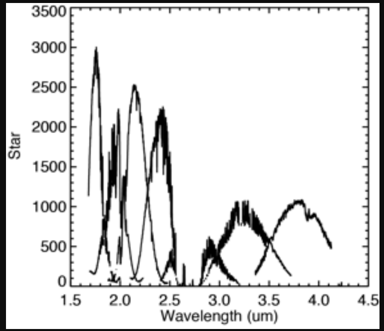
# Sky emission and atmospheric removal

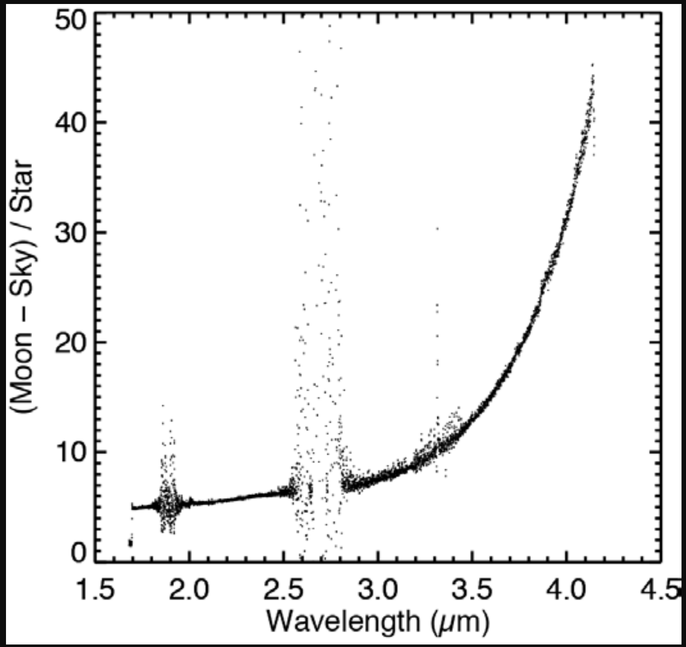
Observe clean sky just off the Moon and subtract from the lunar spectra to remove background emissions

Observe a solar analog star (similar spectral properties as the Sun) and divide out of Moon minus sky data to correct atmospheric absorptions

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# Thermal removal

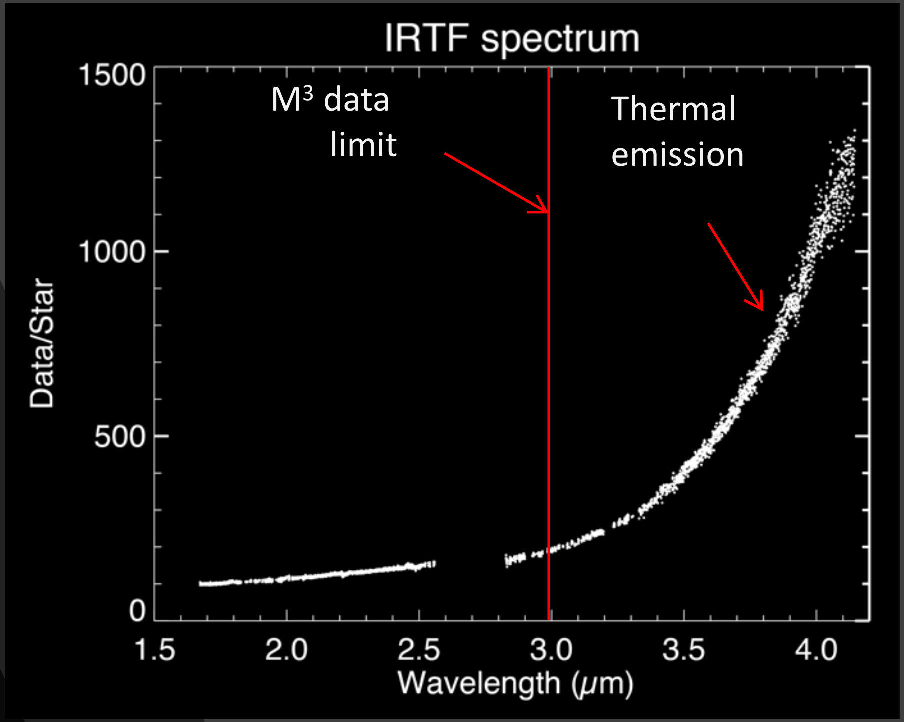
Lunar spectra longword of 2.5 µm are affected by thermal emission

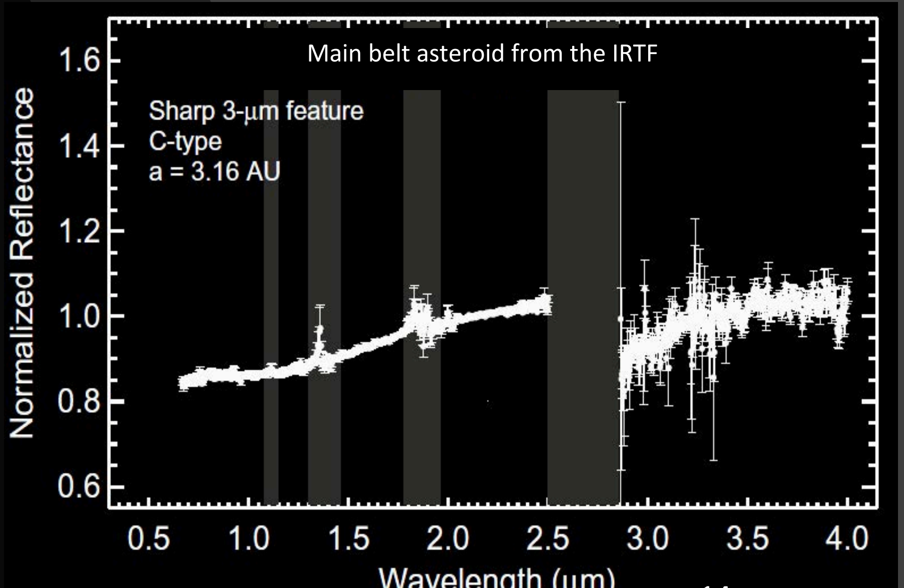
Accurate removal of thermal radiation is vital for proper investigation of the 3 µm band and its spectral properties

Following the methodology used for asteroid thermal radiation removal defined by Takir and Emery, 2012 and Rivkin et al., 2005

- Calculate the amount of thermal emission measured in data
- Model the thermal emission
- Remove thermal component from spectrum

Presence of total water (OH + $H_2O$) is indicated by a step down from 2.5 to 2.9 µm



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# Continuum and thermal excess

Lunar surfaces are affected by space weathering

- causes spectra to have a red slope

Thermal modeling requires removal of the continuum

Thermal excess ($\gamma$) is the measurement of thermal flux found at all wavelengths

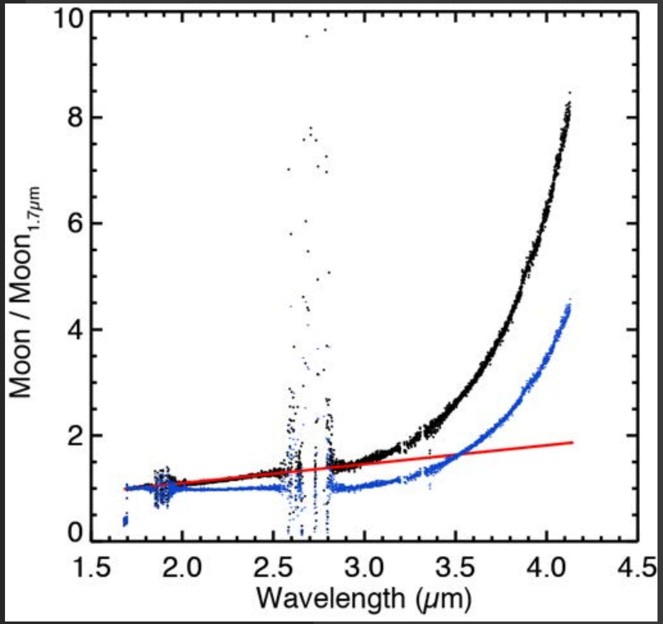
$$\gamma = \frac{R_\lambda + T_\lambda}{R_\lambda} - 1$$

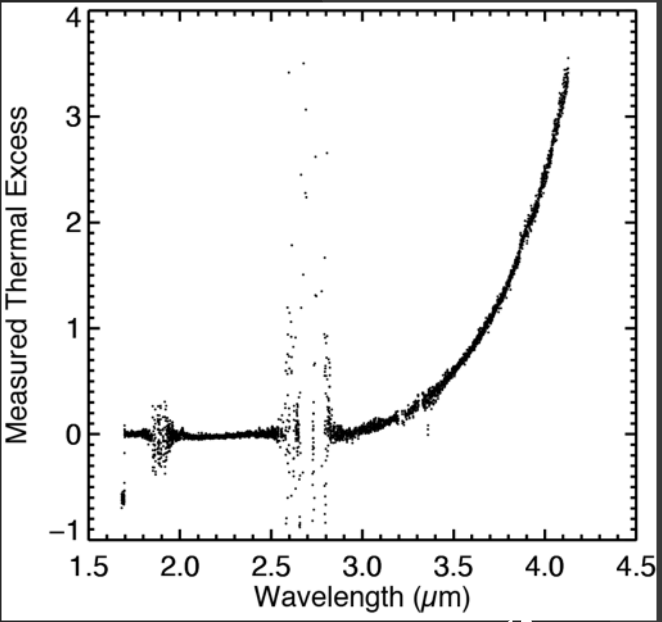
$R_\lambda$ - reflectance

$T_\lambda$ - thermal emission

For us

$$\gamma = \frac{Moon}{Continuum} - 1$$

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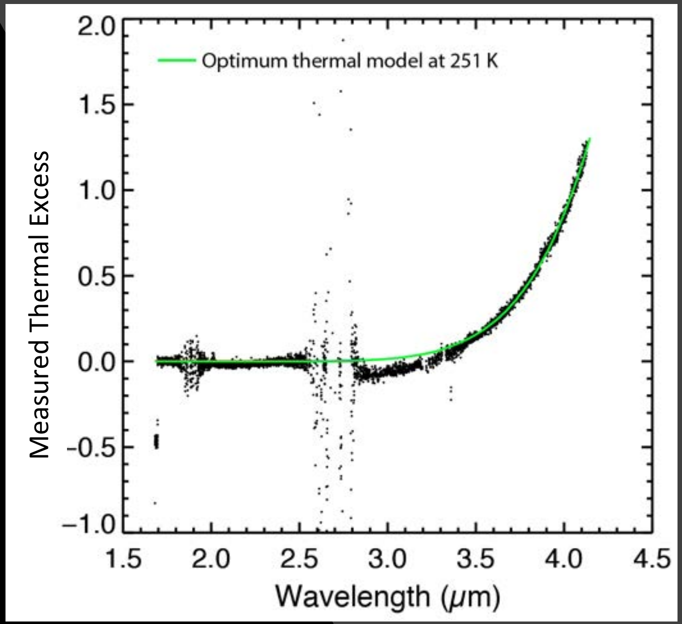
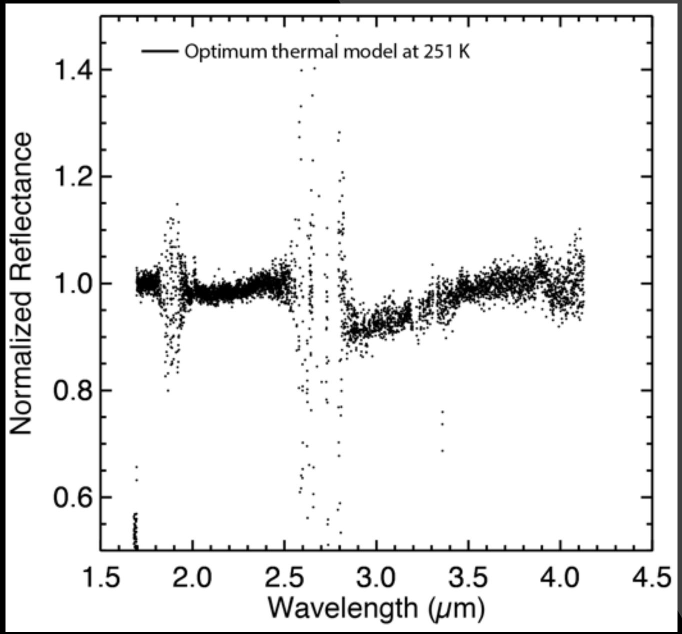
# Modeling thermal excess




Lunar thermal emission is not a simple blackbody

- Multiple temperatures within the field of view caused by a rough surface

Use a rough surface thermal model to model the thermal excess [Bandfield et al., 2011]

$$\gamma_{model} = \frac{R_{MI} * L_{\odot} + T_{bb}}{R_{MI} * L_{\odot}} - 1$$

$R_{MI}$ - Multispectral Imager reflectance

$L_{\odot}$ - Solar radiance

$T_{bb}$ - Rough surface blackbody

Choose the best model that fits the longer wavelengths

- removed from the lunar spectrum to produce a purely reflectance spectrum

Incorrect models over or under correct the longer wavelengths



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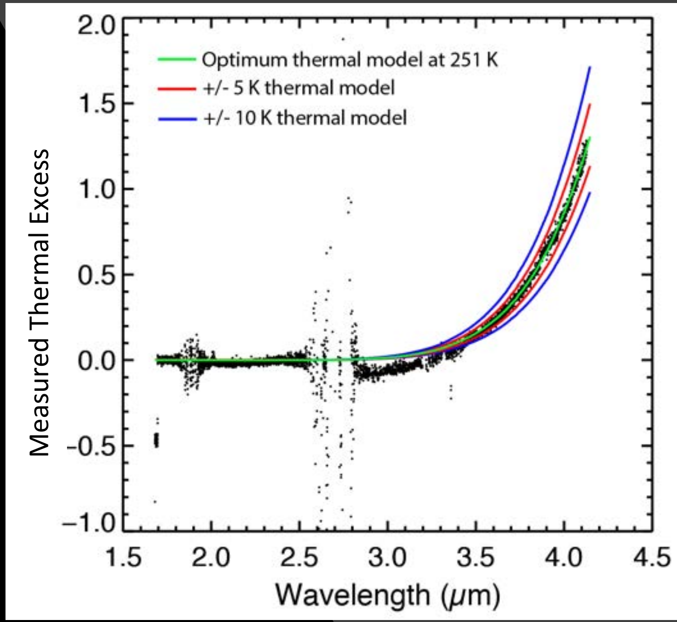
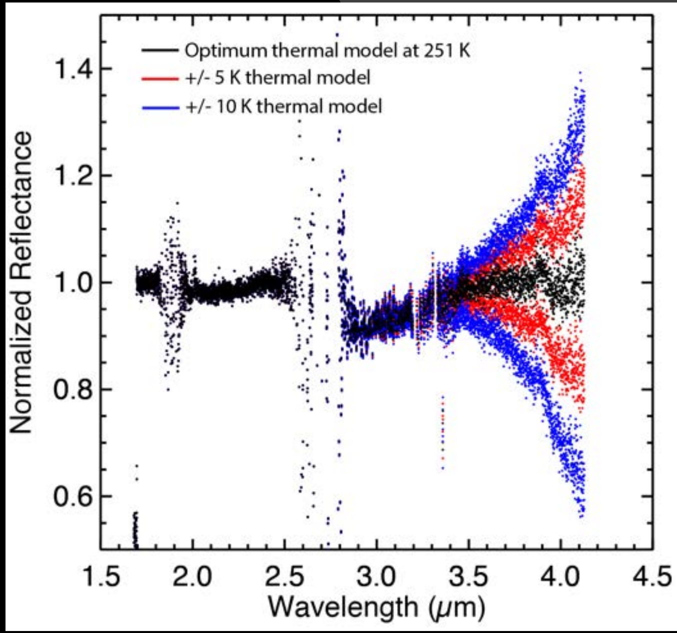
# Modeling thermal excess

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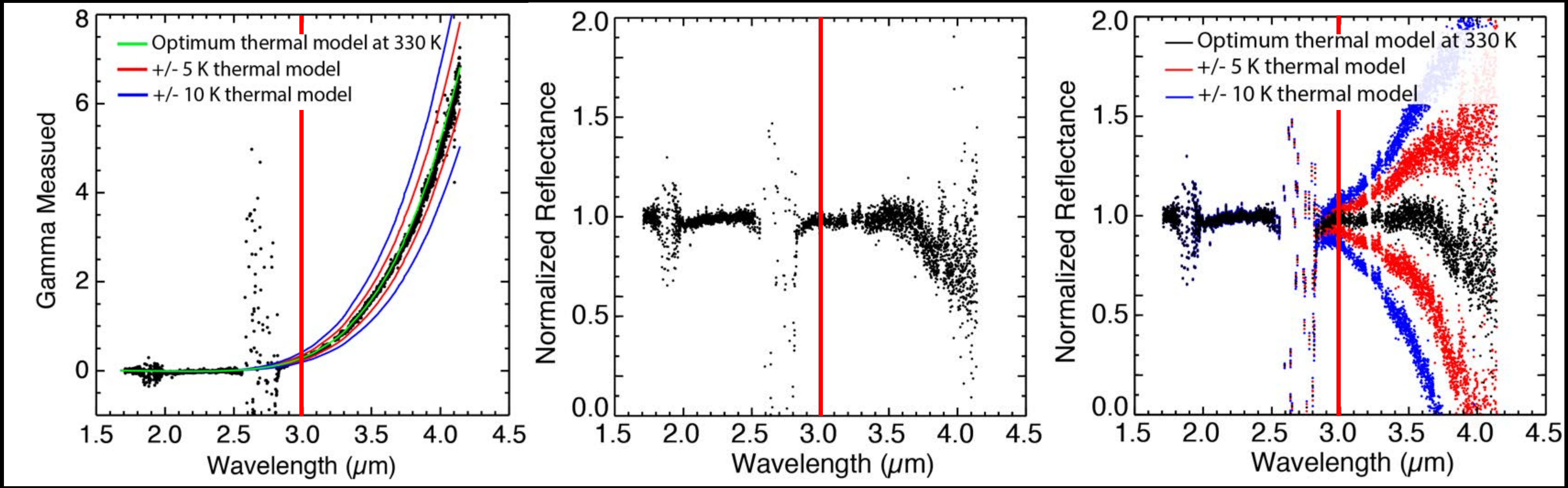
# High temperature example

High temperature sites have much stronger thermal emissions

$M^3$ runs into issues here

- Cannot constrain thermal models and they all look similar at 2.5 to 3 µm

Removal of the wrong model can create or remove a 3 µm band

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# Abundance calculations

After thermal removal, the spectra are in reflectance and can be used to estimate abundance of total water (OH + $H_2O$)

Convert reflectance to single scattering albedo $(w)$ [Hapke, 2001]

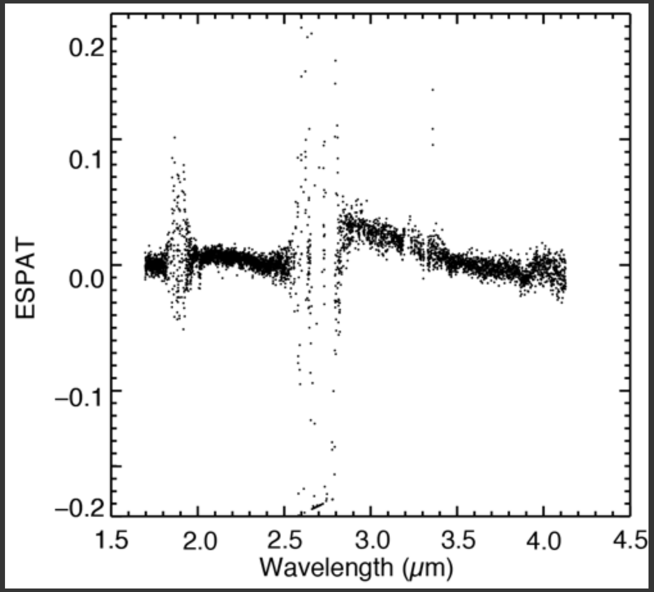
Calculate ESPAT

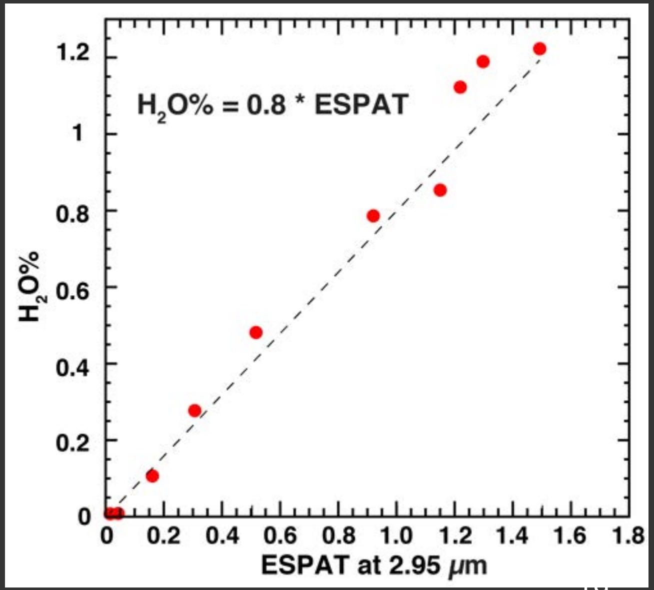
- Effective Single Particle Absorption Thickness: a parameter proportional to water abundance [Li, 2017]

$$ESPAT = \frac{1-w}{w}$$

Calculate abundance

$$H_2O_{ppm} = 0.8 * \text{ESPAT} * 10000$$

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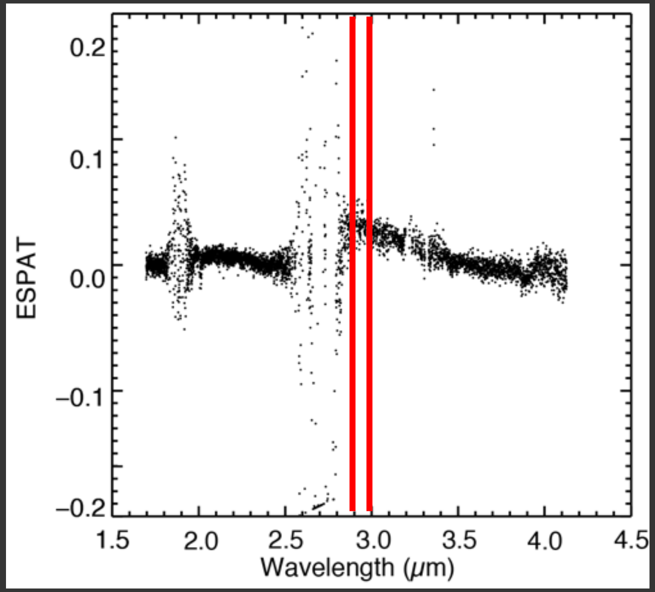


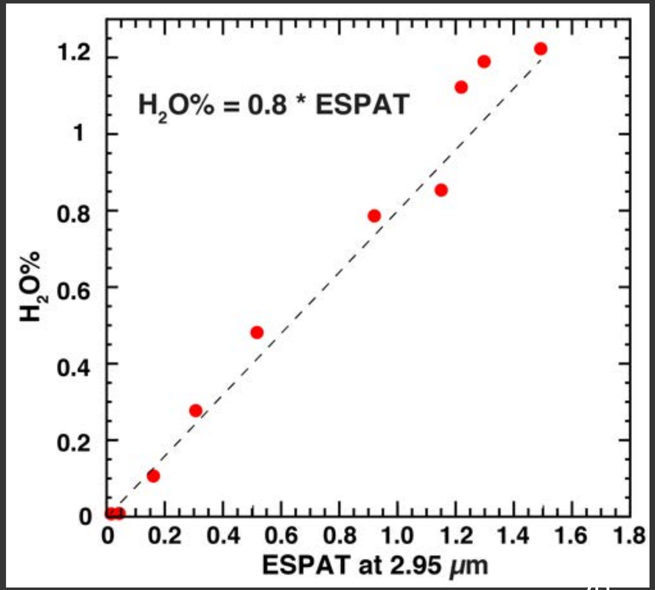


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# Sensitivity of abundance to thermal model errors

<u>Low temperature example</u>

Thermal model selection has ~ 3 ppm error

Calculated abundances

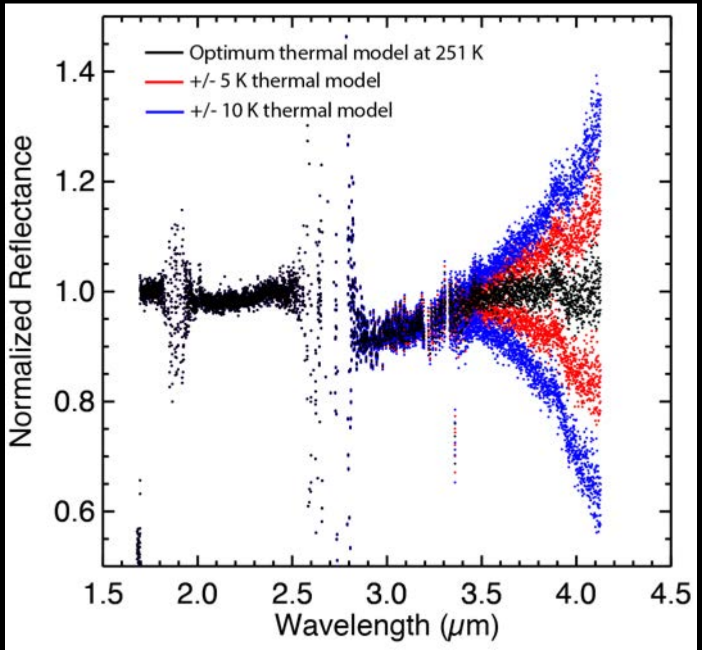
- Optimum – 179 ppm +/- 3
- +/- 5 K error – 56 ppm
- +/- 10 K error – 116 ppm

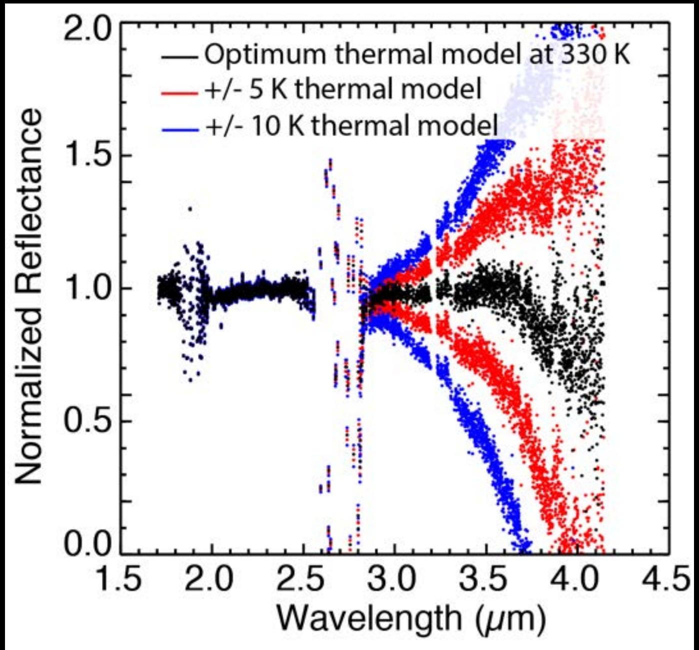
<u>High temperature example</u>

Thermal model selection has < 6 ppm error

Calculated abundances

- Optimum – 103 ppm +/- 4
- +/- 5 K error – 175 ppm
- +/- 10 K error – 364 ppm

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# Observed variations in the 3 µm band

Strong variations in total water (OH + $H_2O$) along each chord

- Increasing abundances with increasing latitude

Maximum abundances ~500 ppm

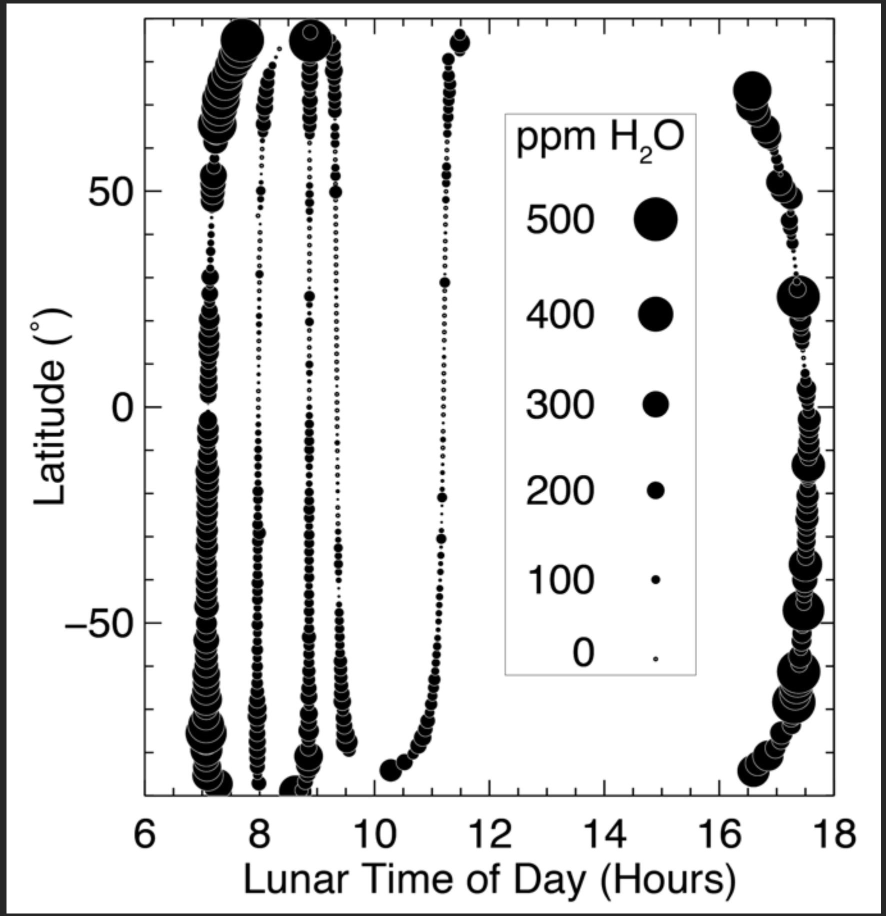
- occurs at high latitudes
- consistent with abundances observed by $M^3$ [Li and Milliken 2017]

Minimum abundances around 0 ppm

- occurs at mid-northern latitudes

Time of day (TOD) variations seen across constant latitude

- decreasing abundance with increasing TOD

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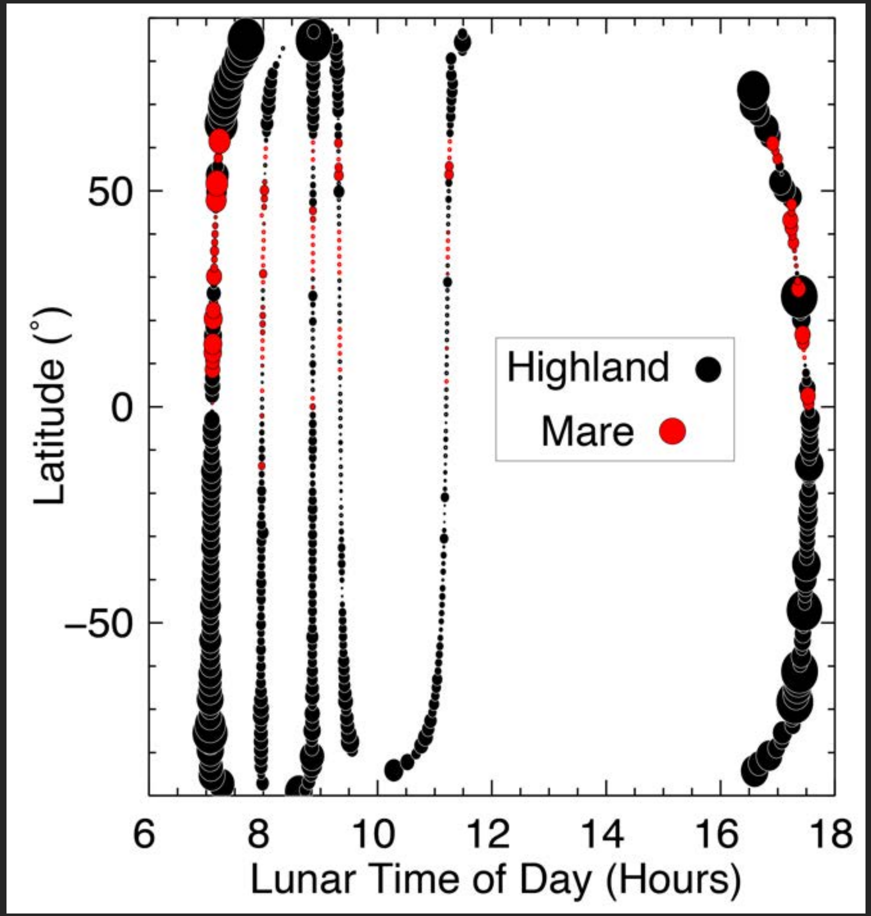


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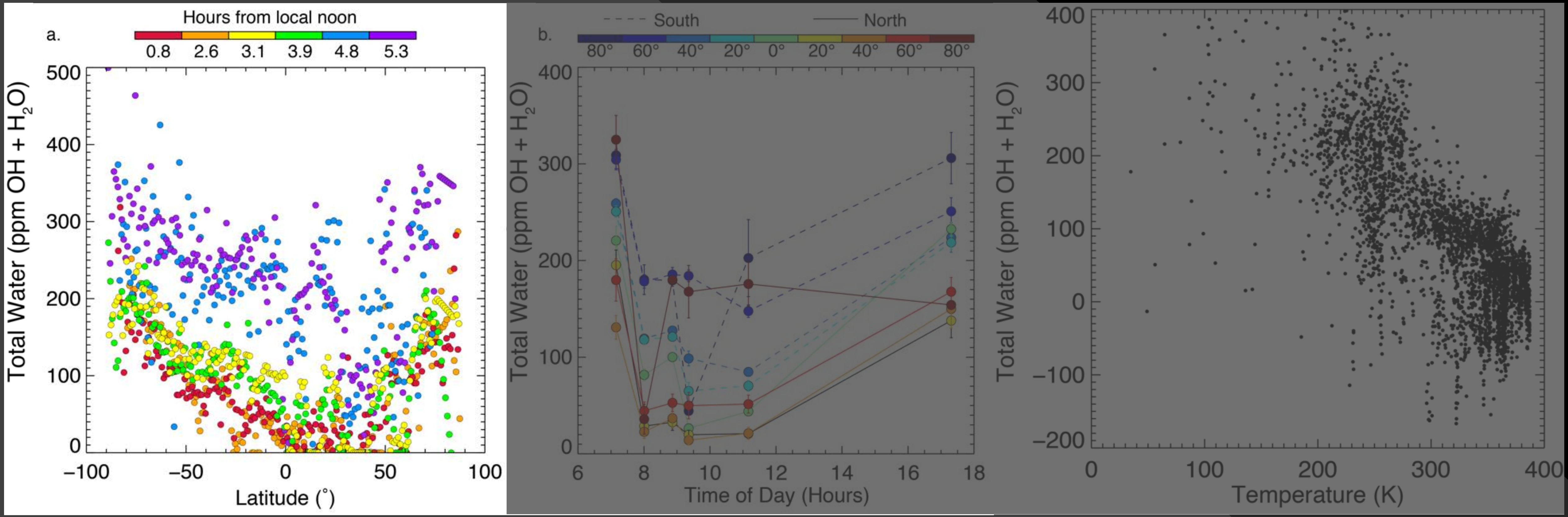


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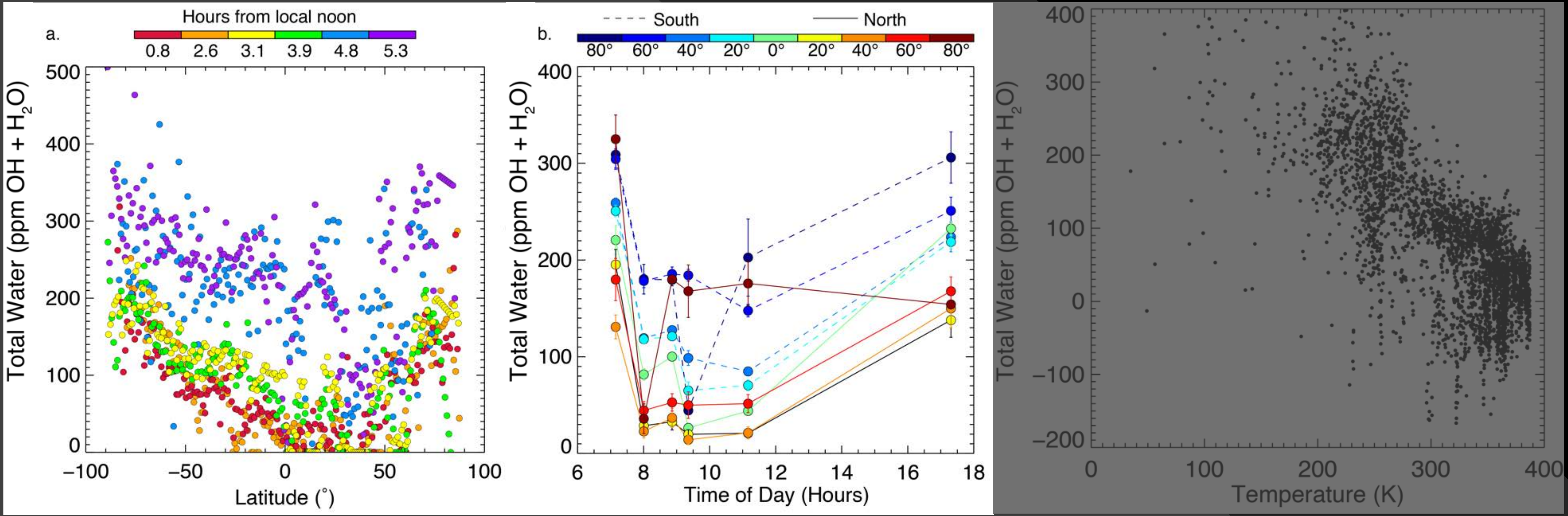


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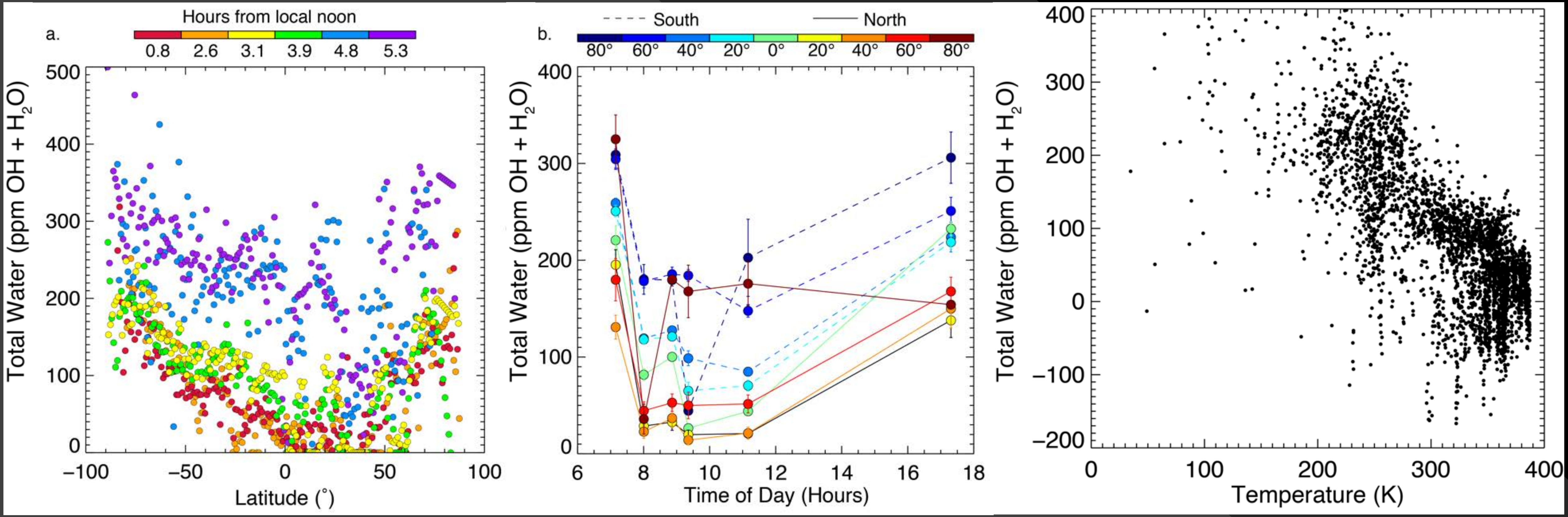


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# Indigenous Lunar Hydration

3 µm hydroxyl signatures

- Pyroclastic deposits
- Silicic domes
- Central peaks of some craters

Lunar samples

- Pyroclastic glass
- Melt inclusions

Hydration assumed to be derived from interior as there is a direct geologic association

These observations suggest a heterogenous distribution of hydration in the lunar interior

# Bullialdus Central Peak Hydration

$M^3$ shows enhanced 3 µm hydration that is not consistent with purely surficial origins [Li and Milliken, 2017; Klima et al.,2013]

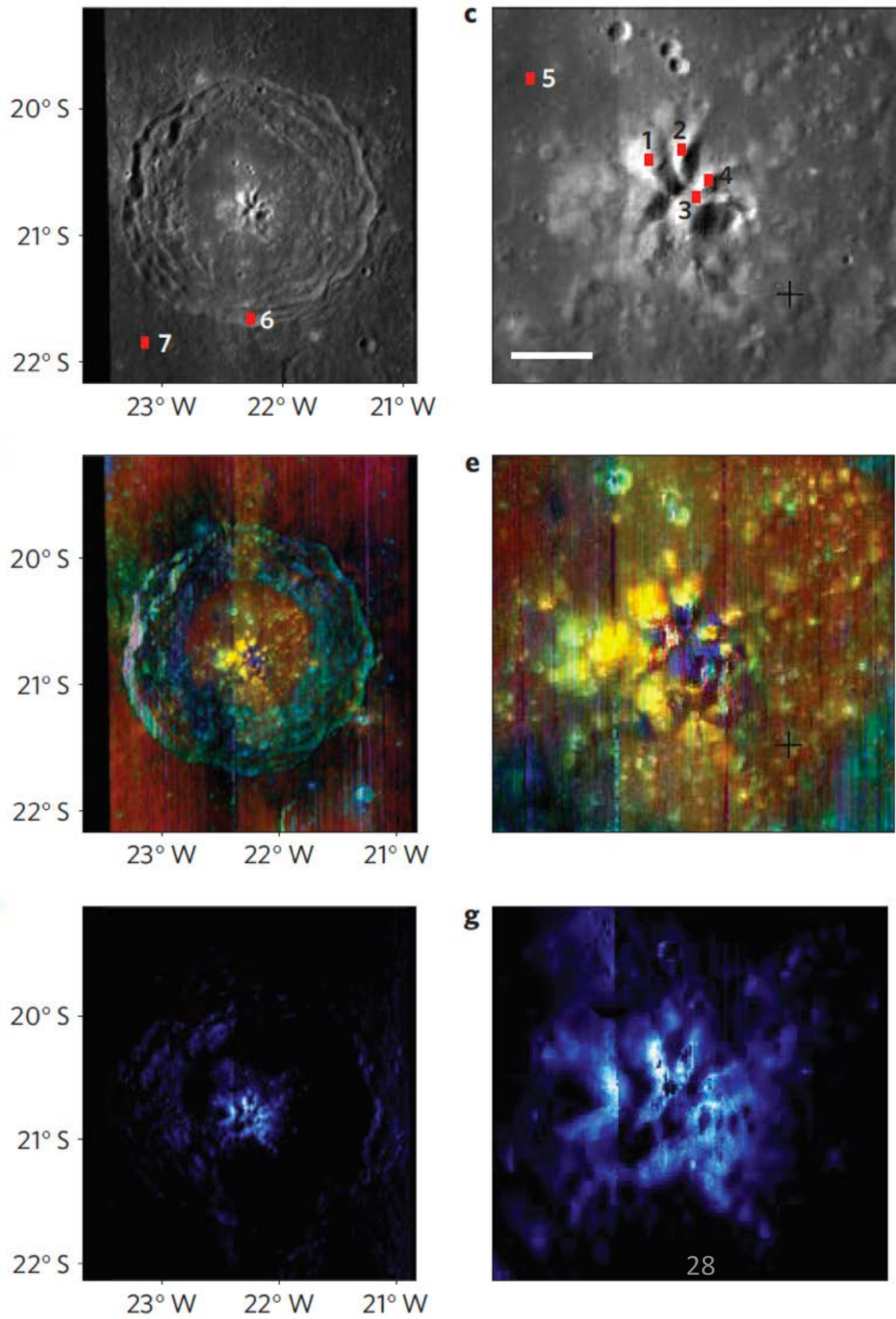
- Likely a magmatic source that was excavated during impact
- Coincides with localized concentrations of thorium and norite

80 ppm total water (OH + $H_2O$) estimated using the original thermal removal procedures for $M^3$ [Klima et al.,2013]

- 250 ppm total water (OH + $H_2O$) using a new thermal removal correction [Li and Milliken, 2017]

The central peak is only part of the crater interior showing hydration

- May not have undergone intense degassing [Young et al., 2016]
- Potentially preserves the internal abundance of hydration

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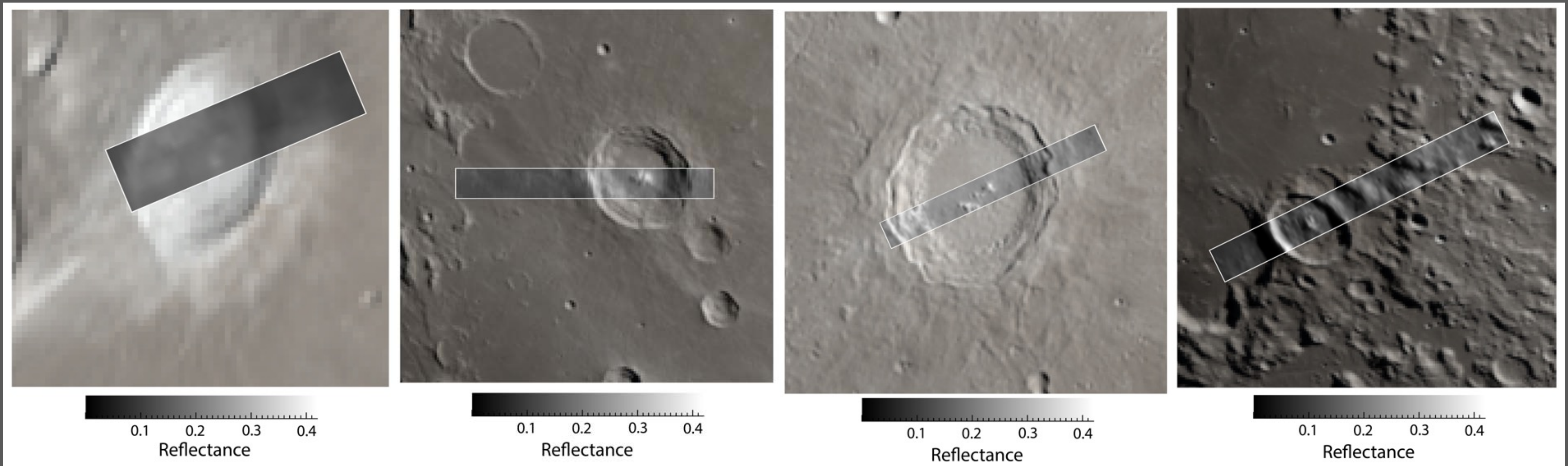
# Observed Craters Reflectance

Aristarchus | Bullialdus | Copernicus | Vitello

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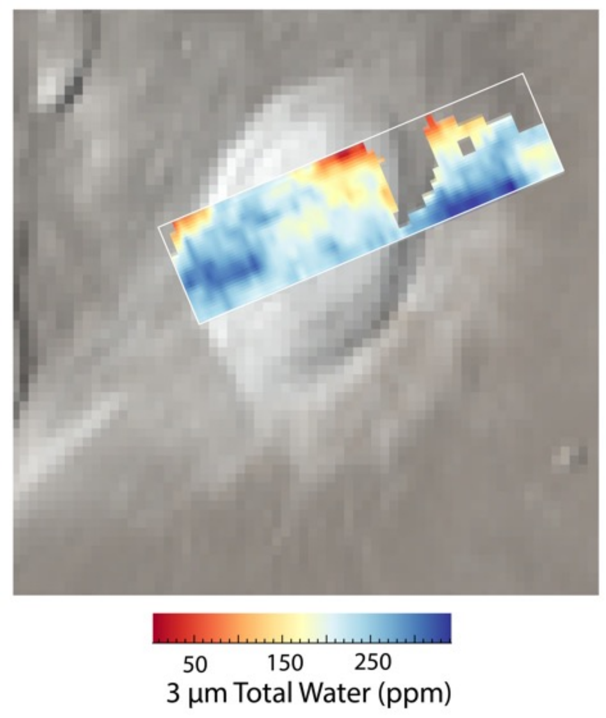
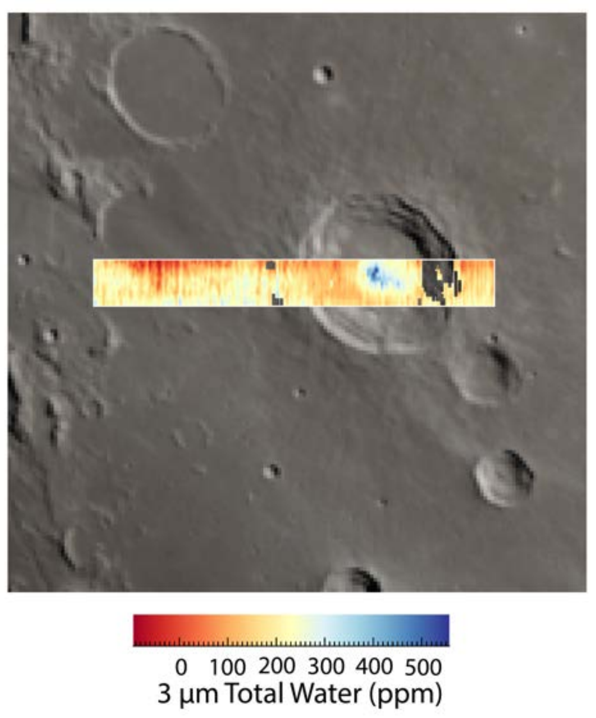
# Total Water: Individual Stretch

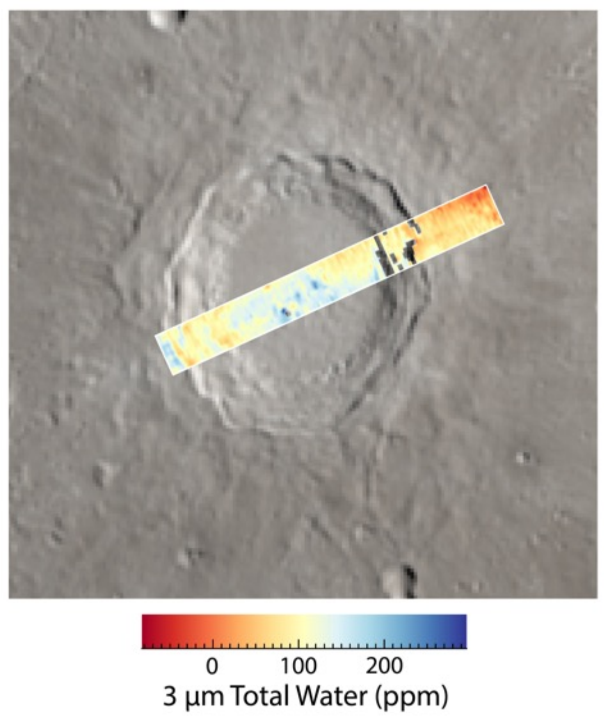
Aristarchus



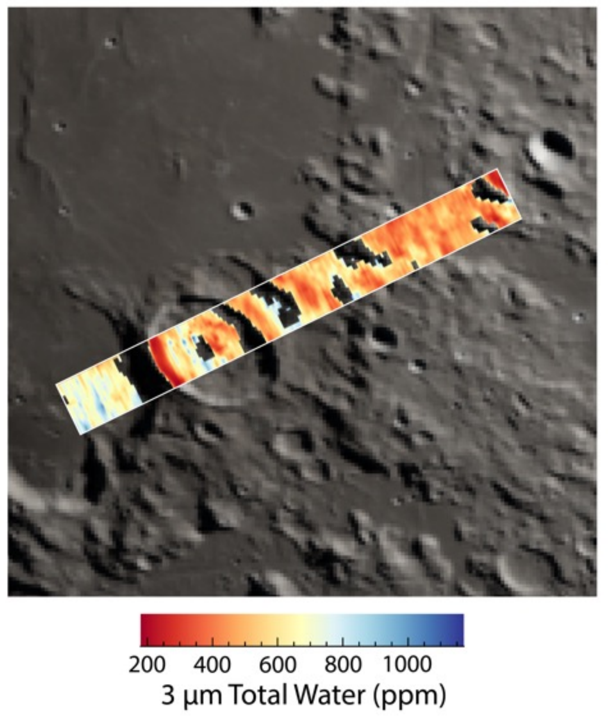

Bullialdus




Copernicus




Vitello

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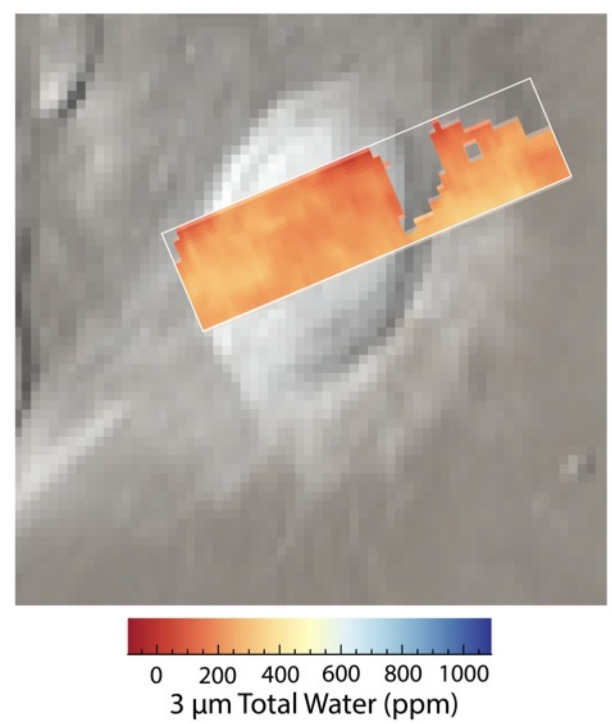
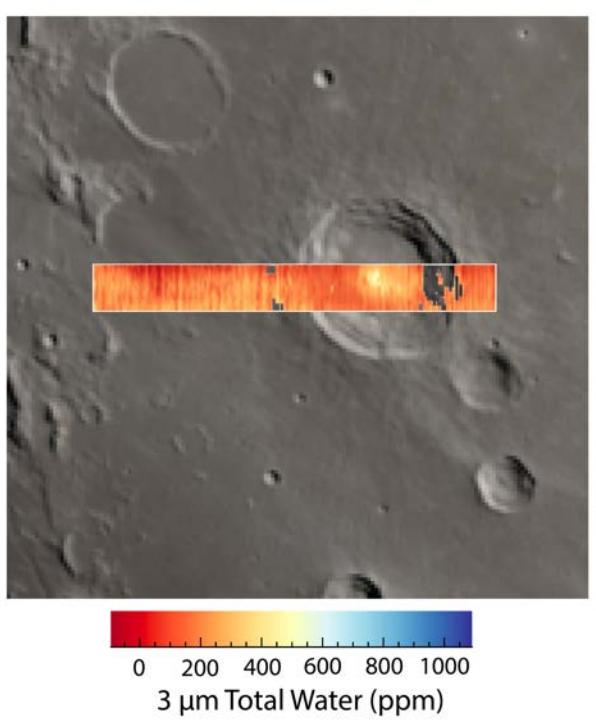
# Total Water: Common Stretch

## Aristarchus



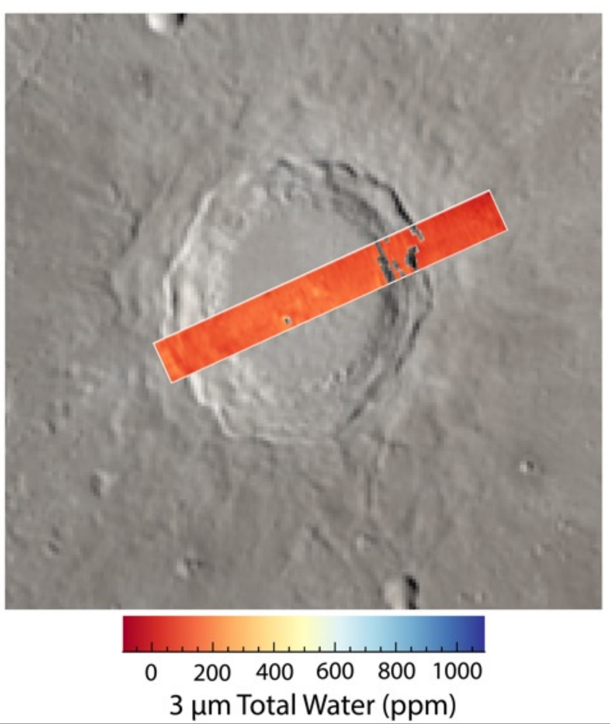

8:13 am

## Bullialdus




7:07 am

## Copernicus

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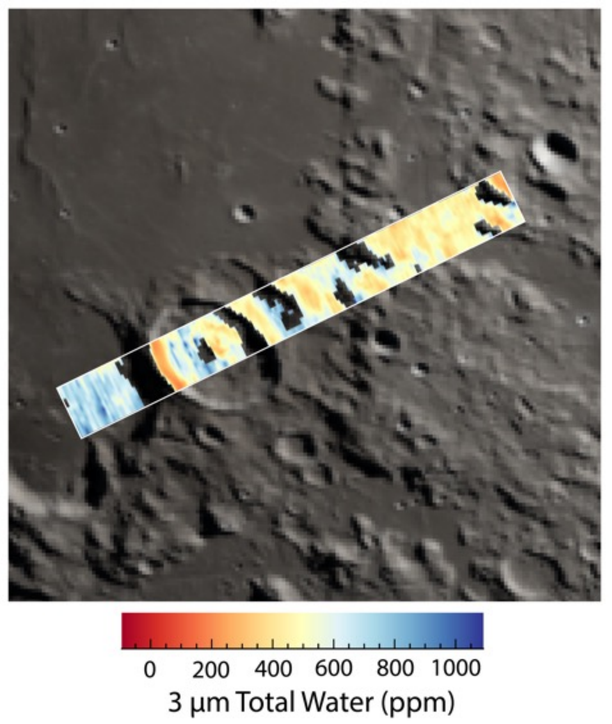
## Vitello




6:47 am

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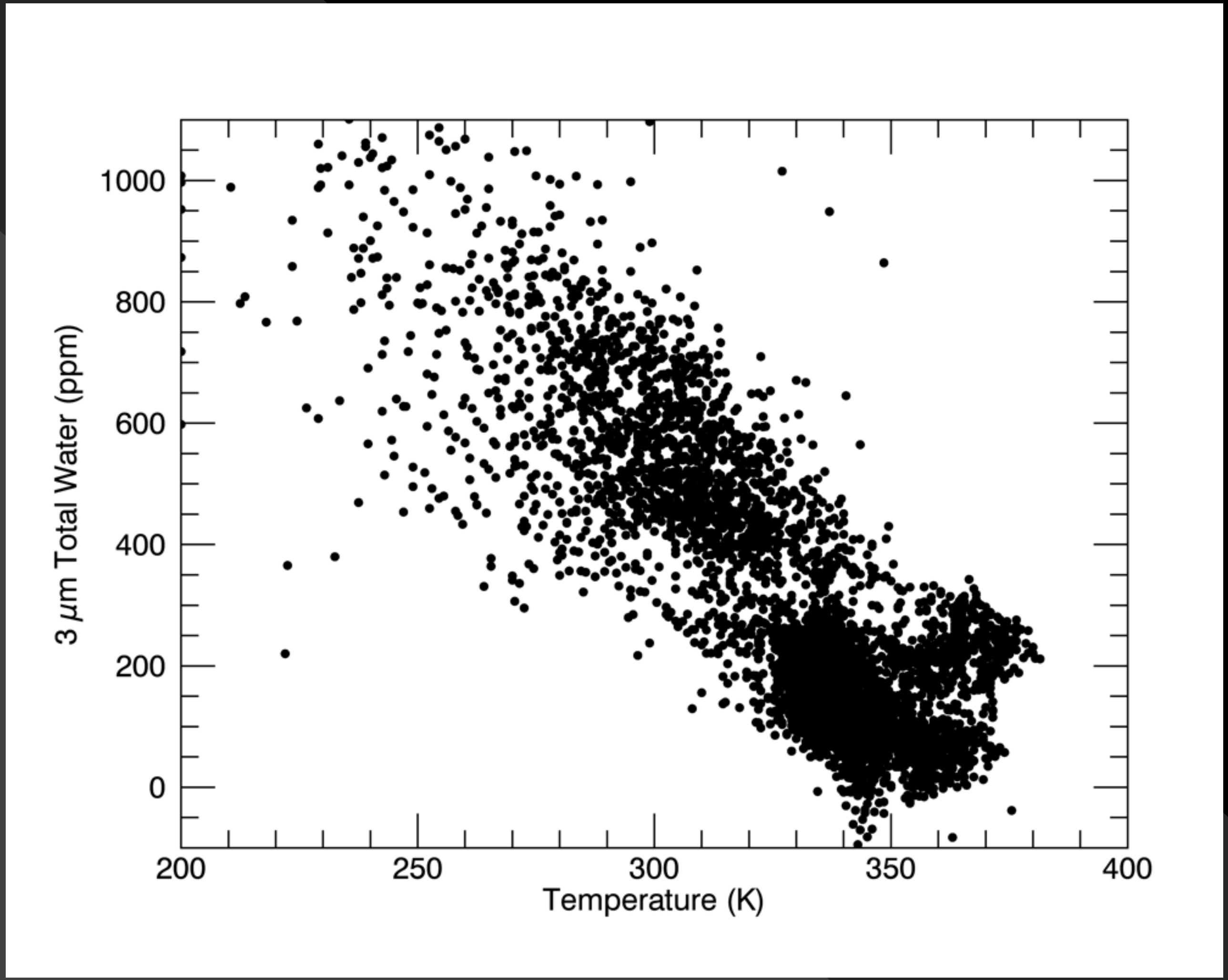
# Temperature Dependence

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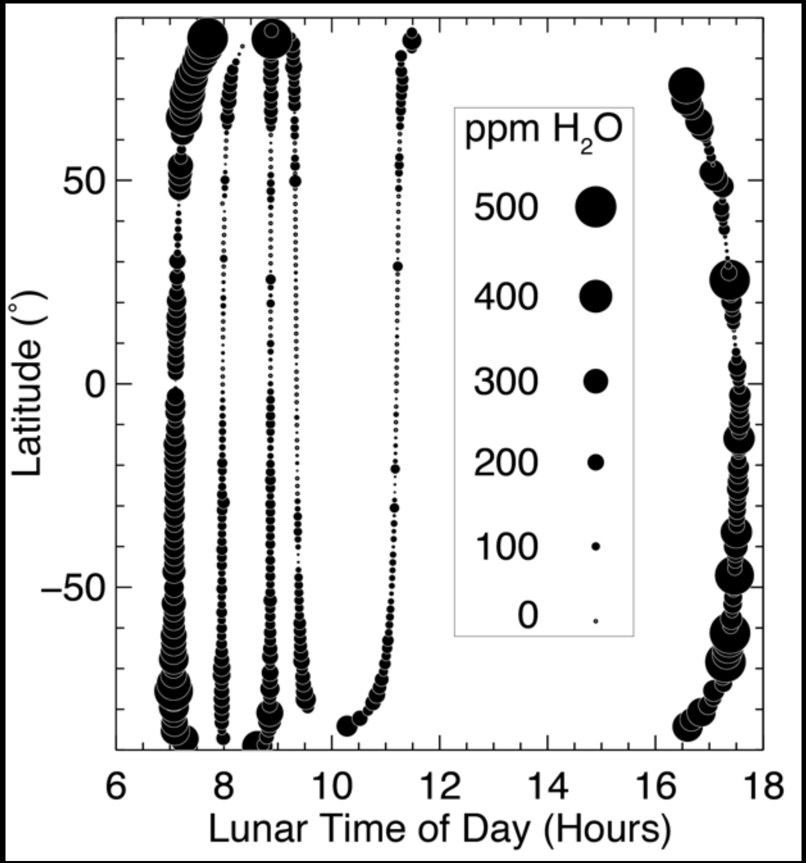
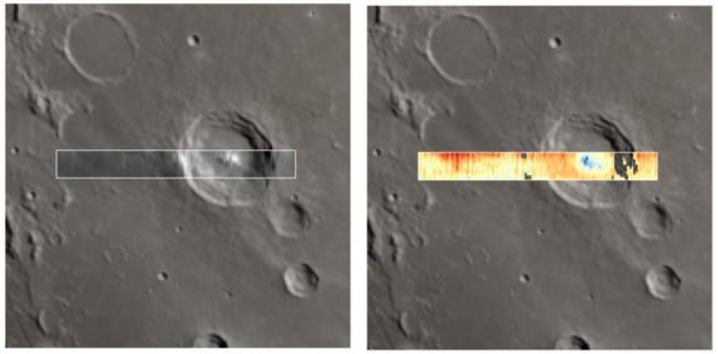
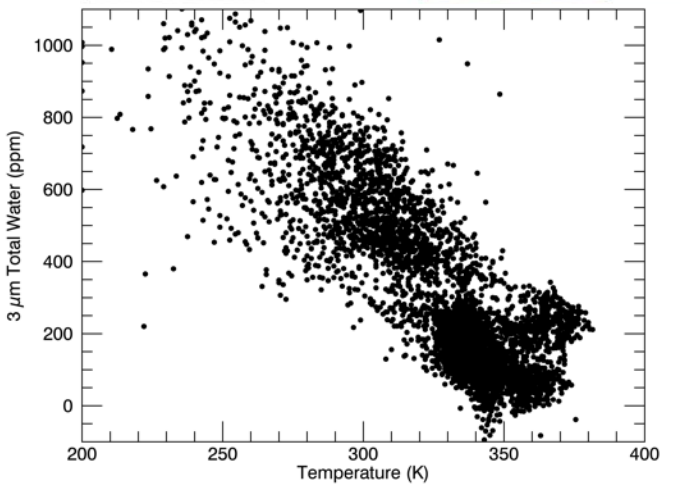
# Conclusions from IRTF data... SOFIA still to come






IRTF provides spectral coverage out to 4.1 µm

- Strong constrains on thermal component
- Removal of thermal emission is unambiguous

3 µm band varies with temperature

- Asymmetric trends about the equator suggest another controlling factor, possibly composition

Results suggest the diurnal variation is real

- $H_2O$ or H migrating on the lunar surface
- Which is responsible is still under debate

Some central peaks show enhanced hydration

- Possibly indigenous hydration

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# Is the 3 µm band due to OH or $H_2O$?

- OH can be converted to $H_2O$ by recombinative desorption
  - Inefficient at lunar temperatures [Jones et al. 2018]

- Micrometeorite impacts provides extremely high temperatures
  - Efficient recombinative desorption of pre-existing OH

- The species responsible for the 3 µm absorption is under debate
  - If OH
    - H forming temporary OH bonds as it diffuses through lunar grains [Tucker et al., 2017, Farrell et al., 2017, Starukhina 2006]
  - If $H_2O$
    - The molecule can migrate on the lunar surface
    - Supply to the poles

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# Prior detection of $H_2O$

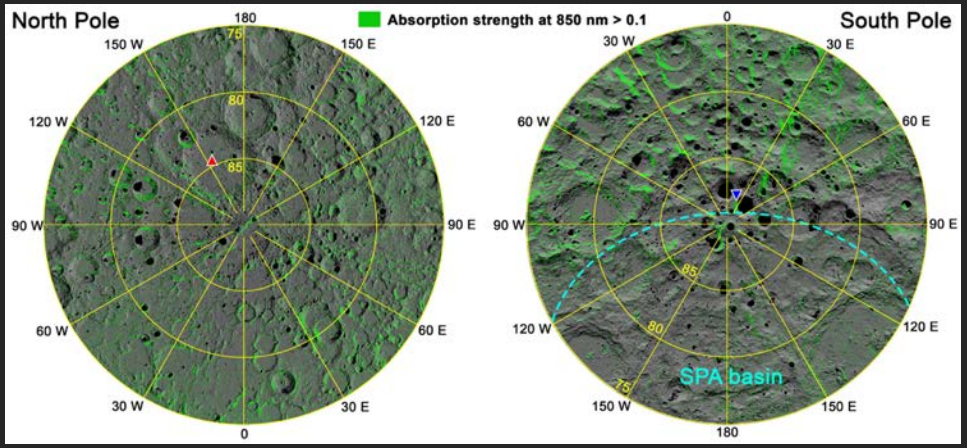
Water ice detected in permanently shadowed regions [Li et al., 2018]

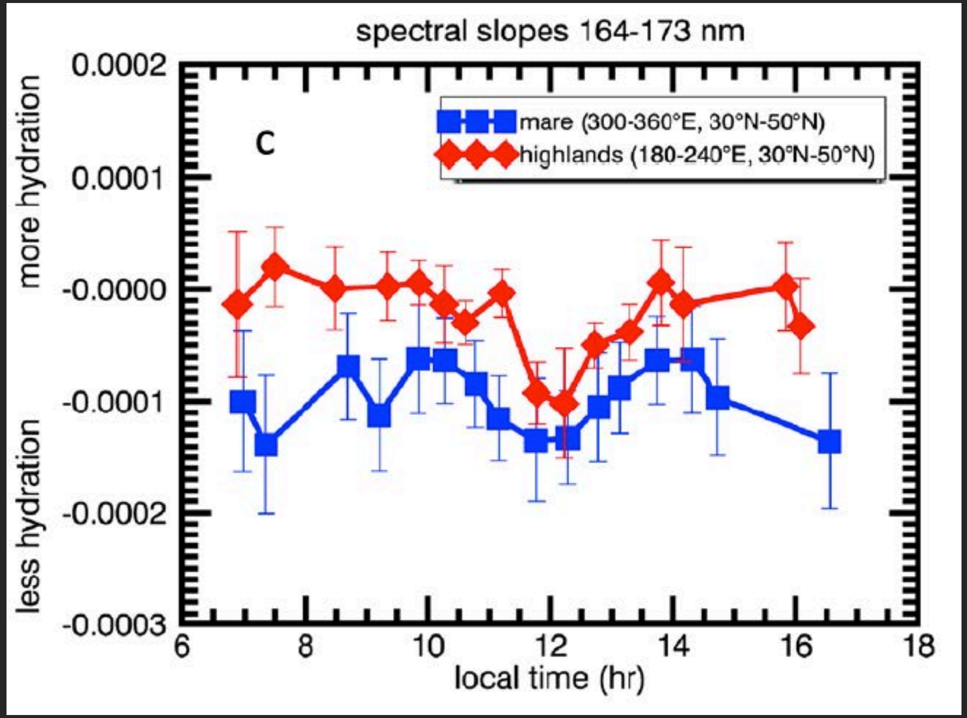
Hematite detected at the lunar poles on illuminated surfaces [Li et al., 2019]

- Hematite likely requires $H_2O$ to form

Anomalous UV ratio detected at local noon by LAMP [Hendrix et al., 2019]

- Assuming adsorbed $H_2O$ behaves like water ice
- Consistent with the presence of < 1% monolayer of $H_2O$

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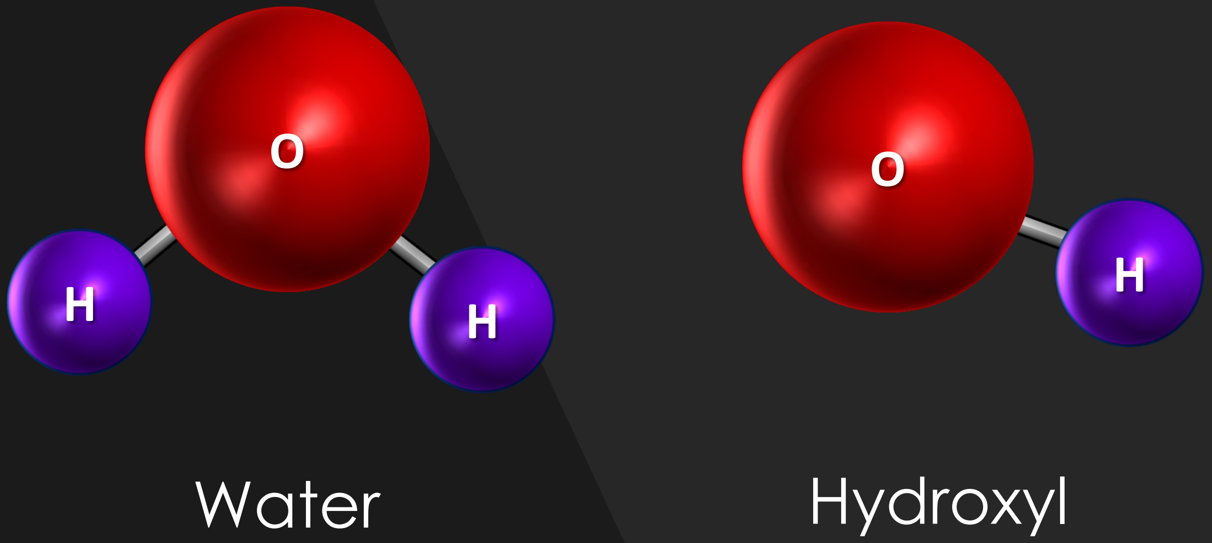
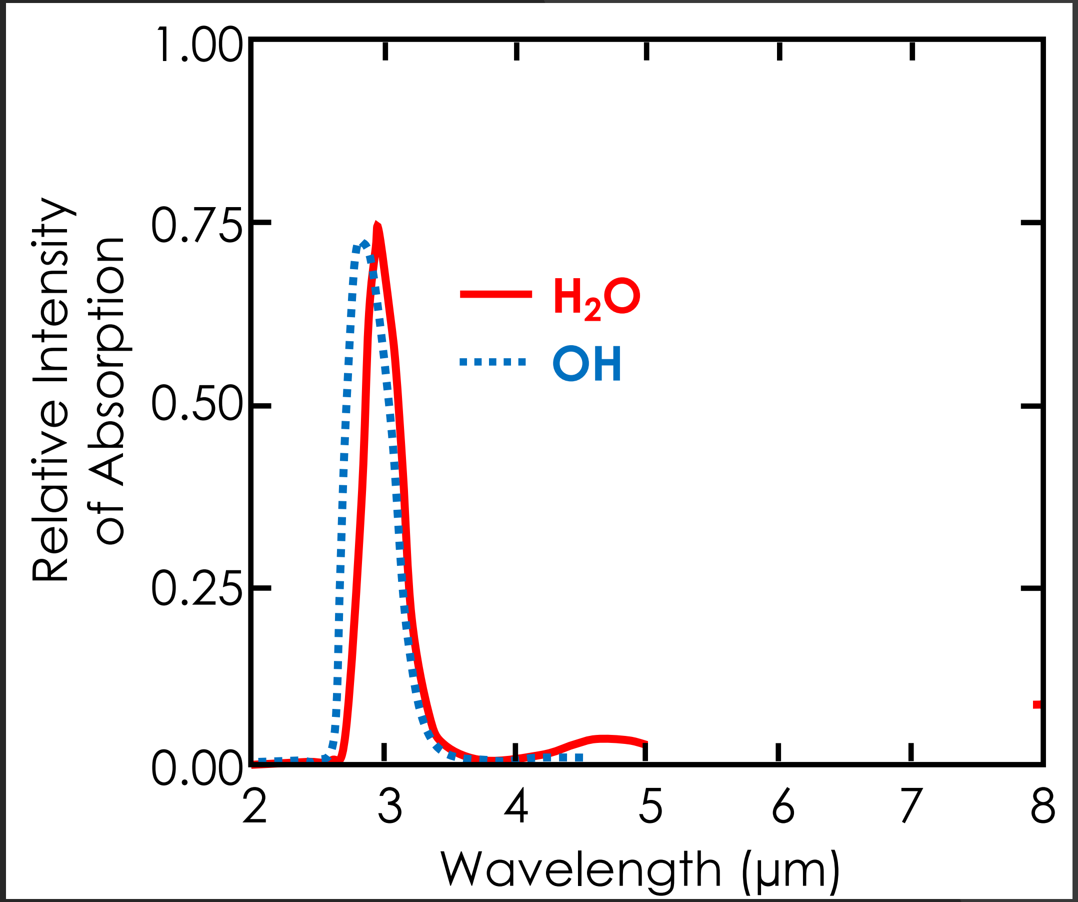
# 3 µm data cannot distinguish OH from $H_2O$

Both create a 3 µm band

- Symmetric and asymmetric O-H stretch
- OH bound to metal cations can mimic $H_2O$ and no methods exist to separate them

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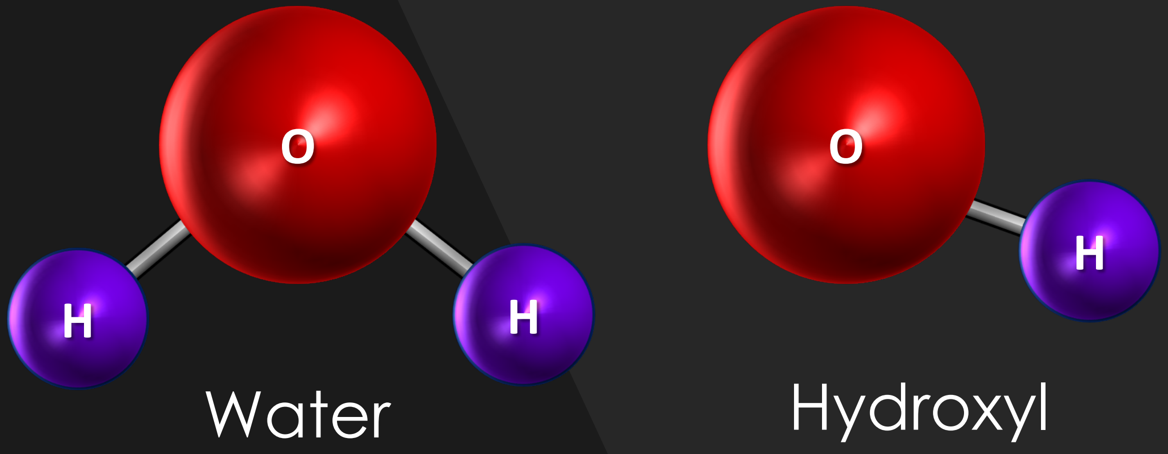
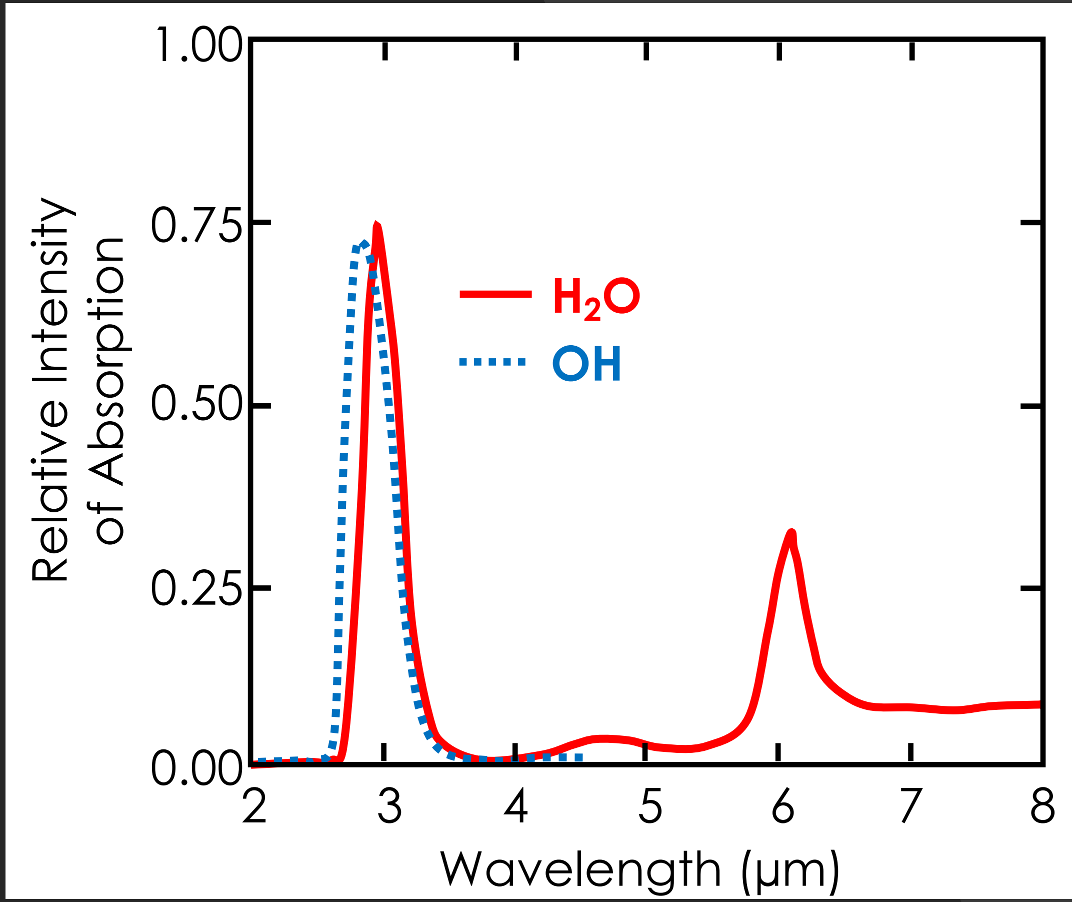
# New method to detect $H_2O$

The H-O-H bend occurring at 6.07 µm is explicitly due to $H_2O$

- strong, narrow and well suited for detection of $H_2O$

Used to measure the $H_2O$ content in thin section in chemical and geological literature [Bartholomew et al., 1980; Glew and Rath 1971; Newman et al., 1986; McIntosh et al., 2017]

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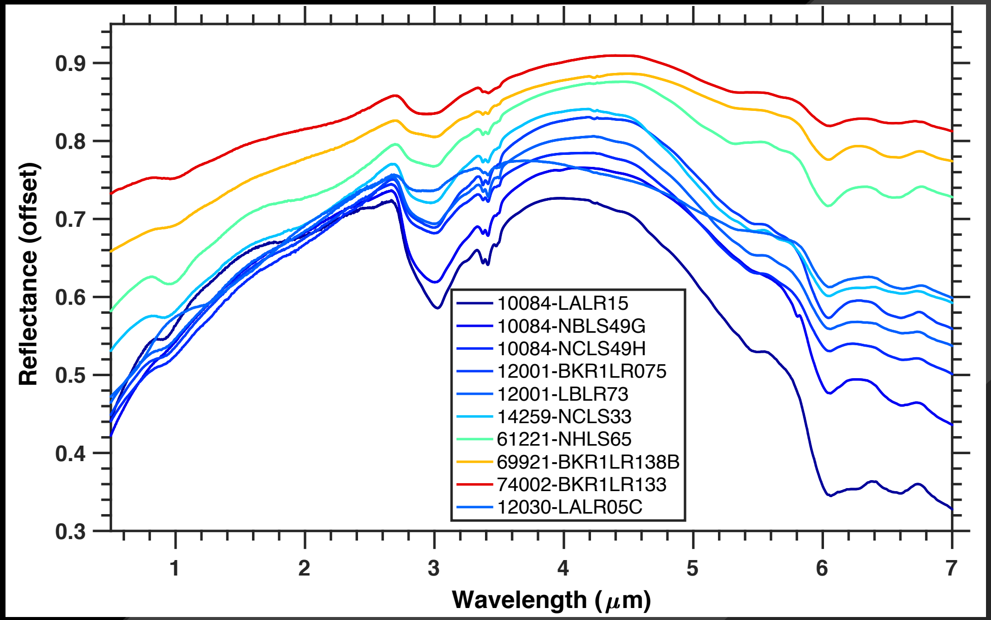
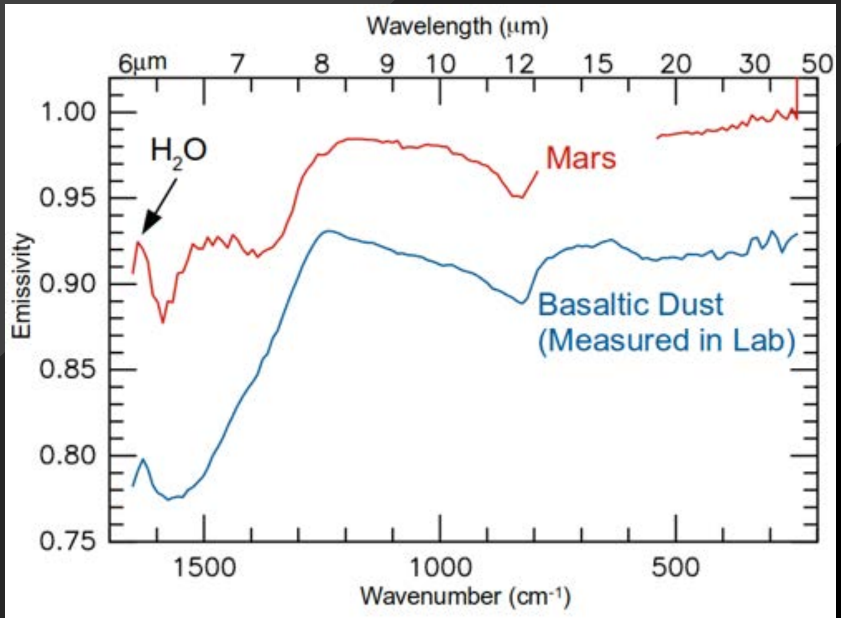
# 6 µm band has been seen on other planetary bodies and in laboratory spectra

Apollo samples



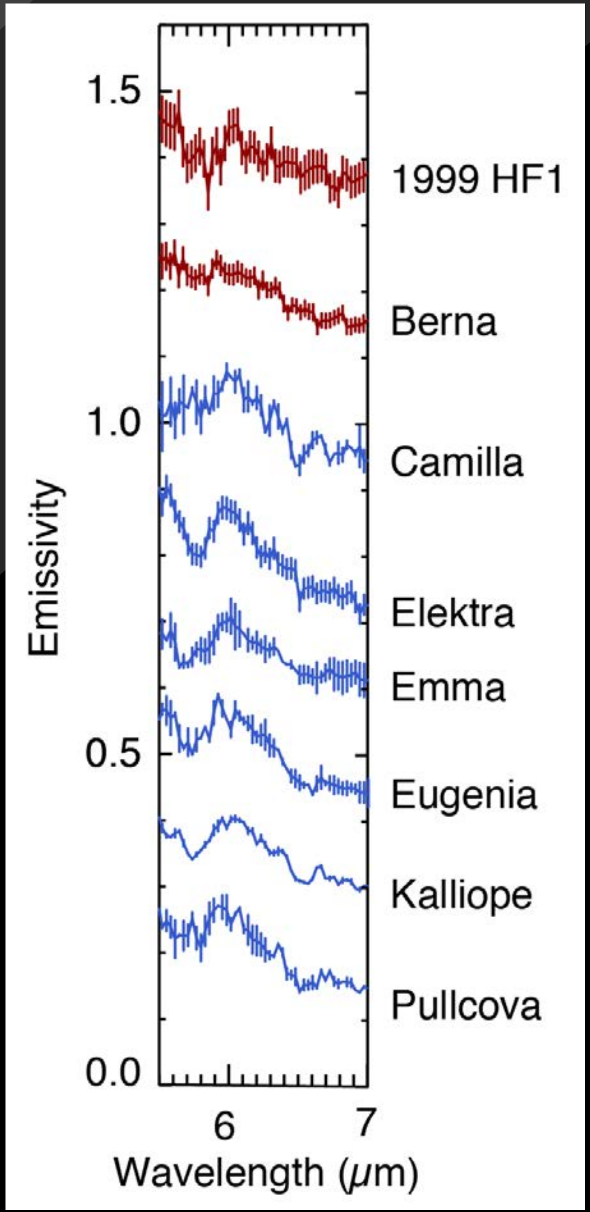

Data from RELAB

Mars




Bandfield et al., 2003

Asteroids




Marchis et al., 2012



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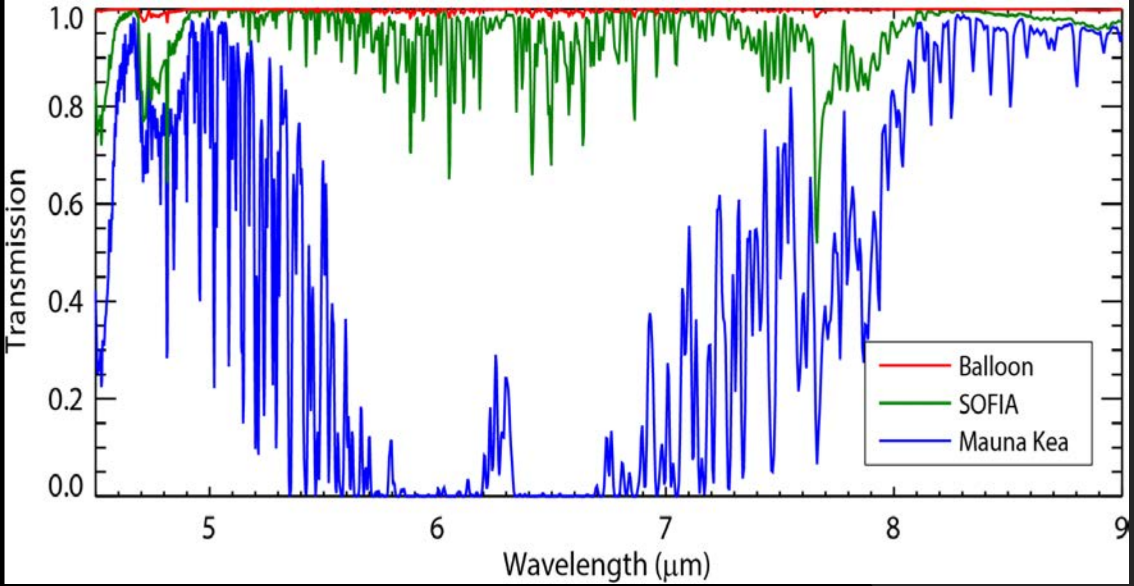
# 6 µm observations with SOFIA




No existing or planned lunar spacecraft capable of performing this unique observation

From the ground 6 µm observations are not possible due to Earth's atmosphere being opaque at 6 µm

The Stratospheric Observatory For Infrared Astronomy (SOFIA)

- flies above 95% (45,000 ft) of the atmosphere
- SOFIA FORCAST instrument
  - 5 to 8 µm
  - ~1 to 2 km spatial resolution

We have conducted the first observations of the Moon at 6 µm to look for water



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# Data Acquired

2 locations

- Mare reference at a mid-northern latitude
- Clavius crater in the south

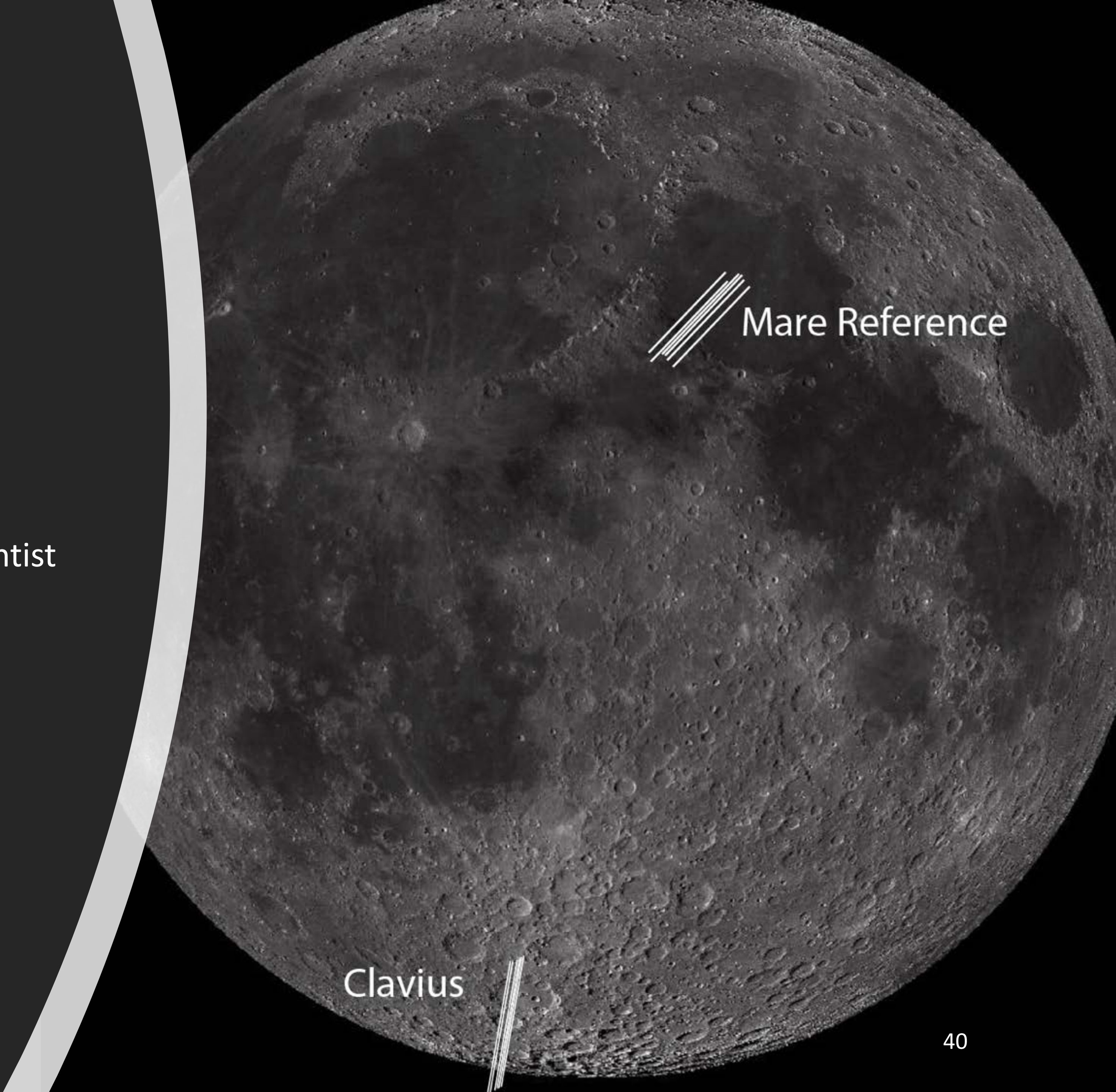
Observations of the Moon are not typical for SOFIA

- manually calibrated by a SOFIA research scientist

SOFIA is not exempt from telluric effects

- Corrected using ATRAN atmospheric model
- Uses the same atmospheric conditions as during the flight

- We receive fully calibrated and telluric corrected spectral frames

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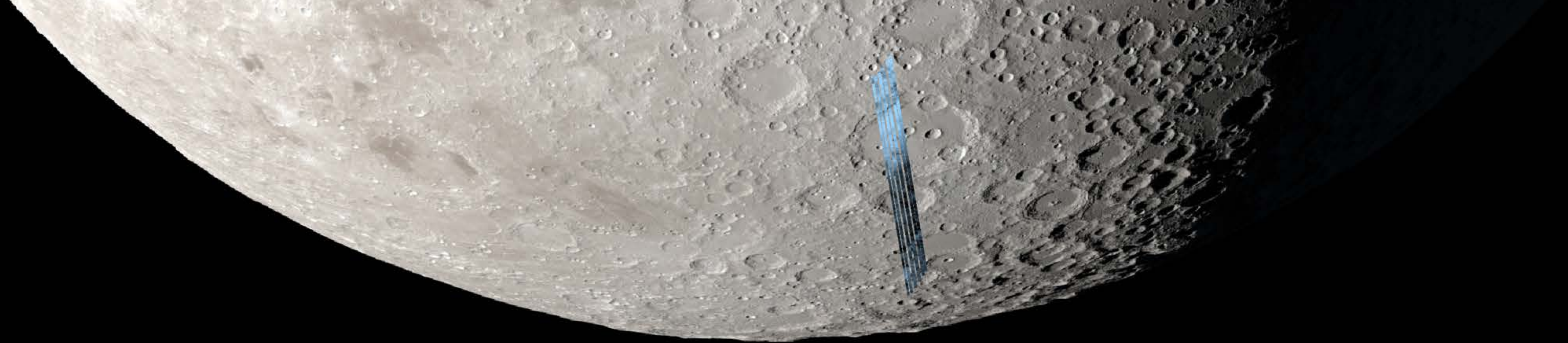
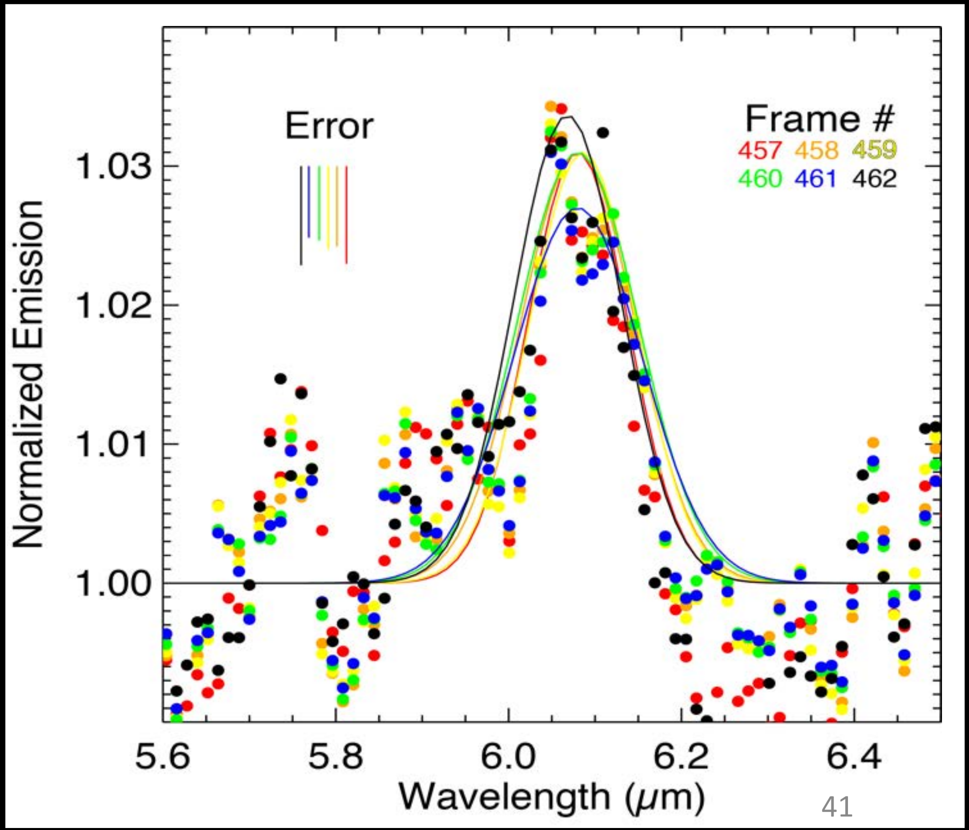


# First unambiguous detection of $H_2O$ on the sunlit lunar surface



# Assignment of 6 µm to $H_2O$

Moon vs. literature [Falk, 1984]

- Survey of H-O-H band centers
- Moon band centers within the cited H-O-H band centers

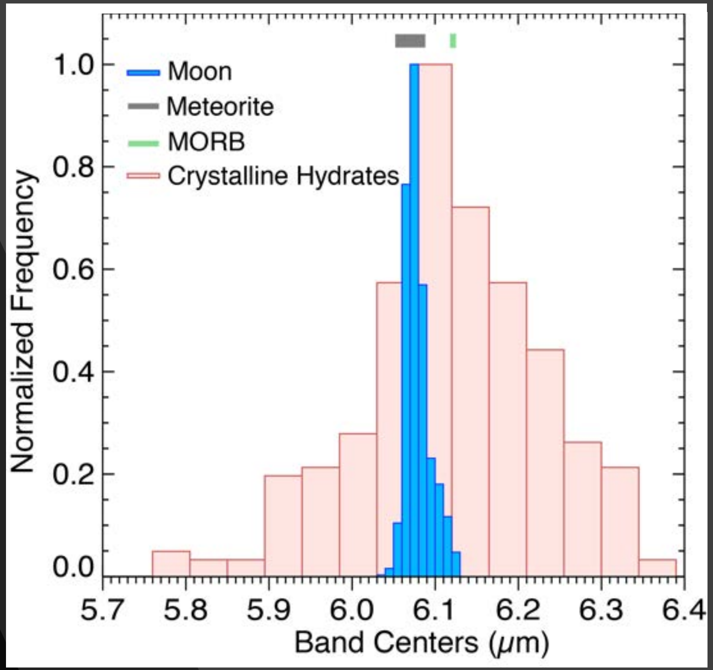
Moon vs. meteorites

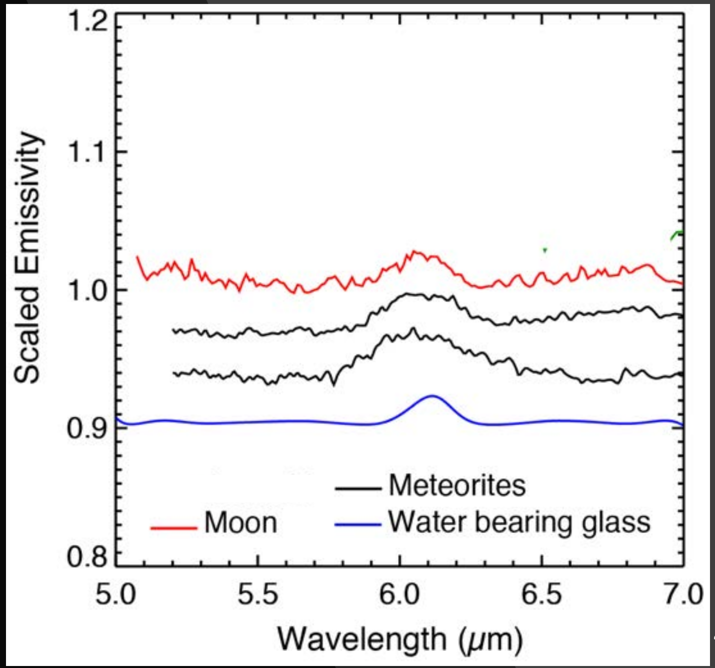
- Almost identical band shape, center, and width

Moon vs. water bearing glass

- Broader band
- Band center shifted to lower wavelengths

Differences can be from differing compositions

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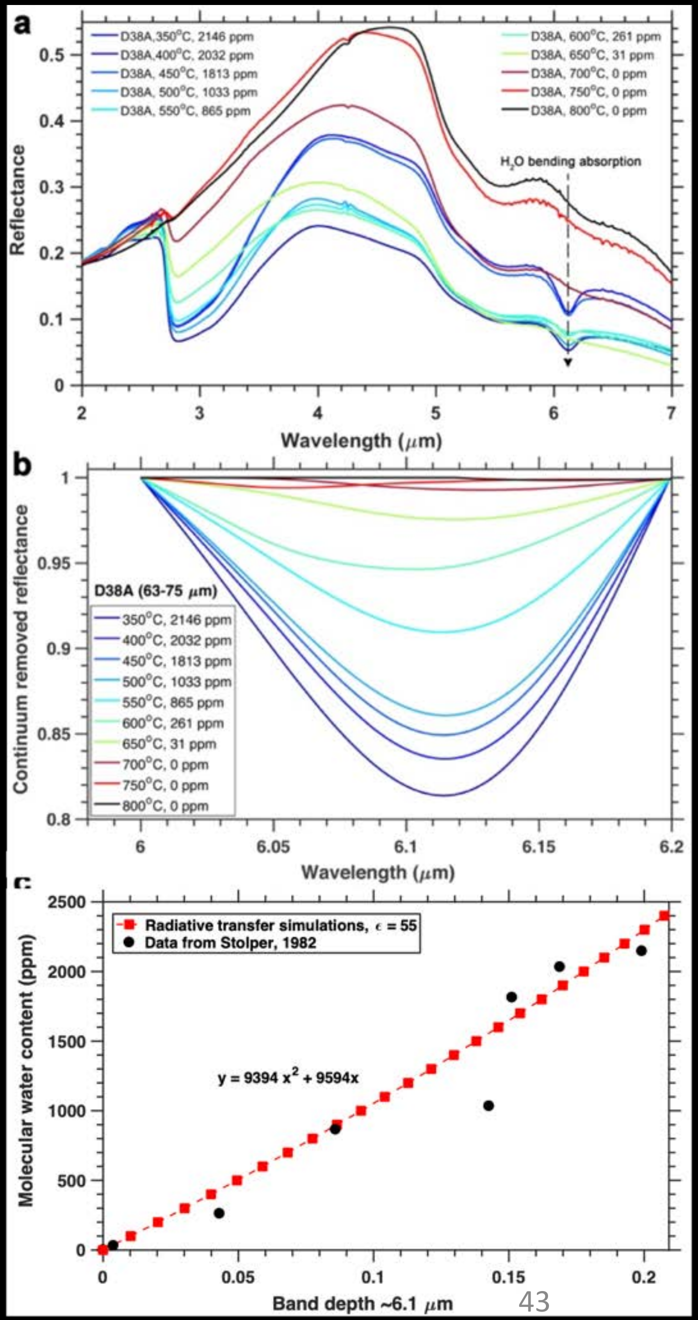
# Estimating abundance of $H_2O$

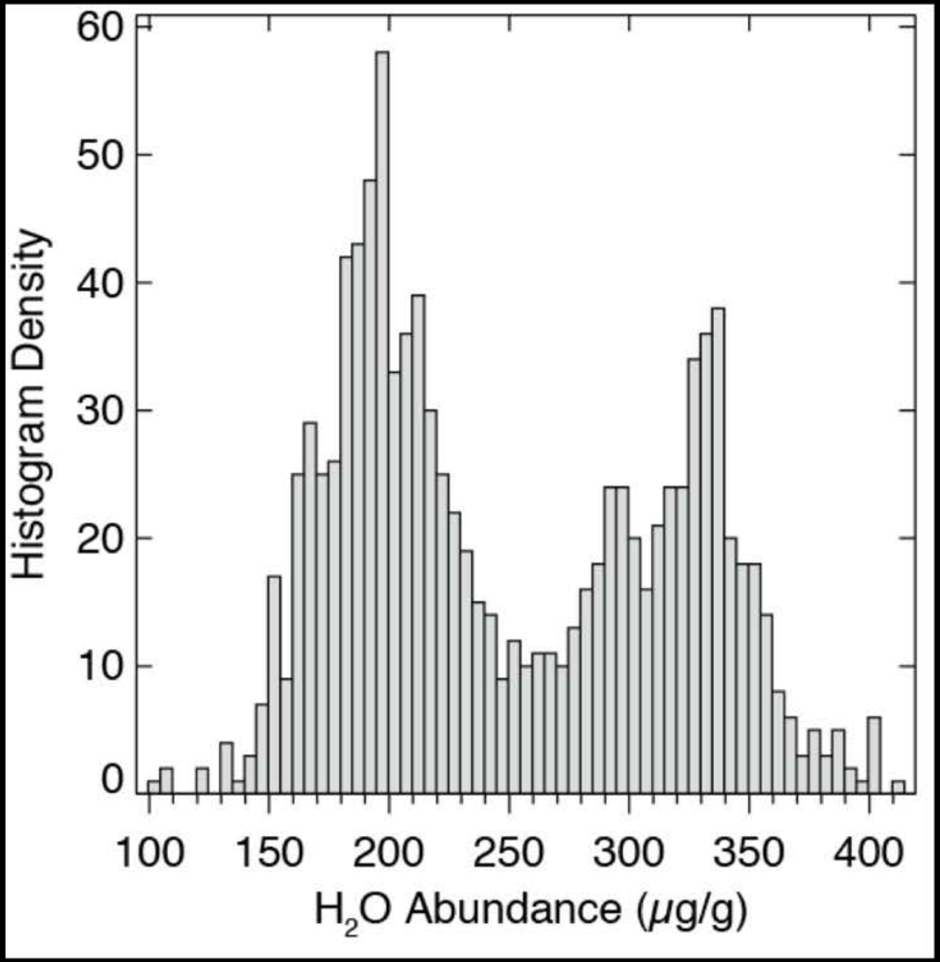
Strength of 6 µm band correlates to abundance of $H_2O$
[Bartholomew et al., 1980; Hale and Querry, 1973; Glew and Rath 1971; Thompson, 1965; Newman et al., 1986; McIntosh et al., 2017]

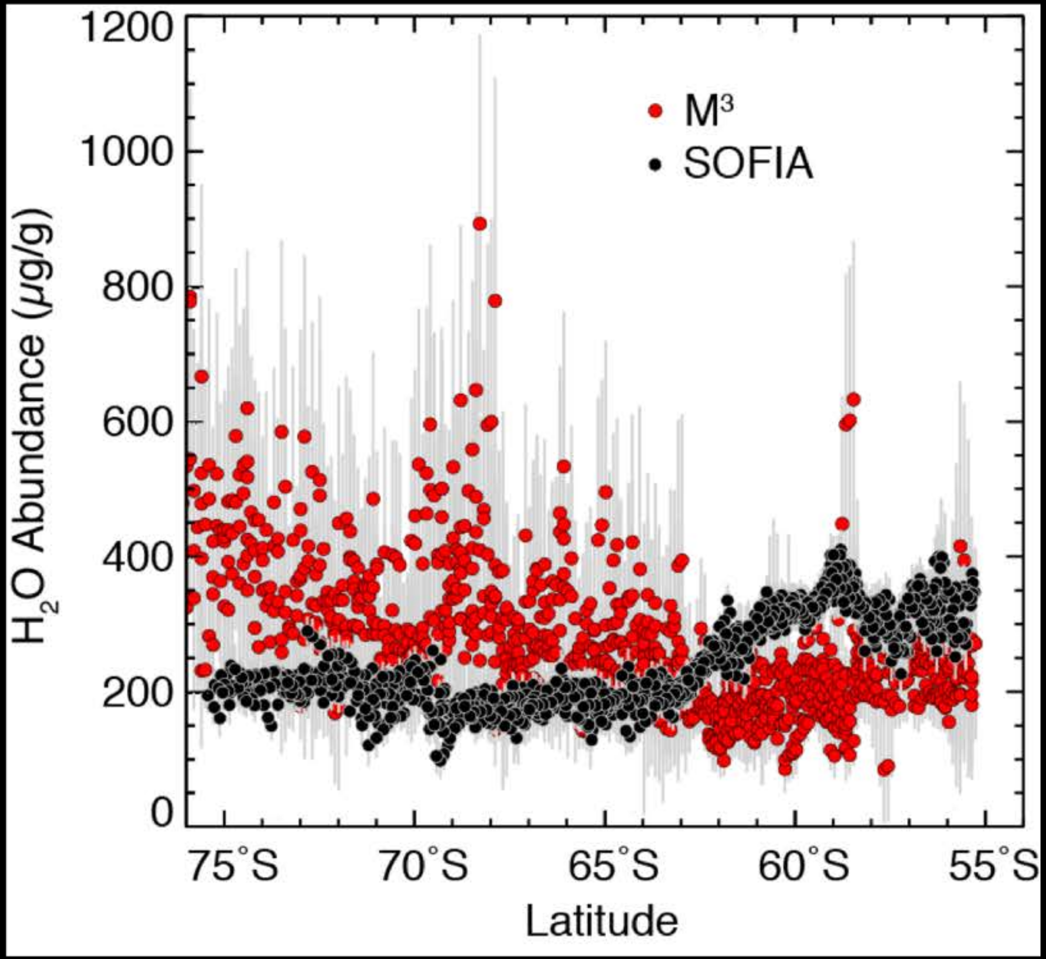
Can be used to estimate $H_2O$ content from remote sensing data

Reflectance spectra of water bearing glass samples feature both 3 and 6 µm bands [Li 2017]

- Used to develop an empirical model for estimating the absolute abundance of $H_2O$ from the 6 µm band






# Estimated Abundance of $H_2O$

About 100 to 400 ppm $H_2O$ in the Clavius crater region

Trend with latitude is due to Tycho crater ejecta

Within 1σ of $M^3$ abundances

Not a global phenomenon

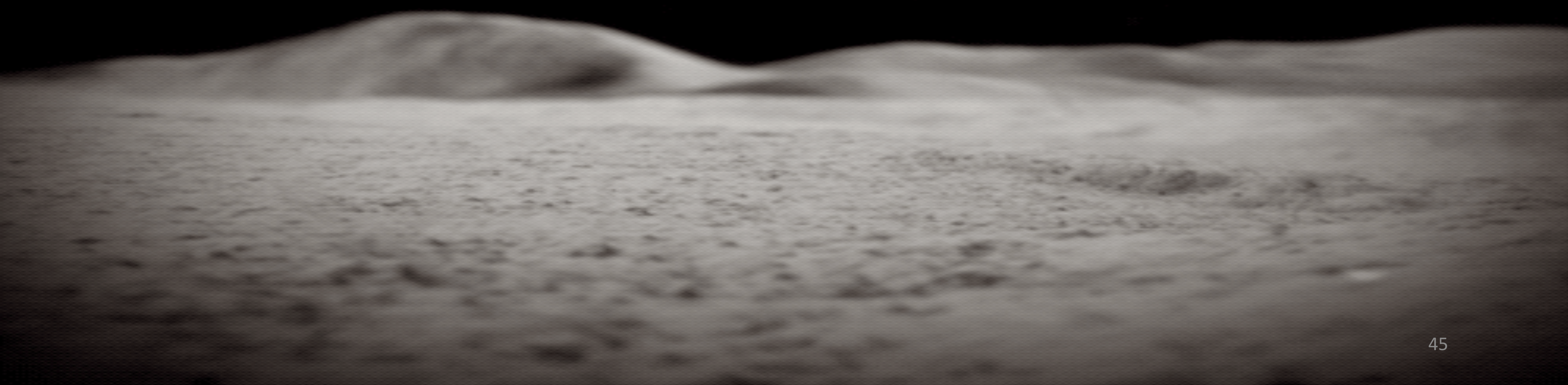
# Storing the Water

At our observing conditions, models suggest only 3 ppm $H_2O$ can be chemisorbed on grains [Poston et al., 2015]

Water resides within impact glasses which make up 30% of lunar soil [McKay et al., 1991]

- About 300 - 1300 ppm $H_2O$ in impact glass

Consistent with water produced from preexisting hydroxyl during micrometeorite impact



# Next Step – Observe More!

SOFIA Cycle 8:

- 2 hours awarded
- Anticipate spring 2021 observing
- Pilot program with 20 hours

SOFIA Cycle 9:

- Legacy program with 72 hours contingent on pilot program
- Asteroid program awarded 6.75 hours

IRTF

- 40 hours awarded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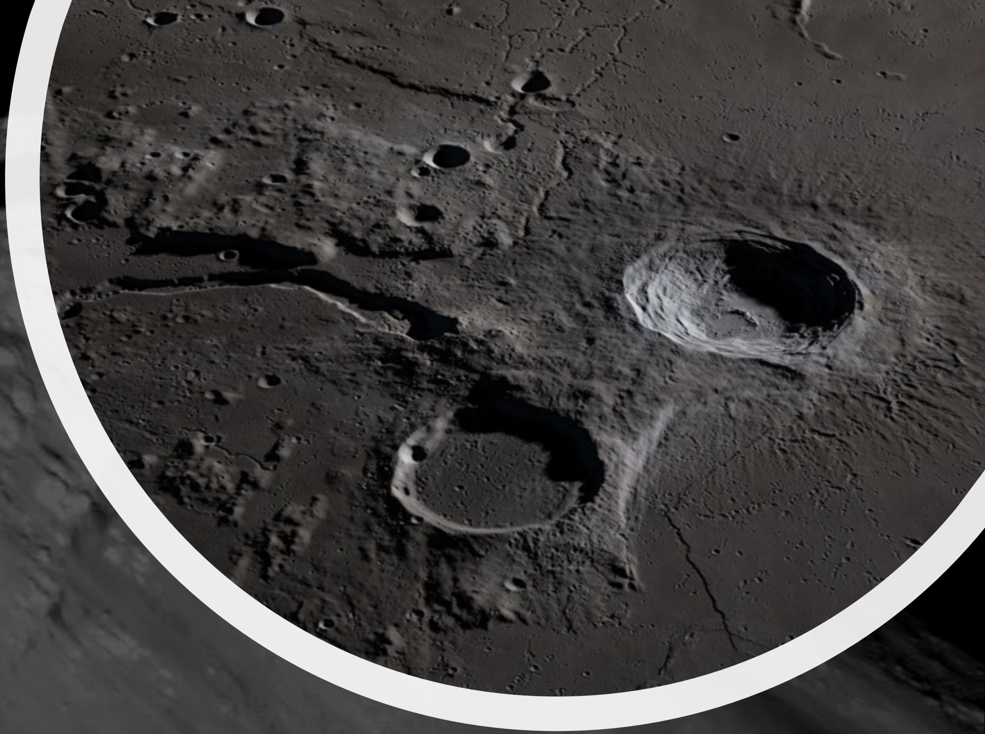
# What We Will Look At



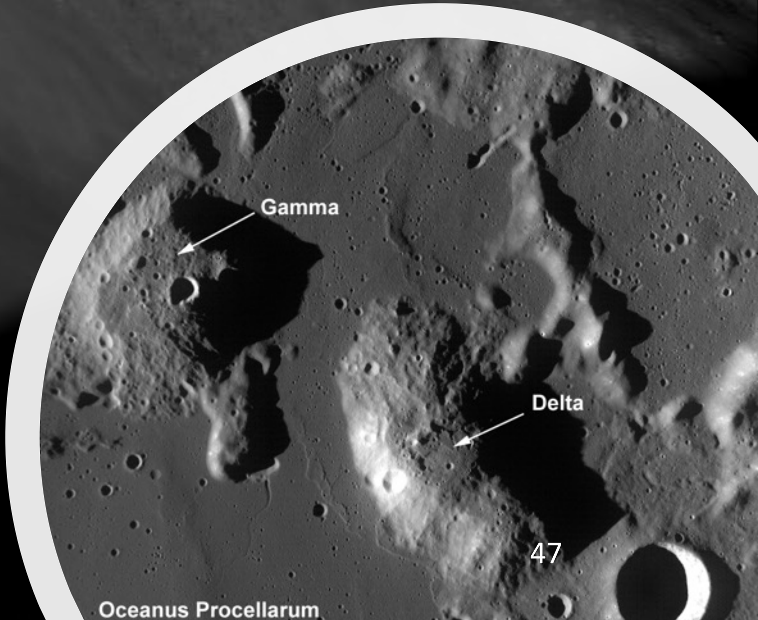
The Moon at different phases

Lunar Poles

Pyroclastic deposits

Silicic Anomalies

Mantle Exposures

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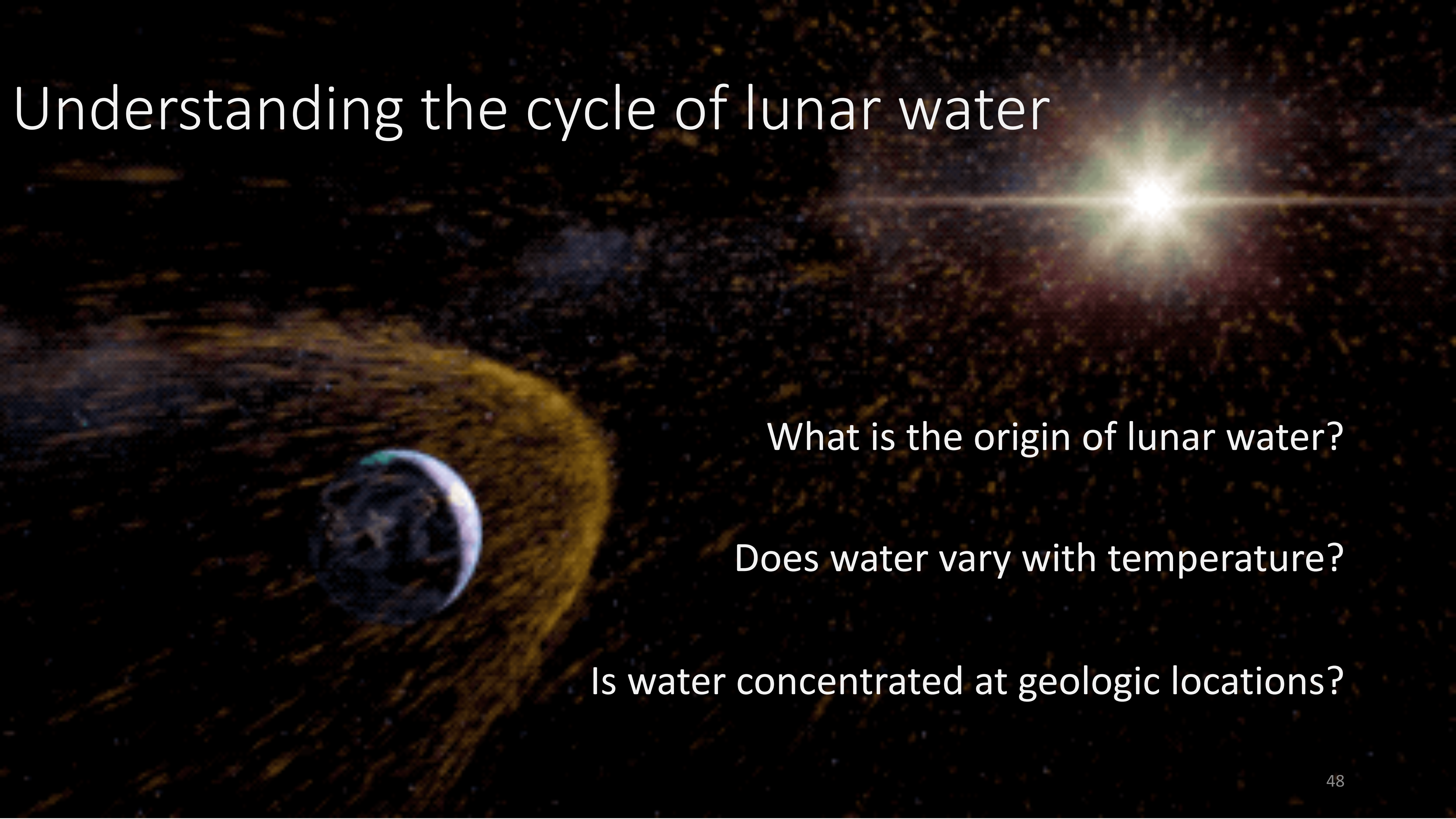

# Understanding the cycle of lunar water

What is the origin of lunar water?

Does water vary with temperature?

Is water concentrated at geologic locations?

# Thank you!

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