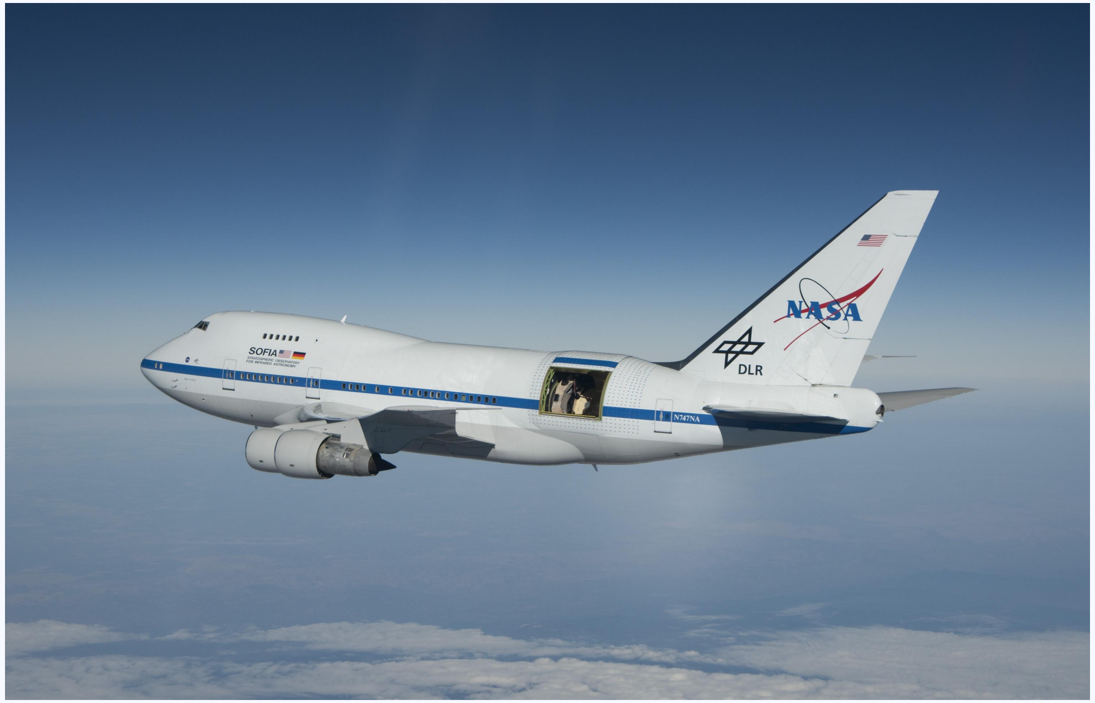
SOFIA SOLAR SYSTEM LEGACY

DAREK LIS

HERITAGE OF SOFIA – SCIENTIFIC HIGHLIGHTS AND FUTURE PROSPECTS

STUTTGART, APRIL 23, 2024



Jet Propulsion Laboratory
California Institute of Technology

OUTLINE

The New York Times

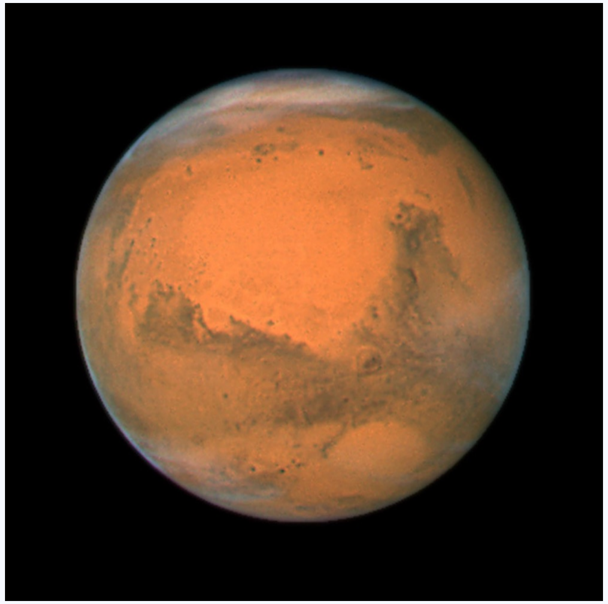
There's Water and Ice on the Moon, and in More Places Than NASA Thought

Future astronauts seeking water on the moon may not need to go into the most treacherous craters in its polar regions to find it.

Selected recent SOFIA highlights:

- Lunar/asteroid hydration
- Phosphine on Venus
- Oxygen on Venus
- Pluto occultations
- D/H in Mars atmosphere
- D/H in comets

Future prospects.



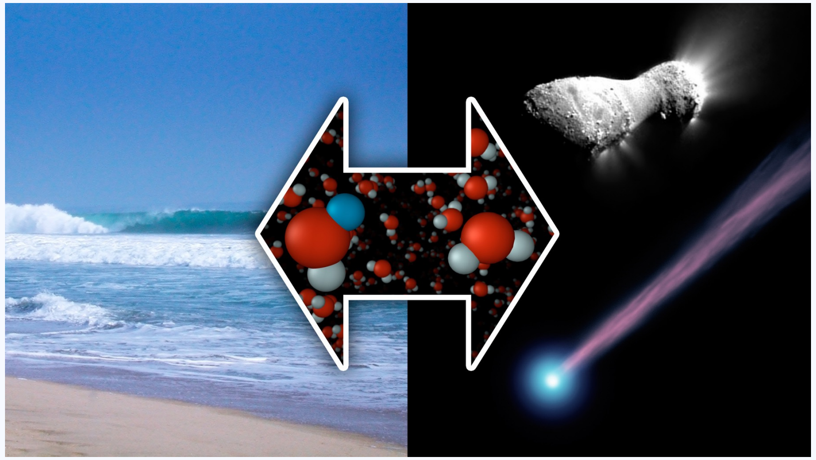
SPACE

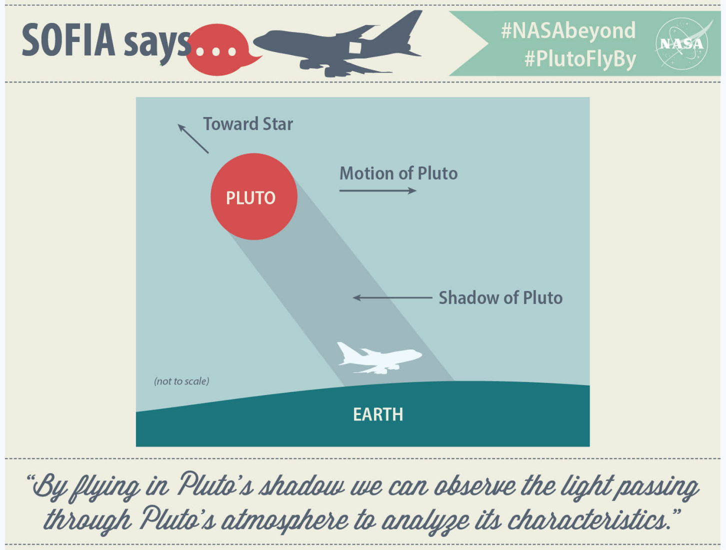
Hyperactive Comets Hint at Origins of Earth's Oceans

A new study suggests primordial seawater may lurk hidden at the hearts of many comets

By Nola Taylor Redd on May 9, 2019

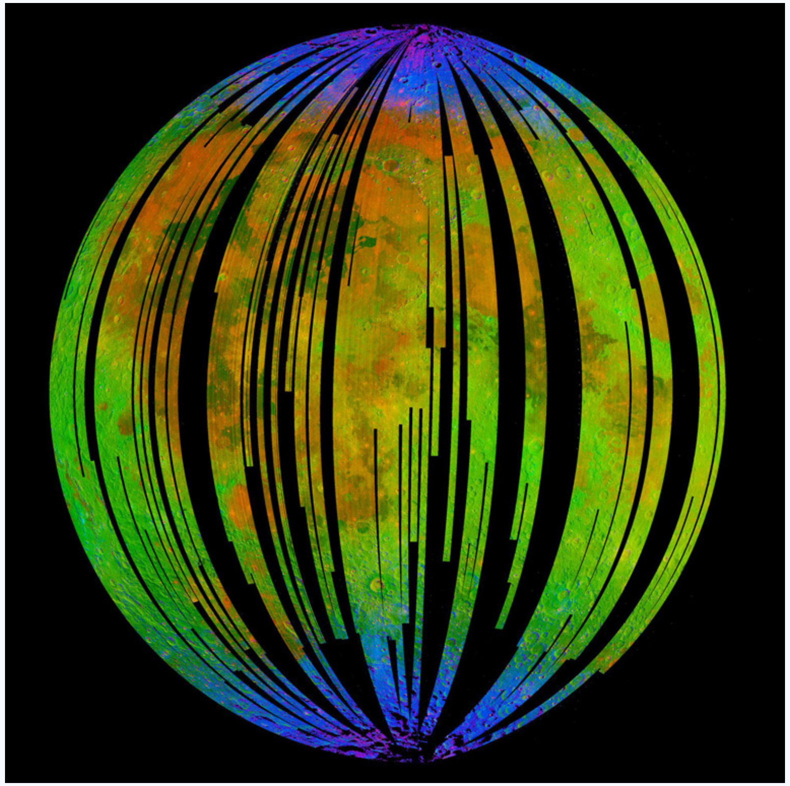
SCIENTIFIC AMERICAN





Credits: NASA/Caltech/SOFIA/USRA

LUNAR HYDRATION – MOON MINERALOGY MAPPER (M^3)



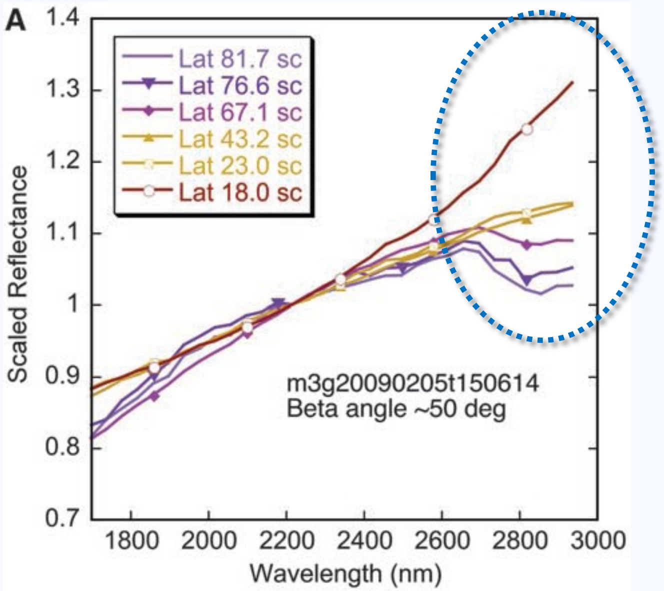
Orange and pink: iron-bearing minerals.
Green: 2.4 μm surface brightness.
Blue: OH and H_2O.

Initial analysis of Apollo samples showed no minerals containing water.

Independent detections of the 3 μm hydration band by Chandrayaan-1, Deep Impact, and Cassini (2009).

Absorption features at 2.8 – 3 μm at high latitudes attributed to hydroxyl or water-bearing materials.

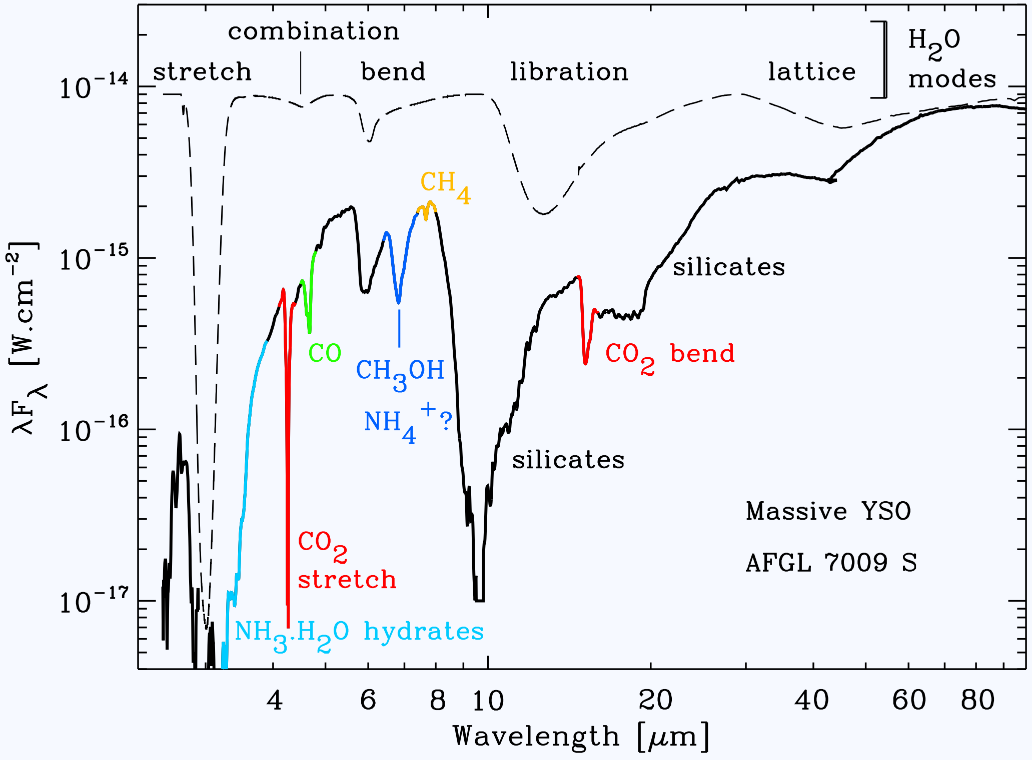
Widespread, shows variations with latitude, temperature, and lunar time.



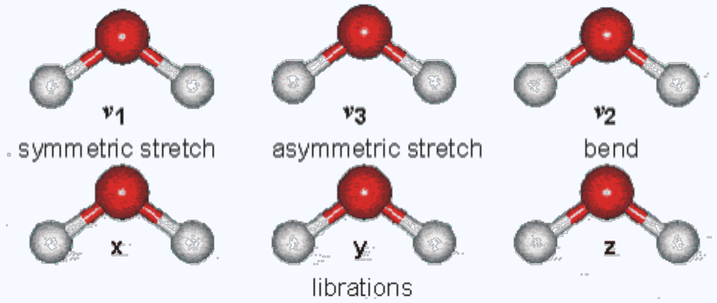
Credits: NASA

Pieters et al. 2009

WATER INFRARED SPECTRUM



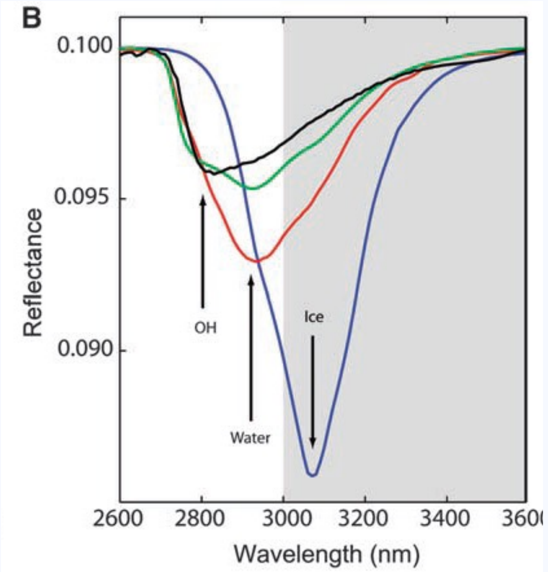
Boogert+ 2015



The 3 µm band (symmetric and asymmetric stretch of the OH bond) cannot distinguish between water and hydroxyl.

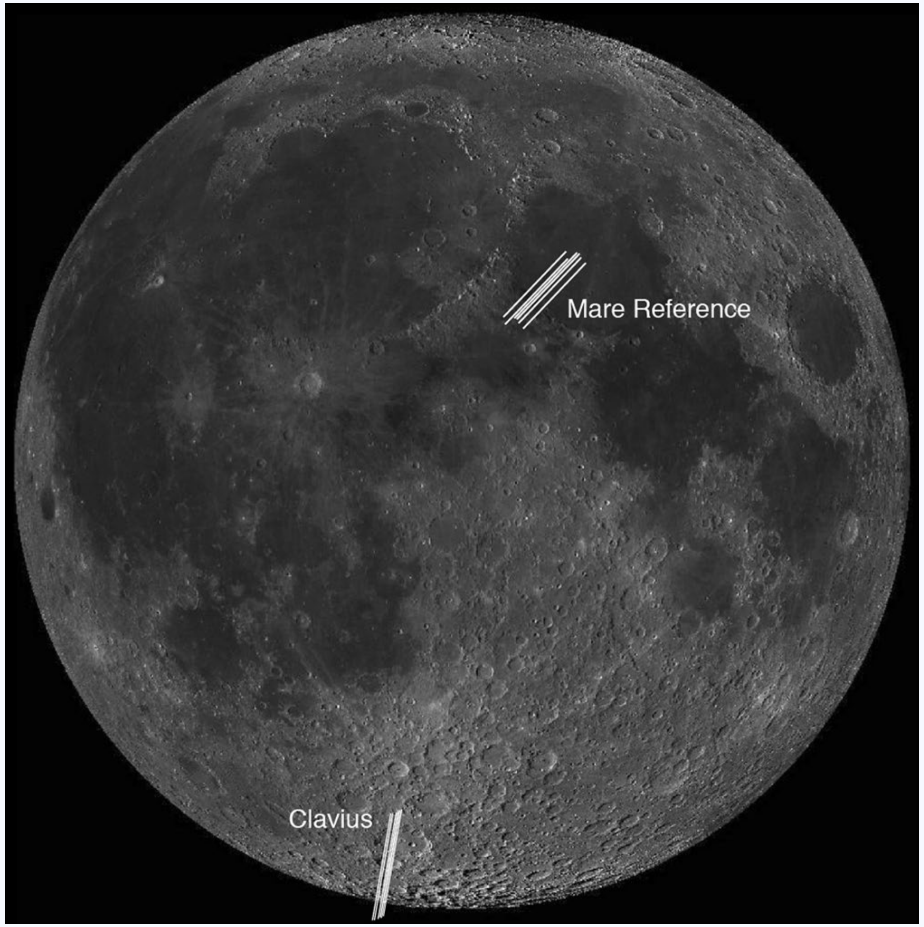
Differences in the center wavelength and band shape, dependence on the mineral composition, surface properties, etc.

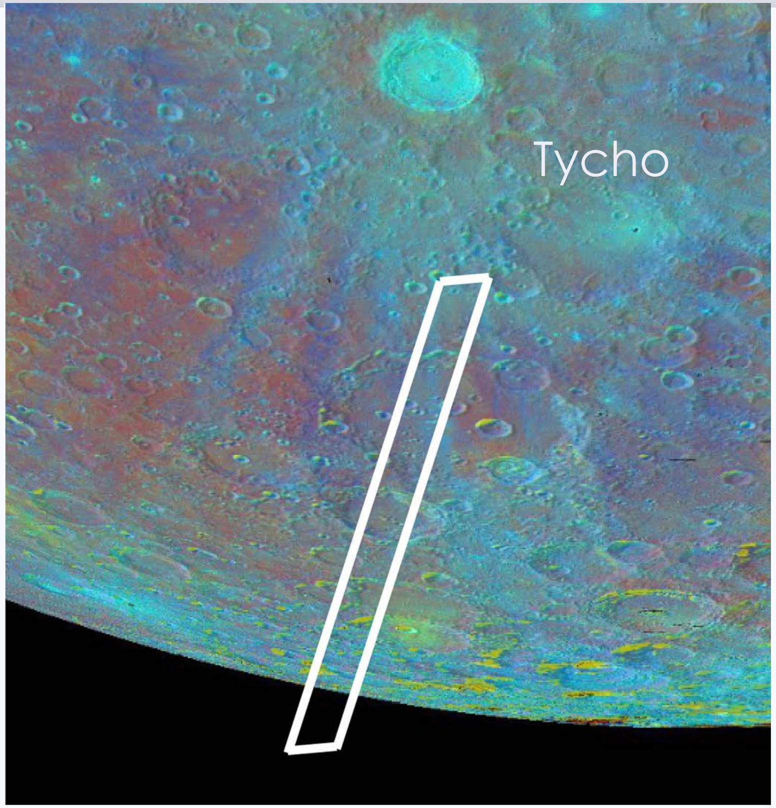
The H_2O bending vibration at 6.1 µm is unique to water molecules.



Credits: LSBU/academia.info

SOFIA OBSERVATIONS





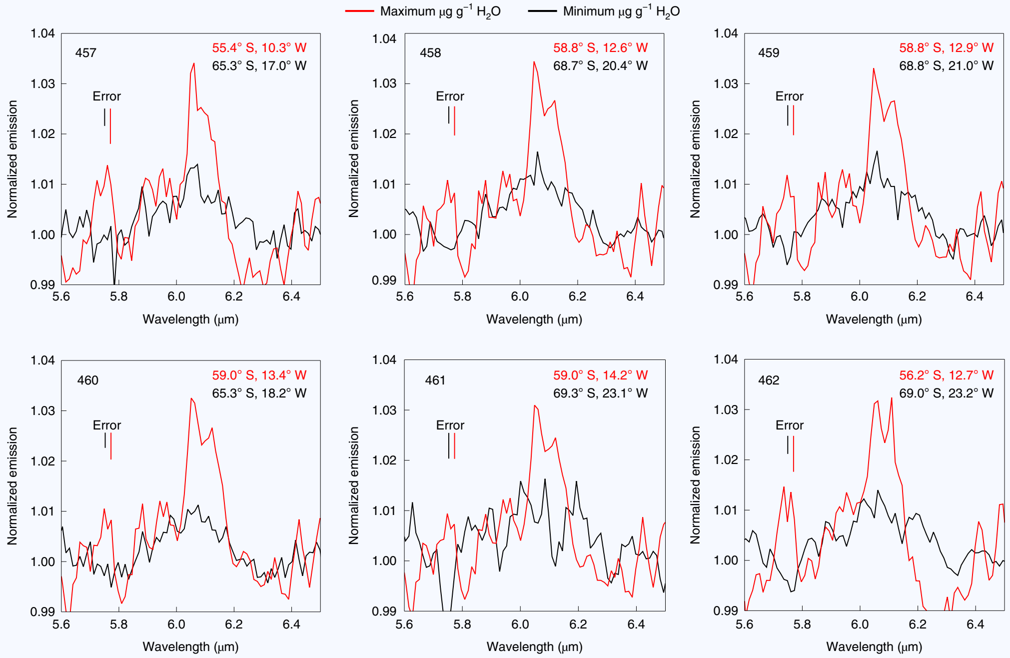
Observations targeted two sunlit locations:

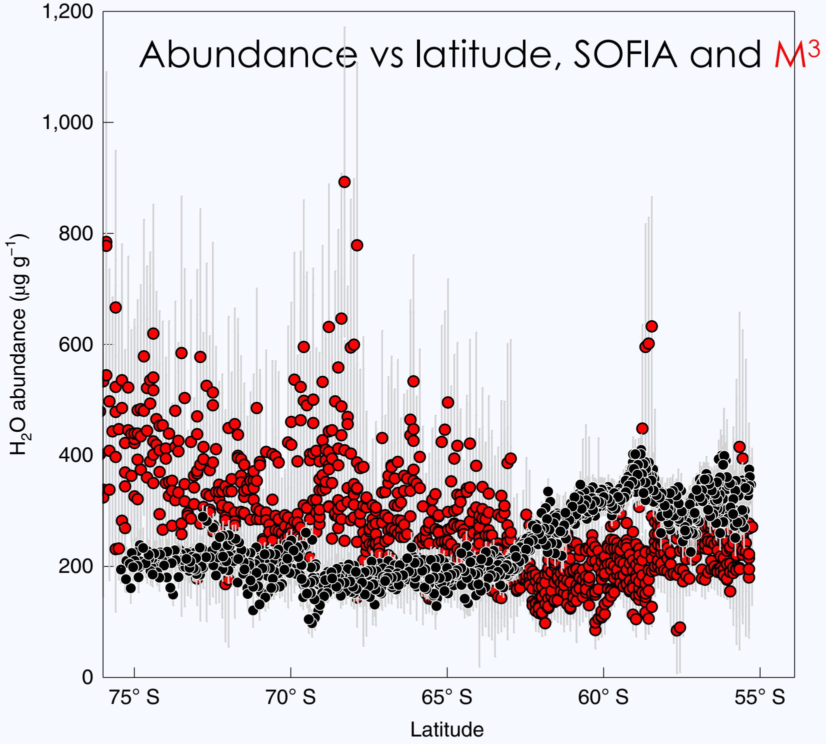
- A high southern latitude region near Clavius crater (high total water abundance in the M^3 data) .
- A low-latitude portion of Mare Serenitalis (control region with little or no water).

Credits: SOFIA/USRA

Honnibal et al. 2021

SOFIA OBSERVATIONS





Strong 6 μm emission at Clavius crater and surrounding terrain relative to the control location near lunar equator.

Mean water abundance in the Clavius region 200 μg g^{-1}.

Latitude distribution different from that implied by M^3 data – local geology rather than a global phenomenon.

The two wavelengths do not probe the same depths, local variations in the location of hydroxyl and water in the regolith grains.

Honniball et al. 2021

ORIGIN OF LUNAR WATER

Water detected by SOFIA resides within the interior of lunar grains (more likely) or is trapped between grains shielded from the harsh lunar environment.

The measured water abundance implies 300 to 1300 $\mu g\ g^{-1}$ H_2O in impact glasses – within the range of laboratory measurements.

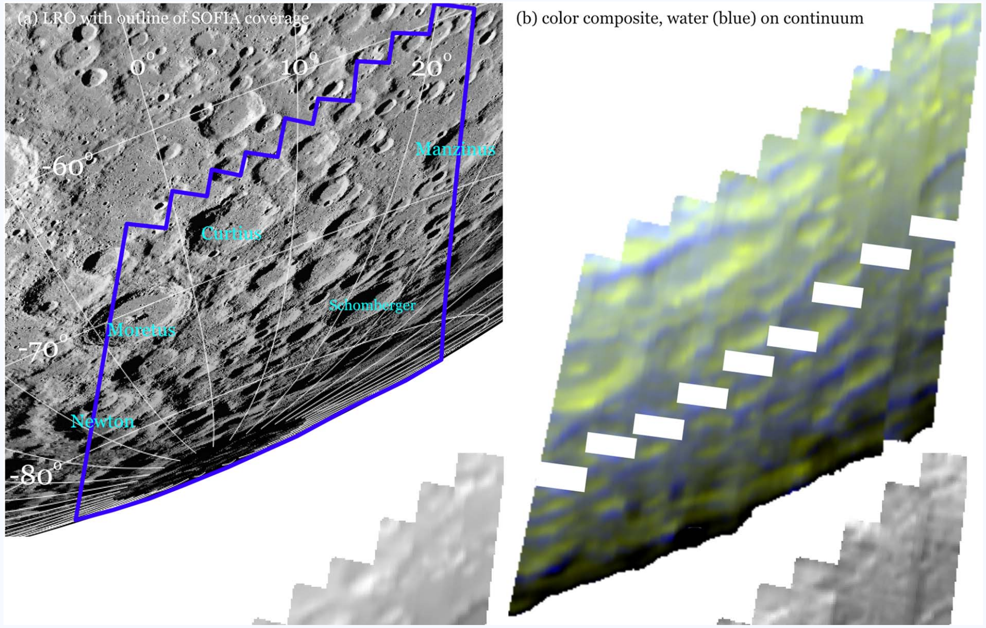
Impactor water entrained in impact glass explains this observations, but the data do not exclude in situ conversion of hydroxyl to water.

Observations are more consistent with a mechanism that produces water by impacts from pre-existing lunar material than impact delivered water.

Credits: SOFIA/USRA

Honnibal et al. 2021

SOFIA LEGACY PROGRAM

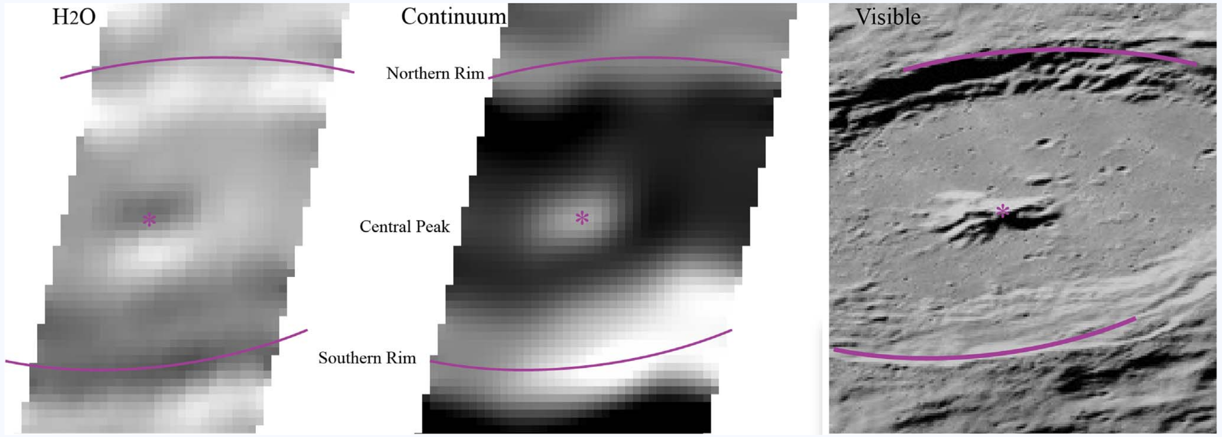


Mapped ¼ of the lunar nearside surface south of -60° latitude at 5 km resolution.

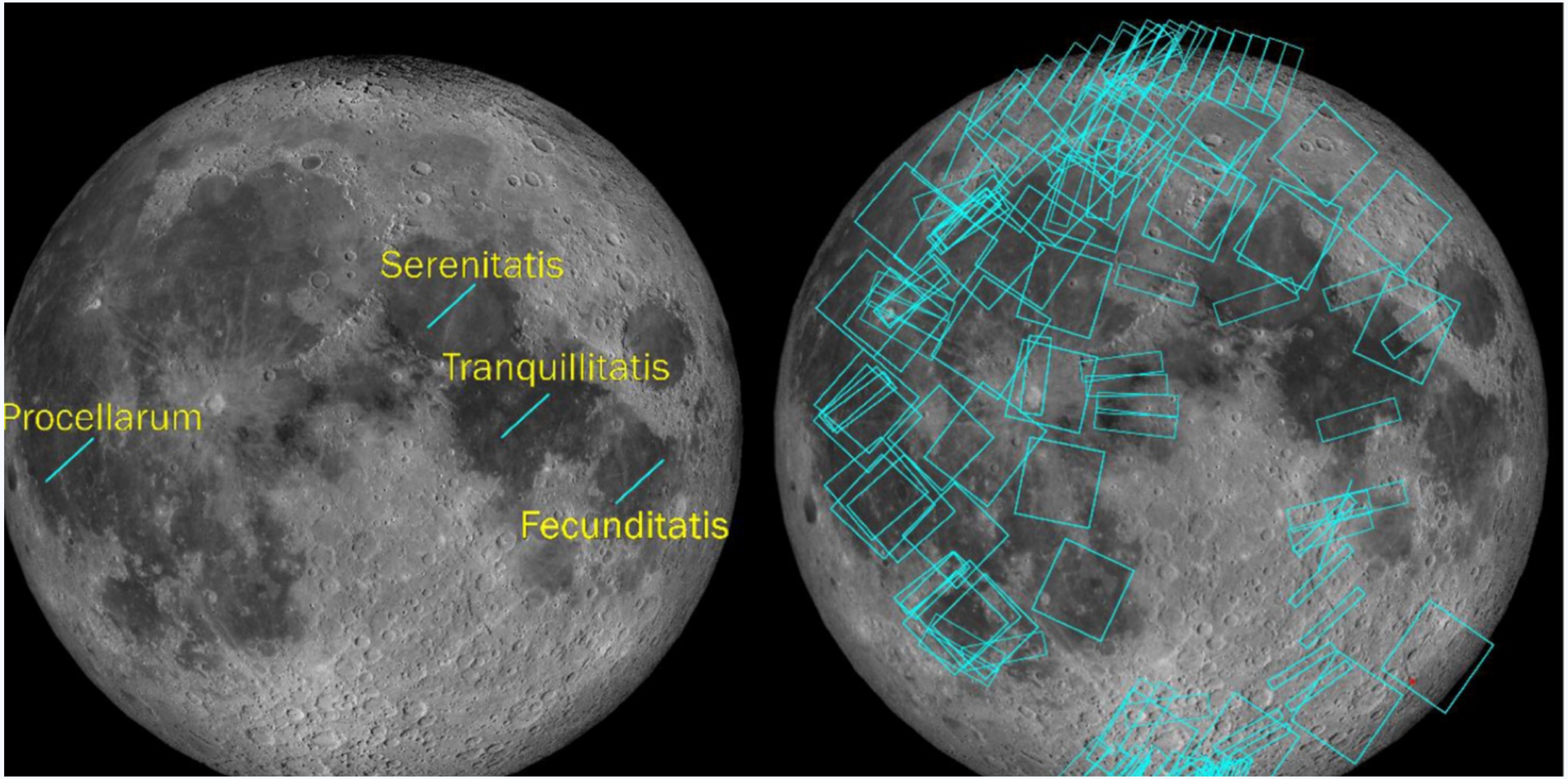
Significant local enhancements associated with south-facing, high-altitude topographic features.

High water concentration in:

- "Wet-ridge" north of the Curtius crater
- South-facing, northern, inner rims of the most prominent craters
- South face of the central peak of the Moretus crater
- Permanently shadowed polar regions



MORE TO COME

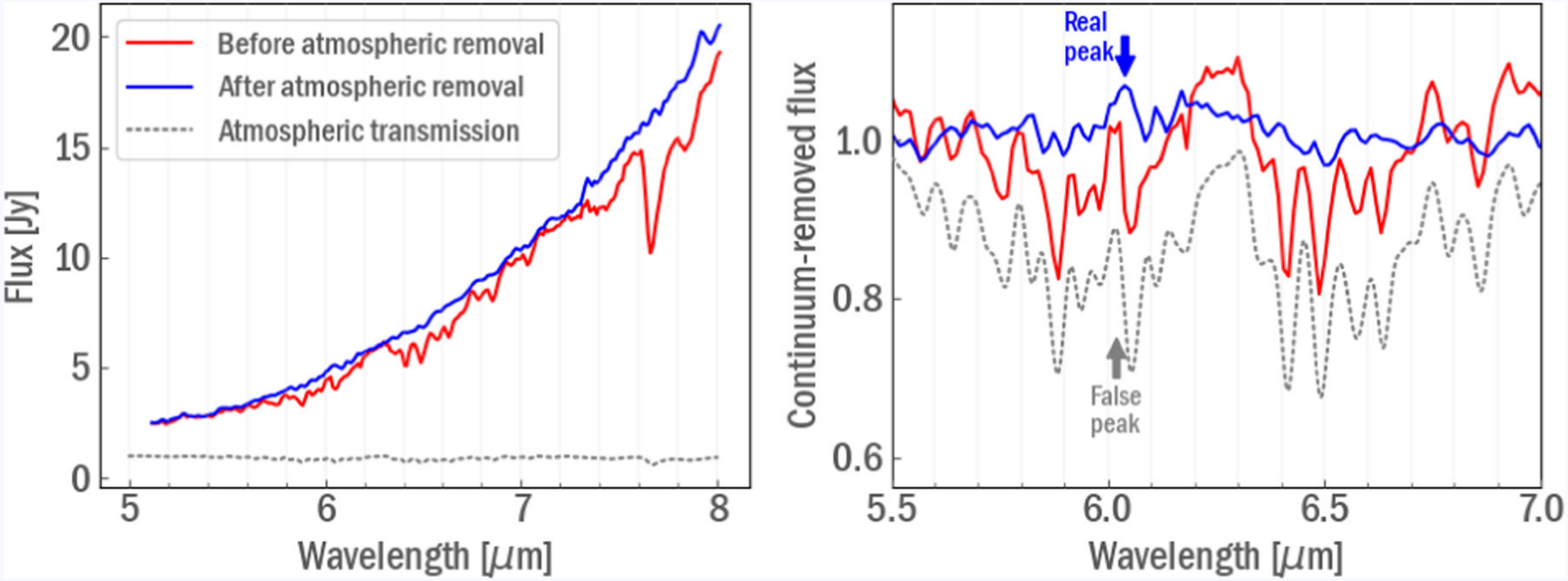


Reach+ in prep.

Scientists Detect Water on the Surface of Asteroids for the First Time Ever

Smithsonian MAGAZINE

Using data from a retired NASA mission, researchers identified unique signs of water molecules on two space rocks, unlocking new insight into how water may have arrived on Earth



Detection of the 6 μm water feature on S-Type asteroids, Iris and Massalia.

Water abundance 454 ± 202 $\mu g\ g^{-1}$ and 448 ± 209 $\mu g\ g^{-1}$, consistent with values found on the sunlit Moon.

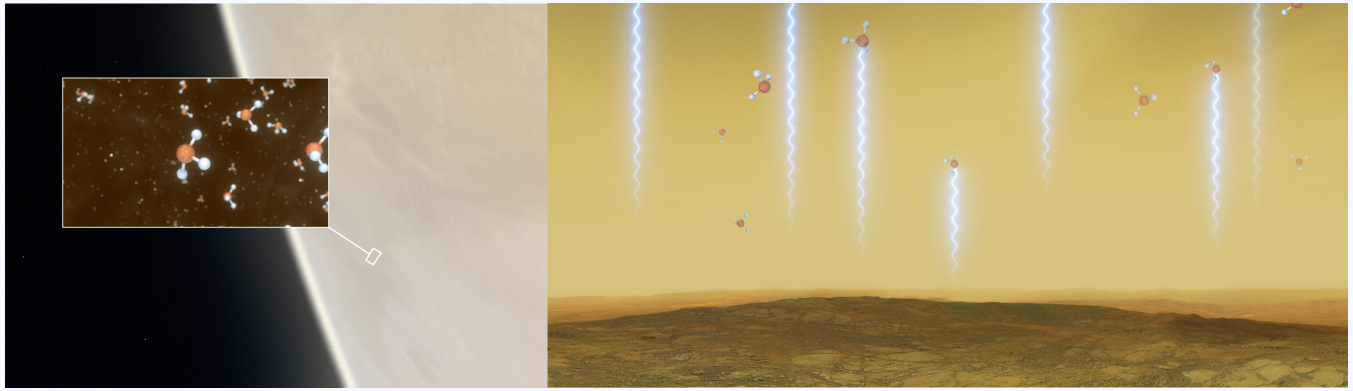
Arredondo+ 2024

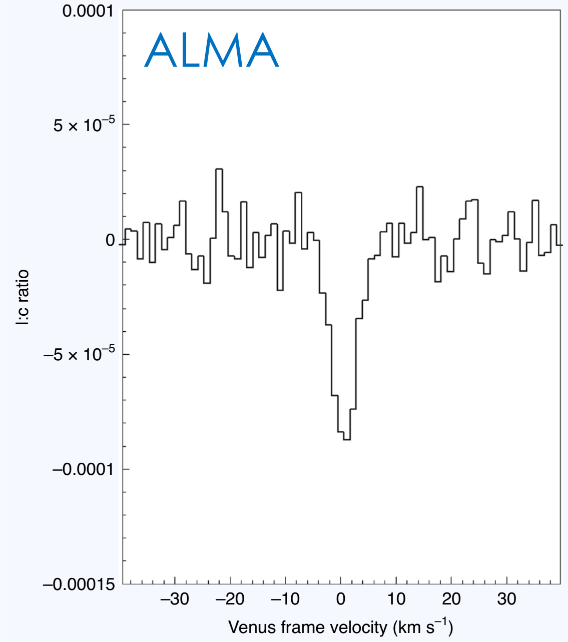
PHOSPHINE ON VENUS

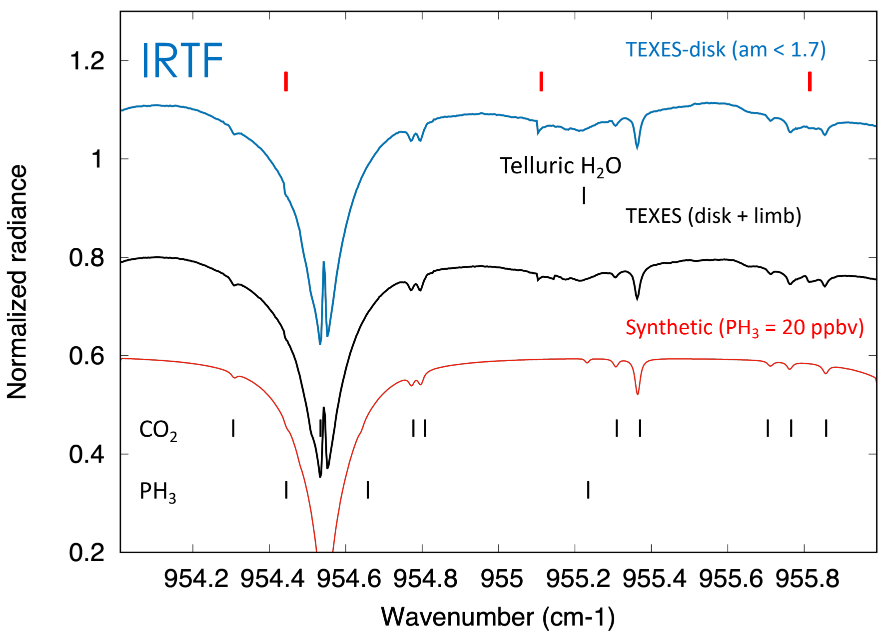
Submmm detection of PH_3 at ~20 ppb in the atmosphere of Venus (ALMA+JCMT).

Could originate from unknown photochemistry of geochemistry, or by analogy with biological production of PH_3 on Earth, from the presence of life.

Inconsistent with a stringent IR upper limit of 5 ppb (3σ).







Greaves+ 2020 — Encrenaz+ 2020 — At last count, 95 papers in ADS.

PHOSPHINE ON VENUS

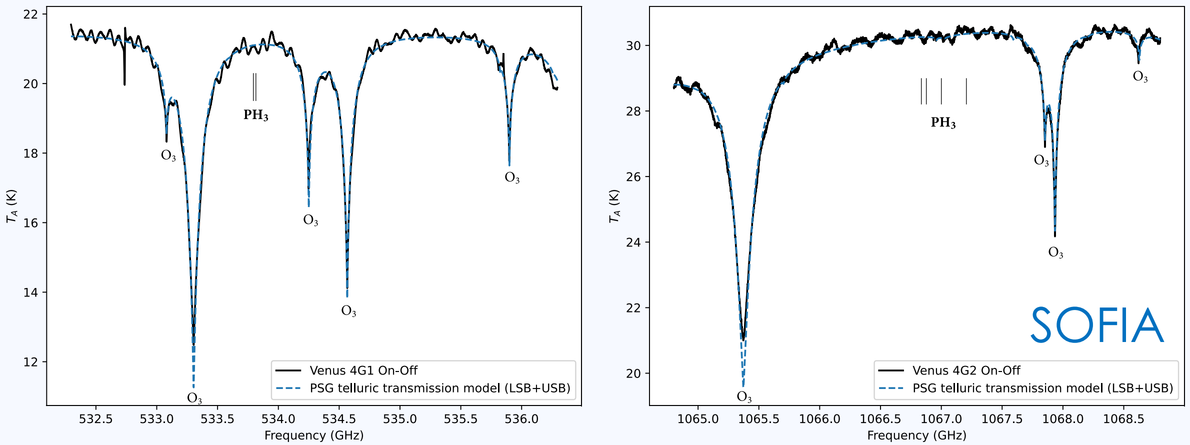
Multiple transitions at 533 and 1067 GHz targeted with SOFIA give a disk averaged upper limit of 0.8 ppb.

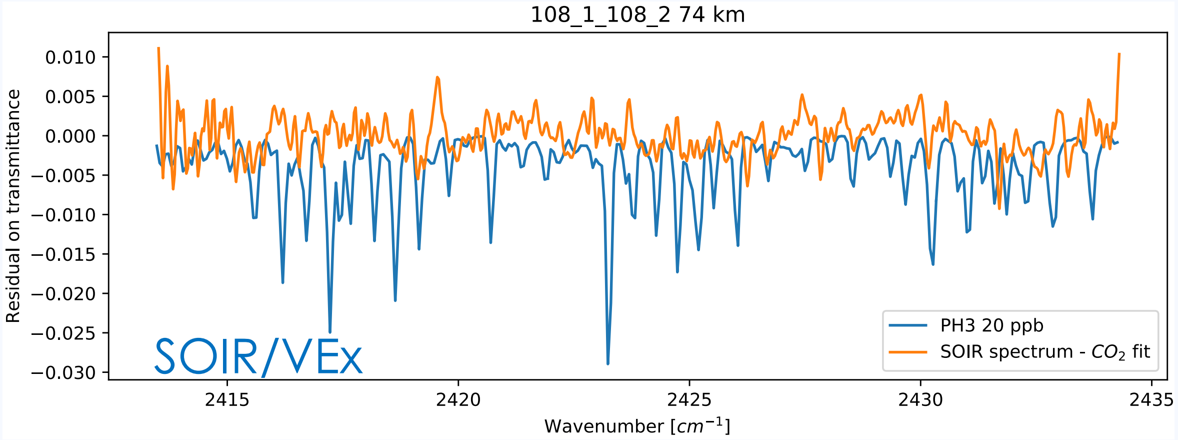
Consistent with and highly complementary to Venus Express solar occultation measurements (<1 ppb).

Two separate questions:

- Is the detection real?
- If so, does it imply a biological source or undiscovered abiotic pathways?

Availability of water in the Venus cloud deck, as quantified by the “water activity” parameter, is 2 orders of magnitude below the limit for known extremophiles.





Cordiner+ 2023 — Trompet+ 2021 — Hallsworth+ 2021

ATOMIC OXYGEN ON VENUS

Key species in the Venus mesosphere and exosphere.

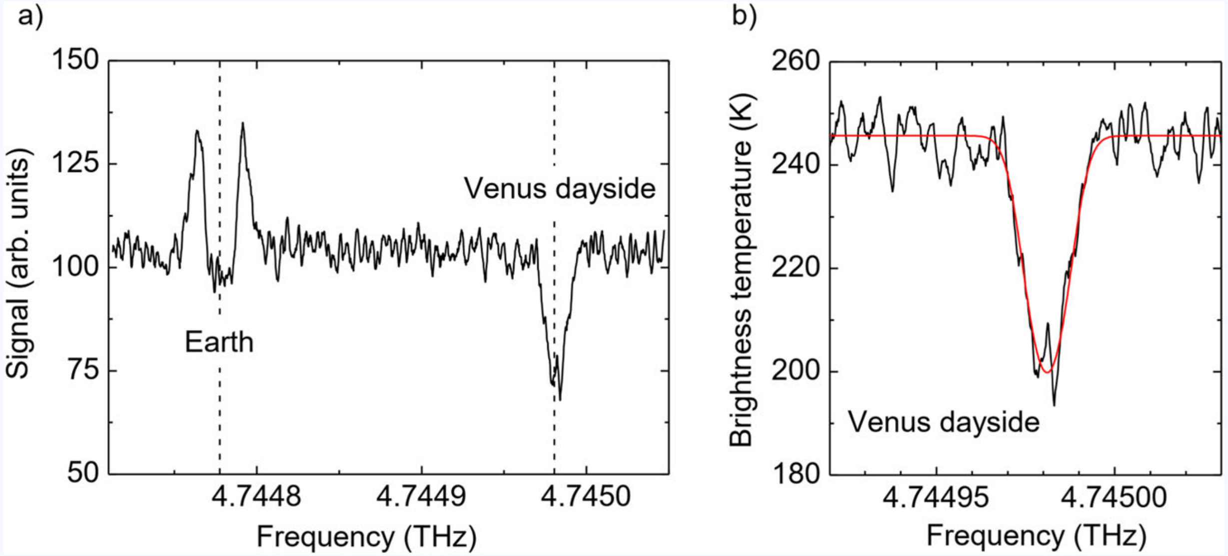
Peaks in the transition region between the retrograde zonal flow below 70 km and the subsolar to antisolar flow above 120 km.

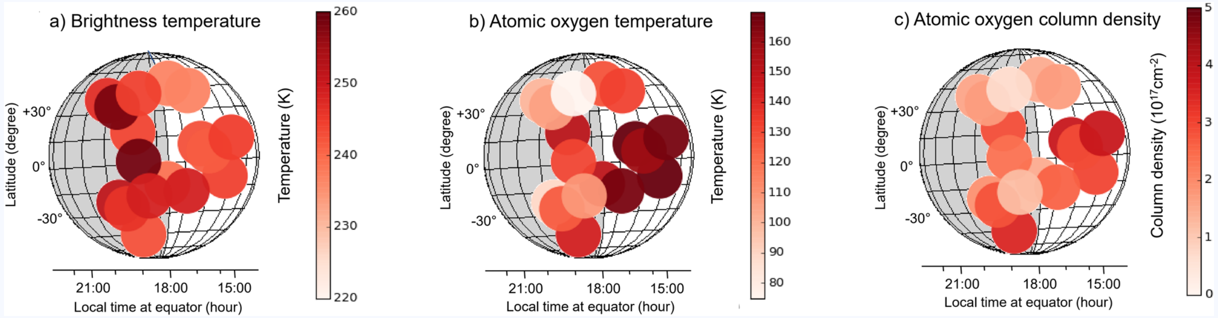
Direct detection of the [OI] 63 µm line on the dayside and the nightside.

Maximum column density on the dayside, produced by photolysis of CO and CO_2.

Transported by the global circulation toward the antisolar point.

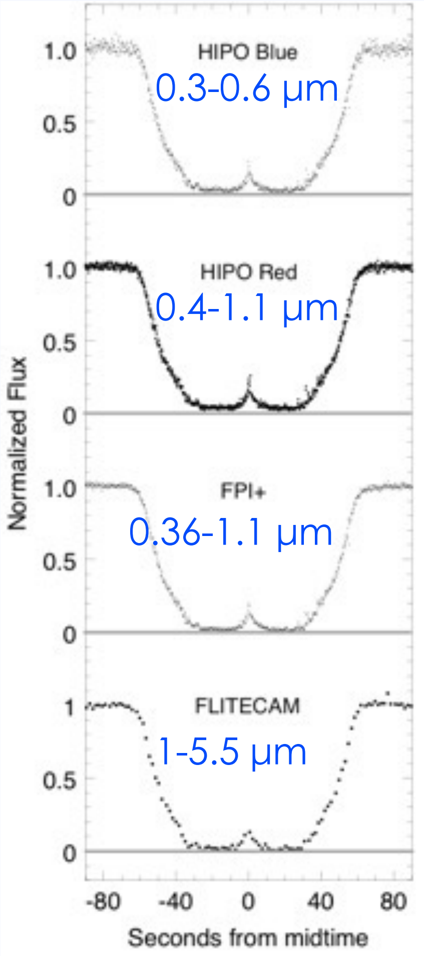
Results support future Venus missions, DAVINCI (NASA) and EnVision (ESA).

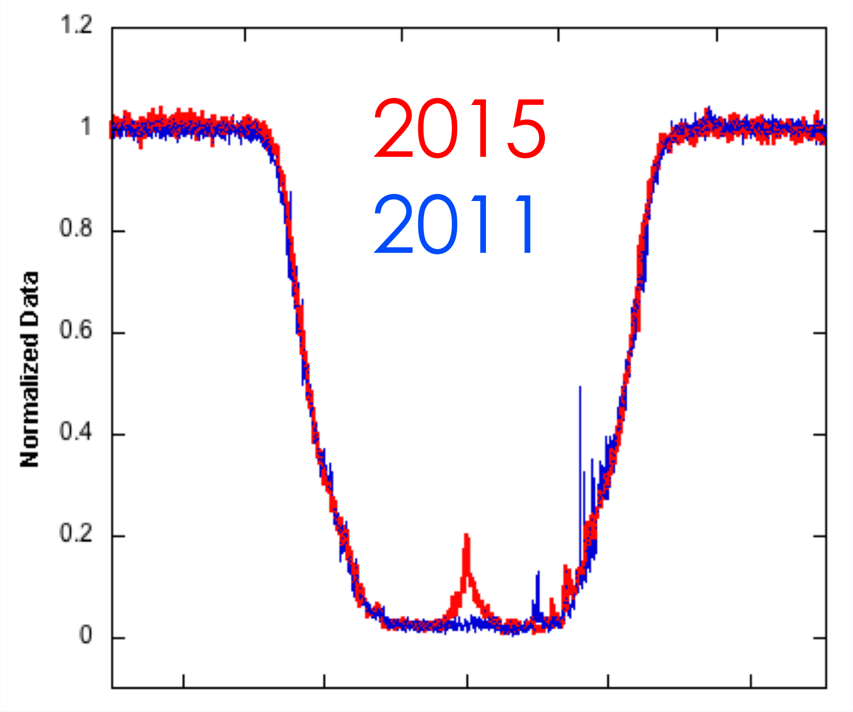




Hübers+ 2023

PLUTO OCCULTATIONS

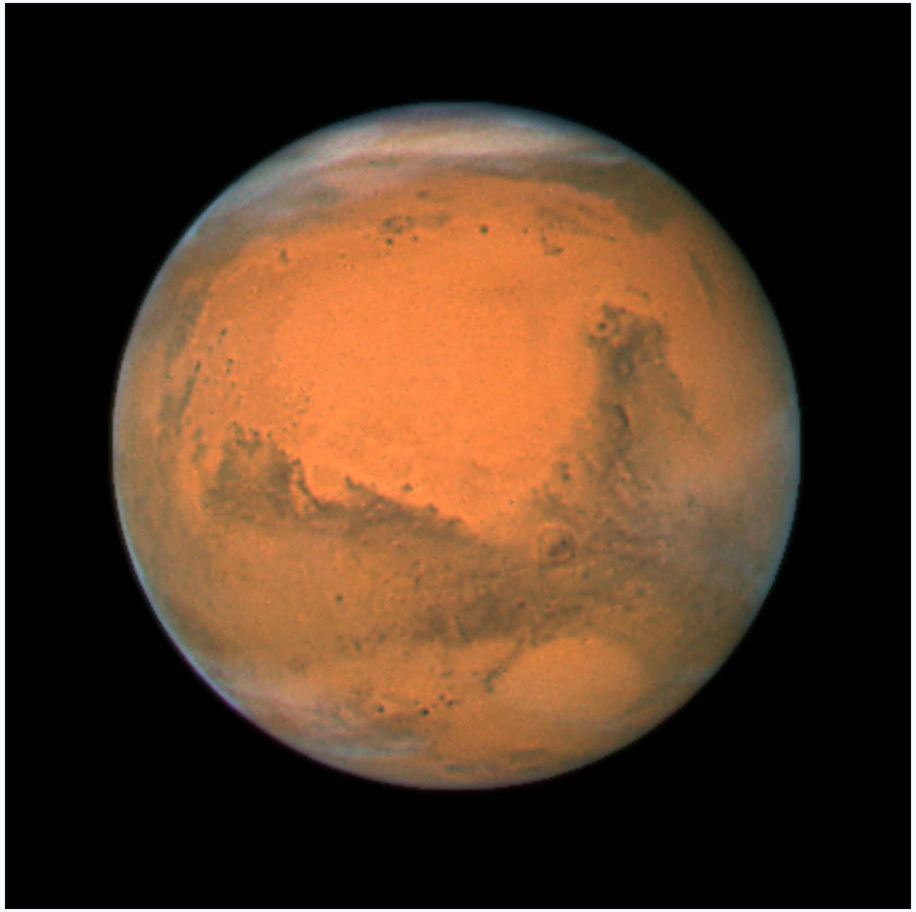




- Early KAO highlights — detection of the Uranian ring system and of the atmosphere of Pluto.
- "Central flash" provides constraints on *haze densities* and thermal gradients in lower atmosphere, bounds on haze particle sizes.
- Multi-wavelength observations allow analysis of atmospheric profiles and aerosol or haze content.
- Multi-epoch observations allow studies of a possible *temporal variability*.
- Stability of Pluto's atmosphere over 25 years.

Person et al. 2017

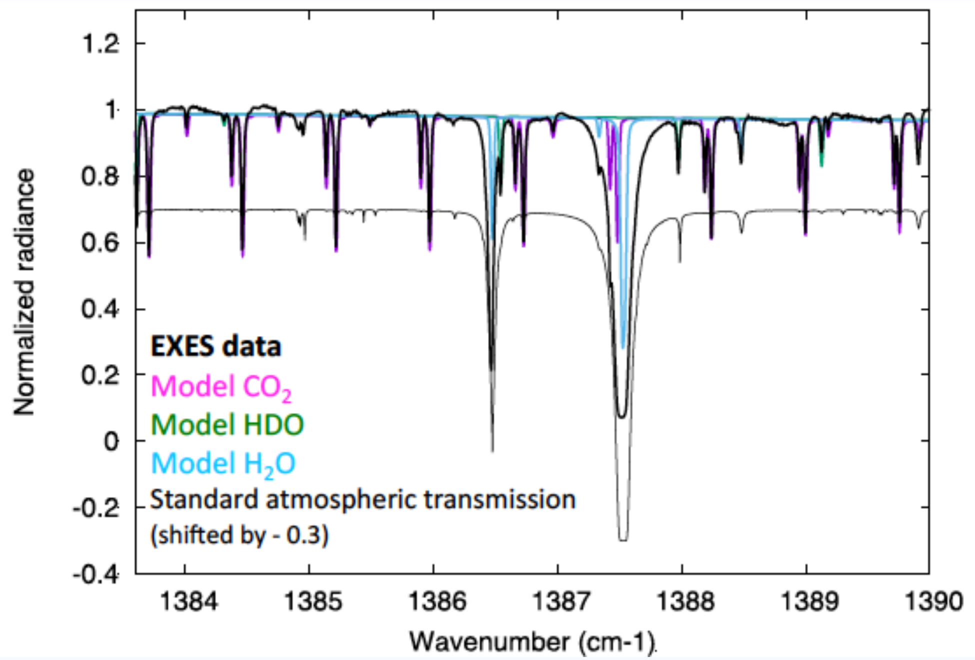
D/H ON MARS

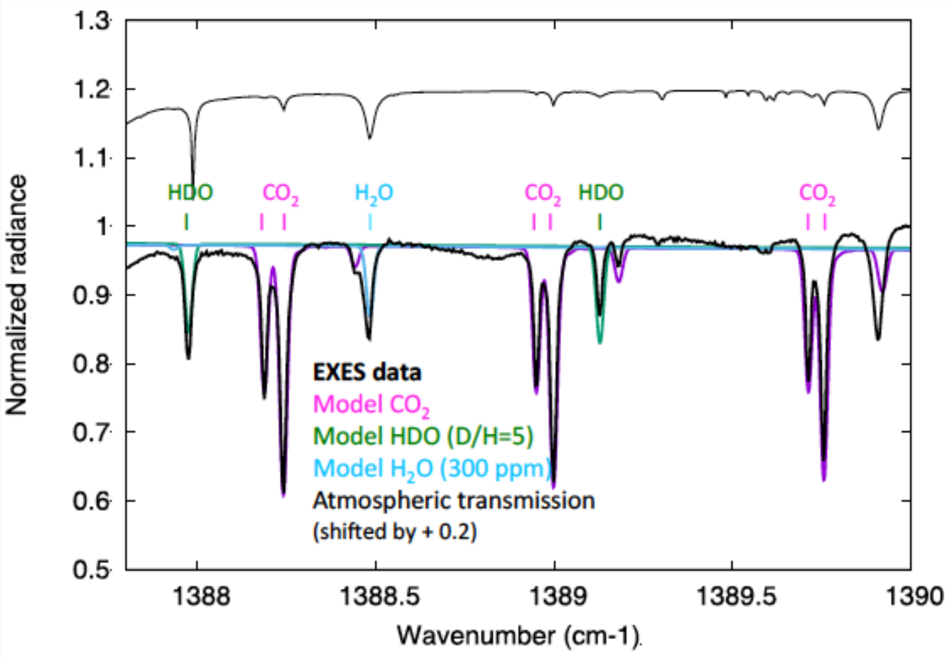


- D/H is a key diagnostic of history of water on the planet
- Main mechanism responsible for D enrichment is fractionation through *different escape rates*
- Vapor pressure isotopic effect (VPIE) — fractionation mechanism associated with sublimation/condensation processes
- At condensation, D/H enhanced in the ice
- D/H in water vapor expected to be maximum at north pole at northern summer solstice
- Observations help understanding the *sources and sinks* through monitoring sublimation and condensation processes

Credits: NASA

EXES OBSERVATIONS OF MARS

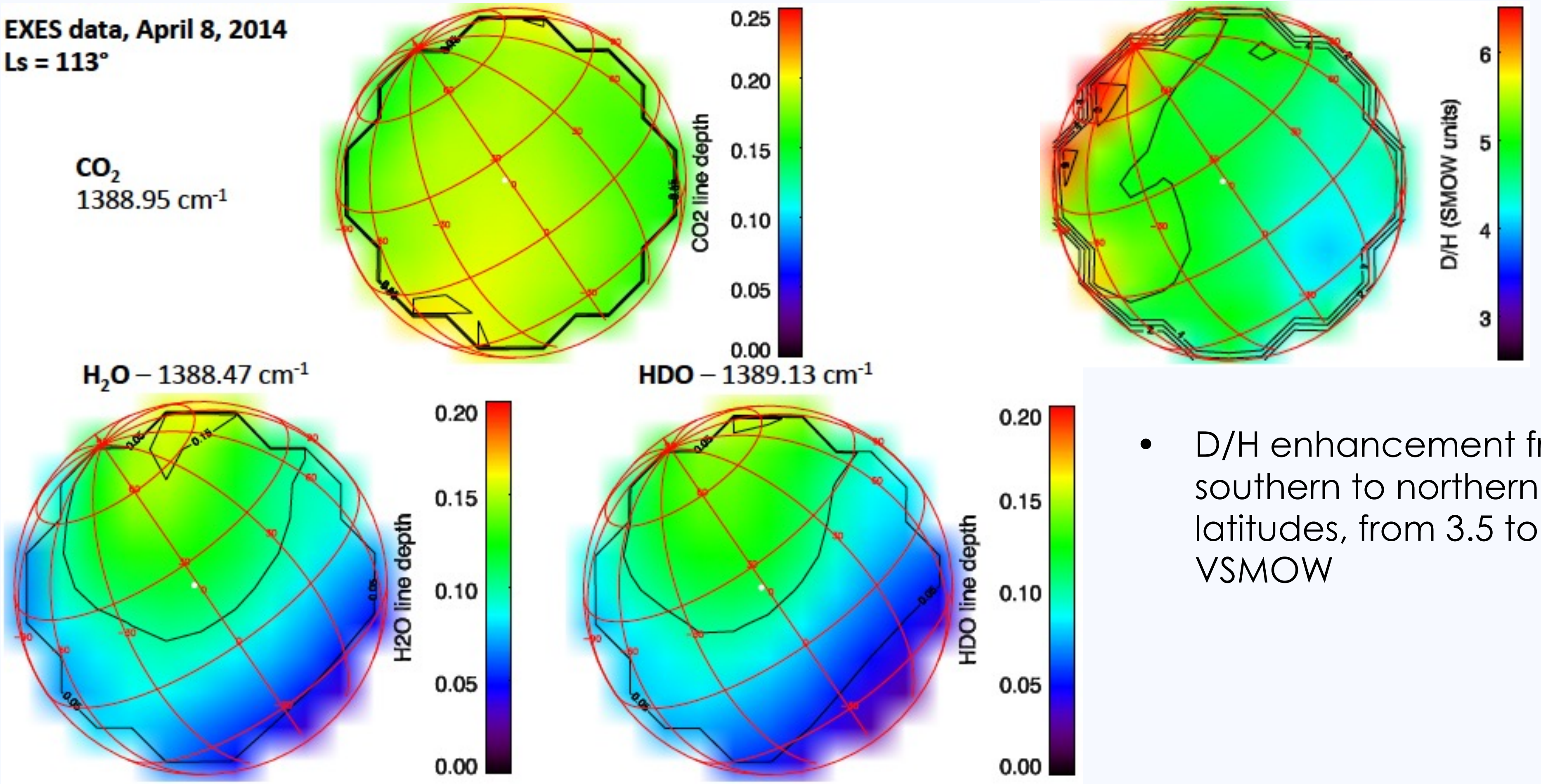




- EXES, R=60,000, 7.2 μm range
- Mars disk diameter close to opposition ~15", beam size 3"
- A combination of weak and strong lines of water, HDO, and CO_2

Encrenaz+ 2017

D/H IN MARS ATMOSPHERE



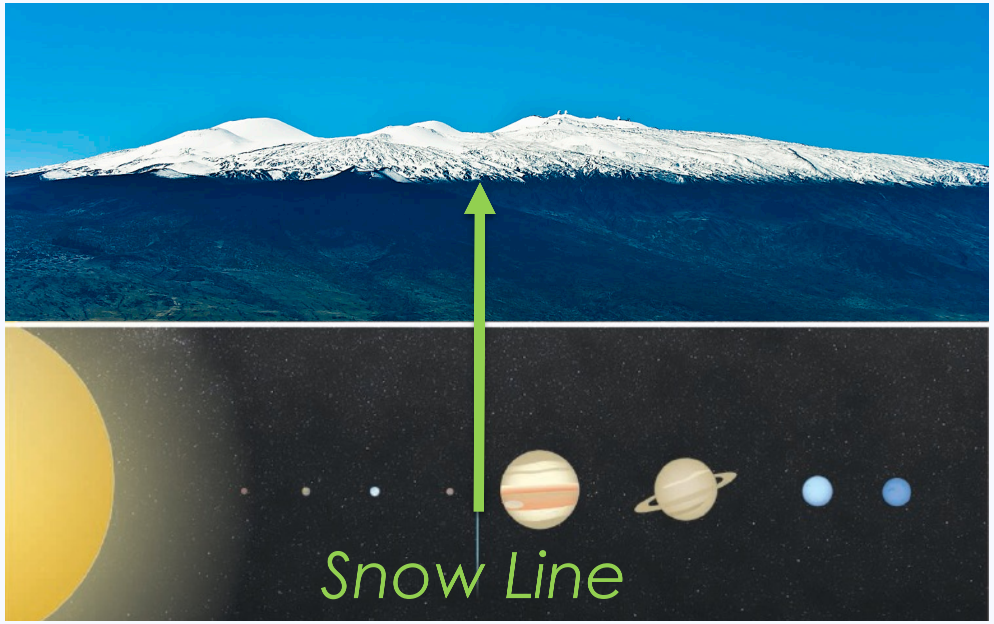
- D/H enhancement from southern to northern latitudes, from 3.5 to 6.0 × VSMOW

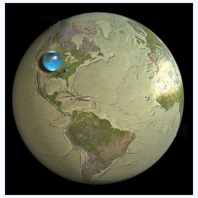
- Distinct enhancement of H_2O and HDO with respect to CO_2 toward the polar region
- Disks integrated D/H = $6.8(+1.6,-1.0)\times10^{-4}$ or 4.4 times VSMOW

Encrenaz+ 2017

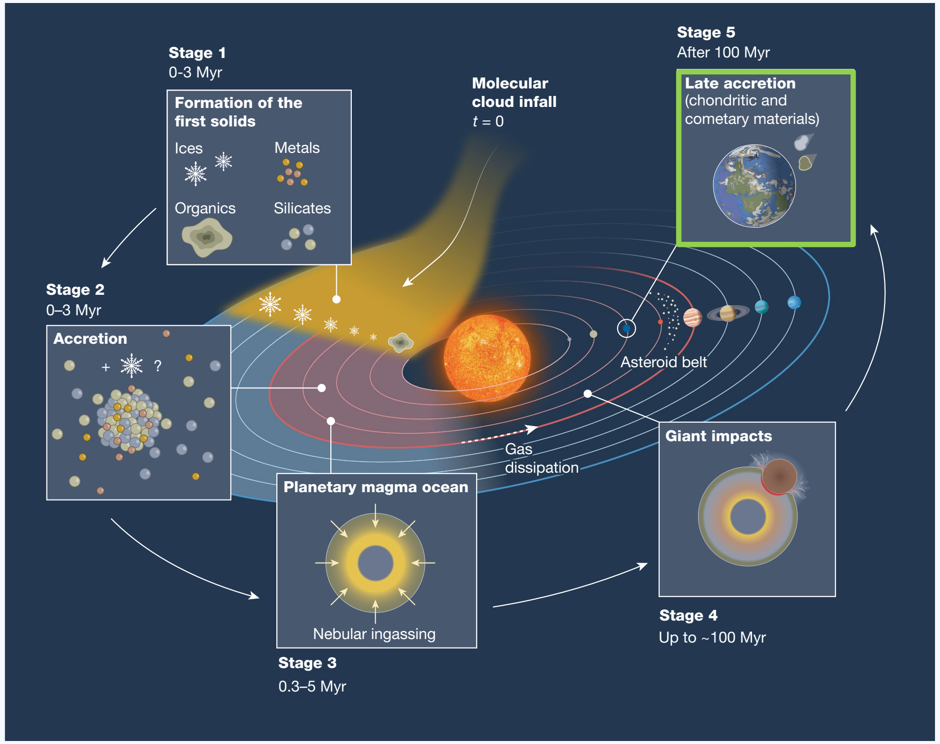
WATER IN THE SOLAR SYSTEM

- Water mass fraction increases with distance from the Sun (from 0.1% at 1 au to 50%).
- "Textbook model": temperature in the terrestrial planet zone too high for water ice to exist.
- Water and organics had to be delivered later by impacts of comet- or asteroid-like bodies.





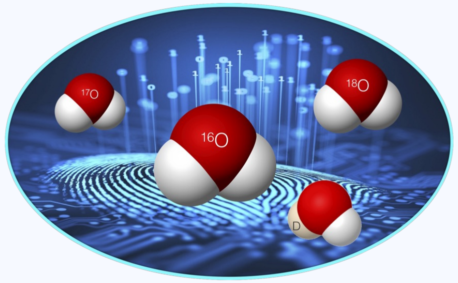
Multiple stages of volatile incorporation



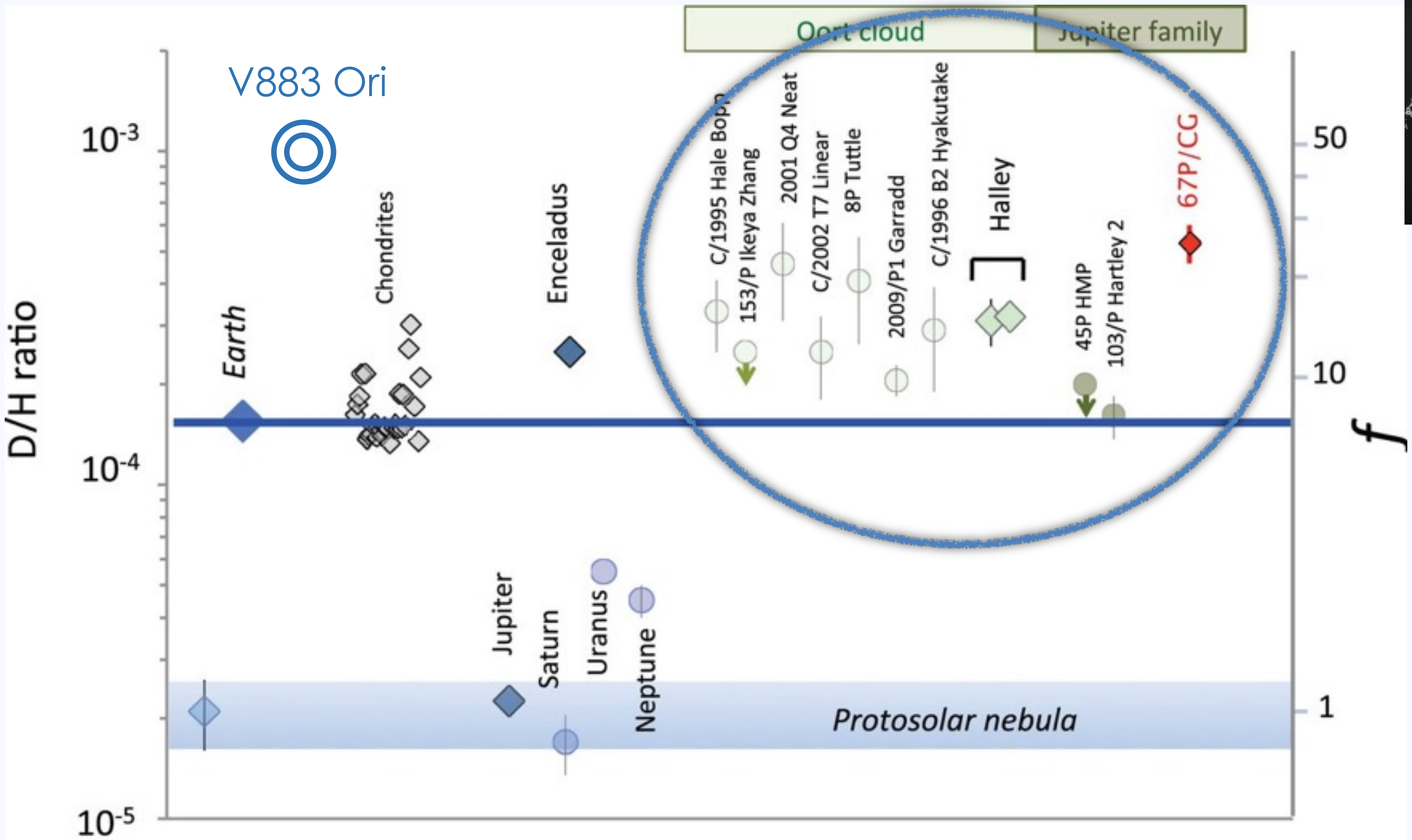
- Volatiles on Earth and the other terrestrial planets appear to have been heterogeneously sourced from different Solar System reservoirs.
- Late accretion of chondritic and cometary materials is an important stage.

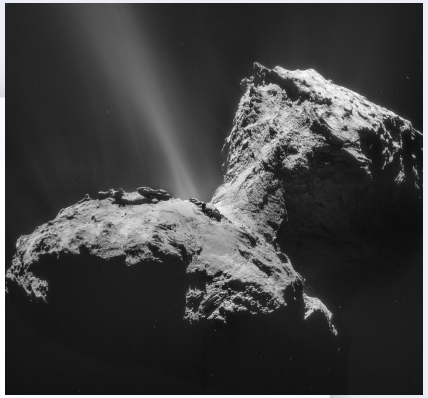
van Dishoeck et al. 2014 *Broadley et al. 2022* *Woo, Morbidelli et al. 2023*

D/H RATIO IN THE SOLAR SYSTEM



Unique Fingerprint

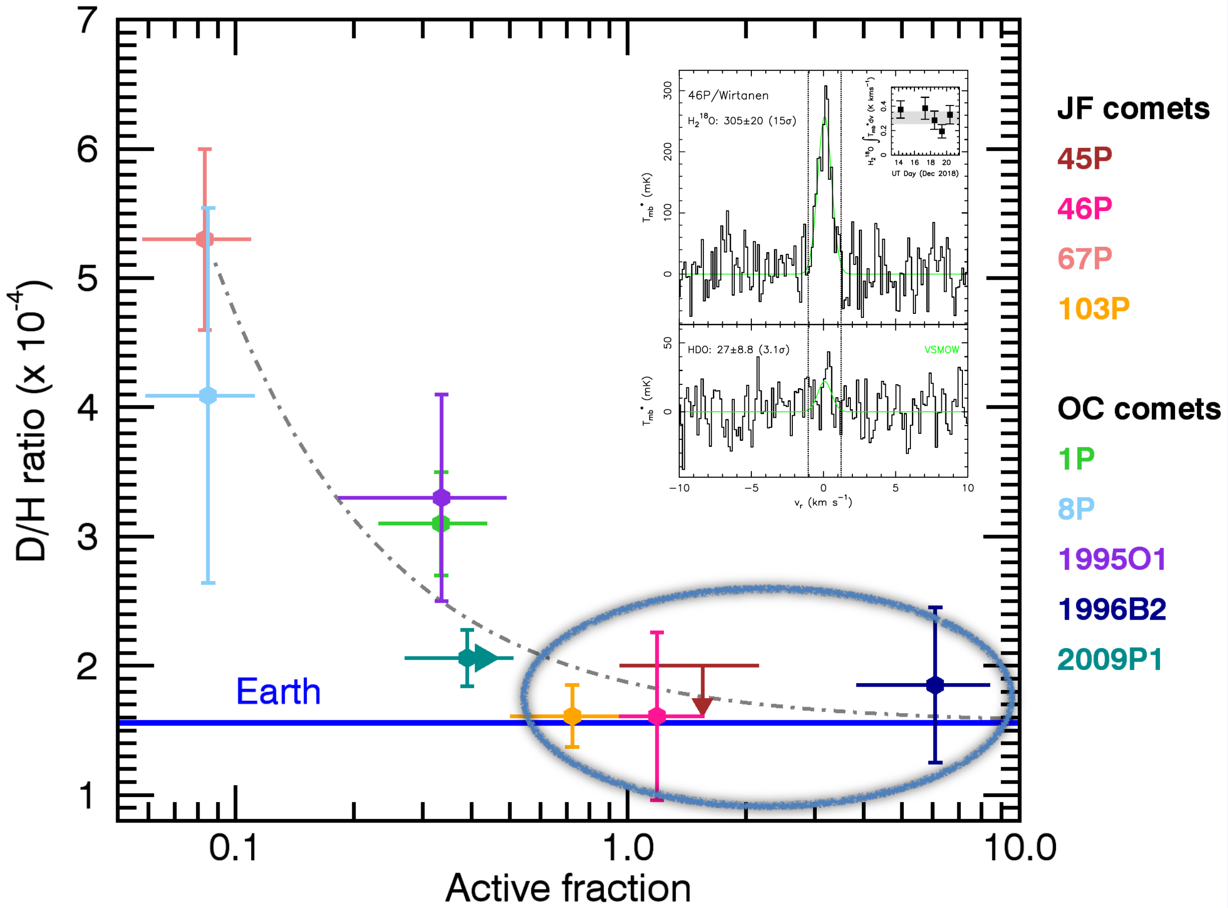




- Comets are tracers of the present day outer Solar System that can be studied using remote sensing techniques (atmospheres)
- Focus on D/H because it is strongly temperature dependent and the observed variations are large, a factor of 3.

Altwegg et al. 2015 *Tobin et al. 2023*

TERRESTRIAL D/H RATIO IN HYPERACTIVE COMETS



Hyperactive typically have terrestrial D/H ratios.

Emit more water molecules than expected given the size of the nucleus.

Presence of sublimating water-ice-rich grains in the coma.

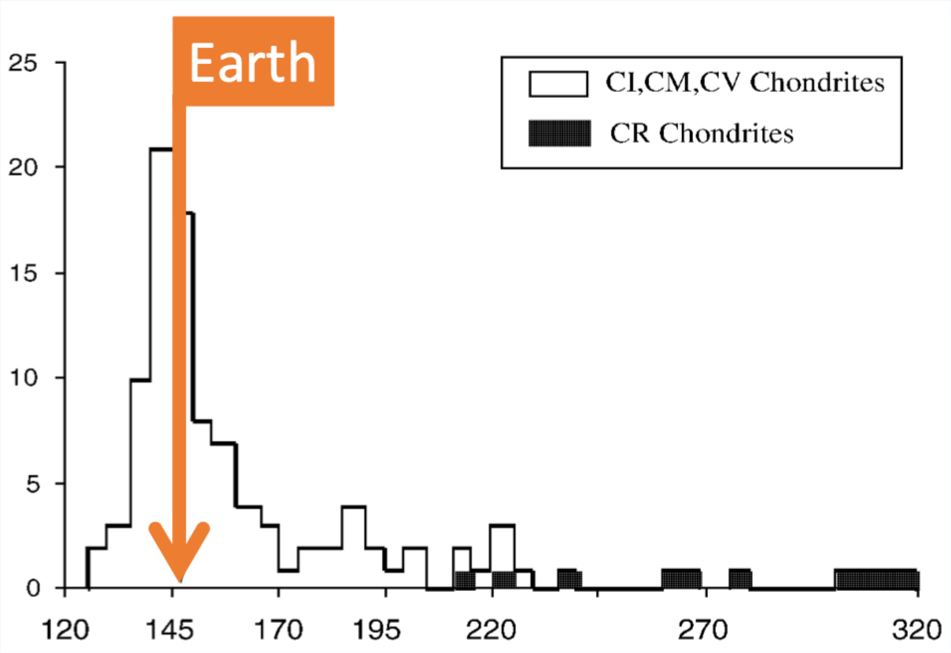
103P/Hartley 2 studied by Deep Impact — both icy grains and water overproduction were observed.

Sublimating icy grains may be more pristine and more representative of the bulk composition of the nucleus.

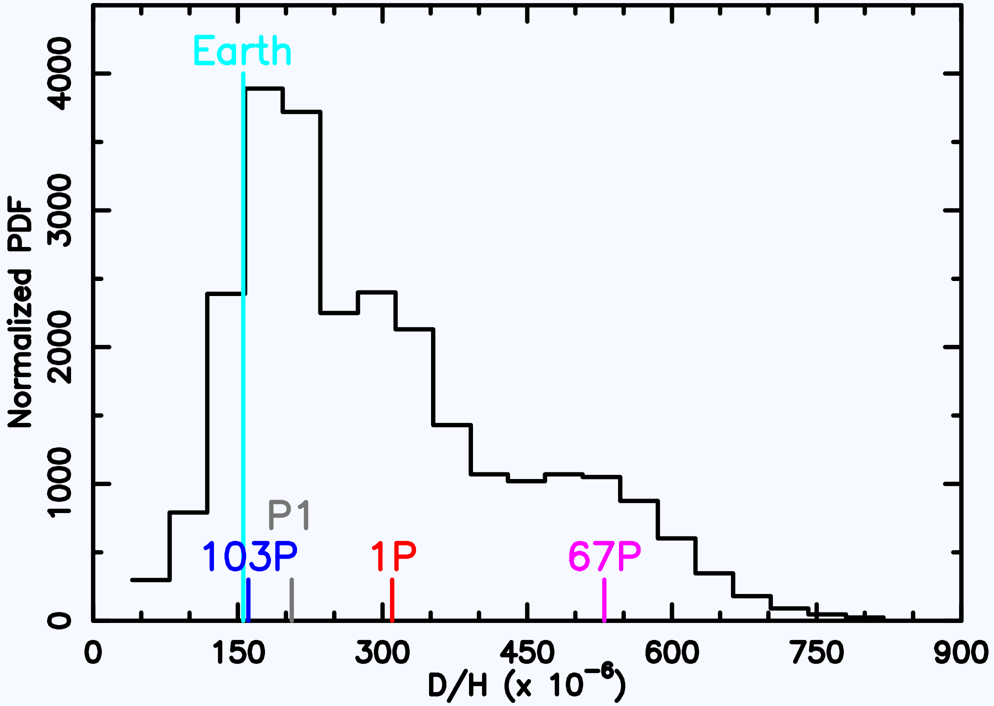
Lis+ 2019

Sunshine+ 2021

D/H DISTRIBUTION: INNER VS. OUTER SOLAR SYSTEM



D/H in the inner Solar System relatively well constrained by measurements in meteorites (100+ measurements).

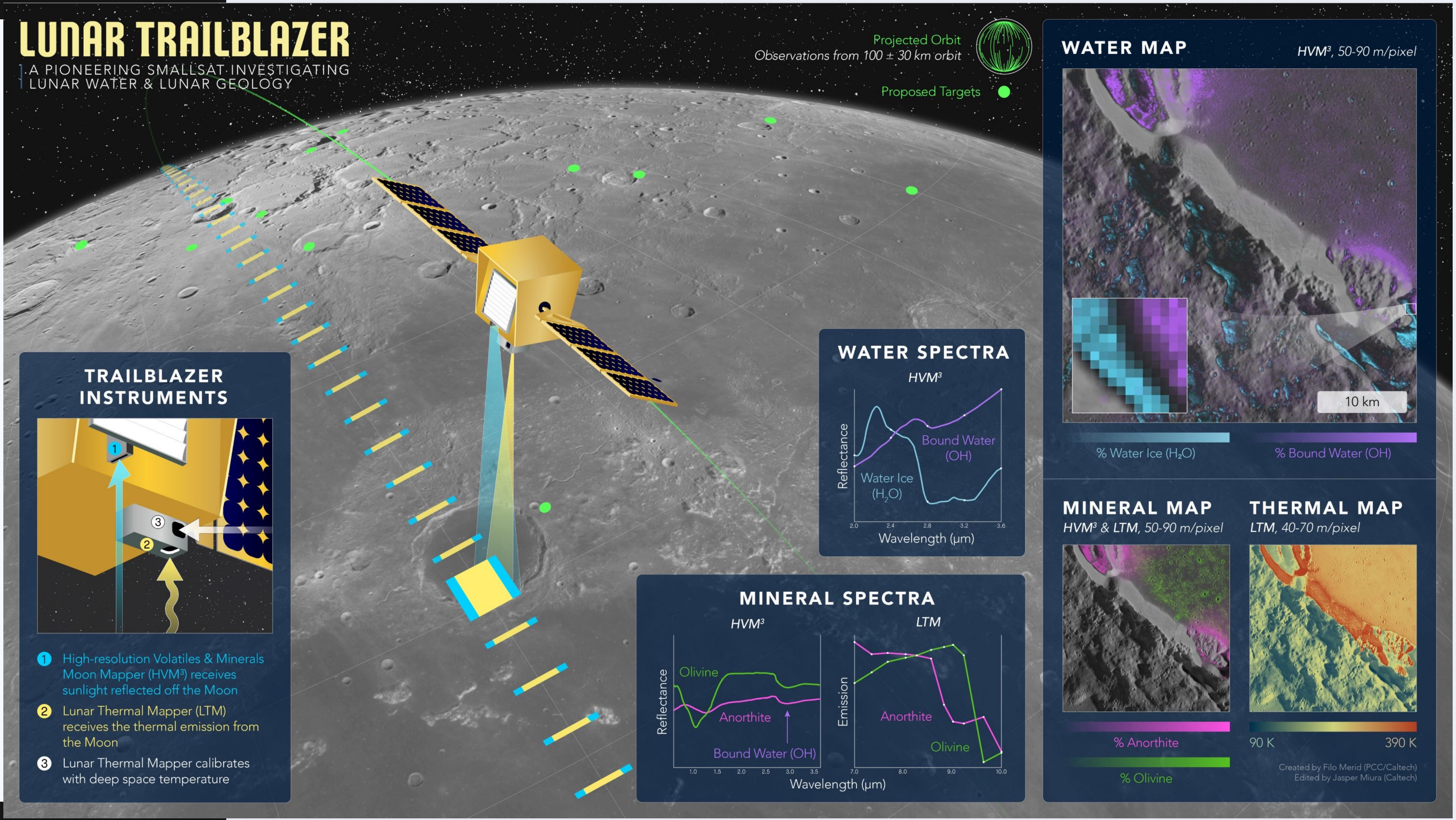


D/H in the outer Solar System poorly constrained – 10 measurements in comets, only 4 accurate (8-10%, 1σ).

Robert 2003

Need a statistical sample to make a meaningful comparison!

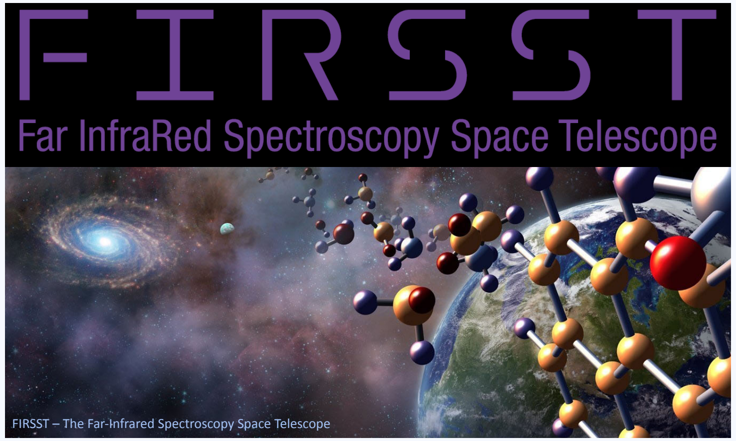
LOOKING INTO THE FUTURE

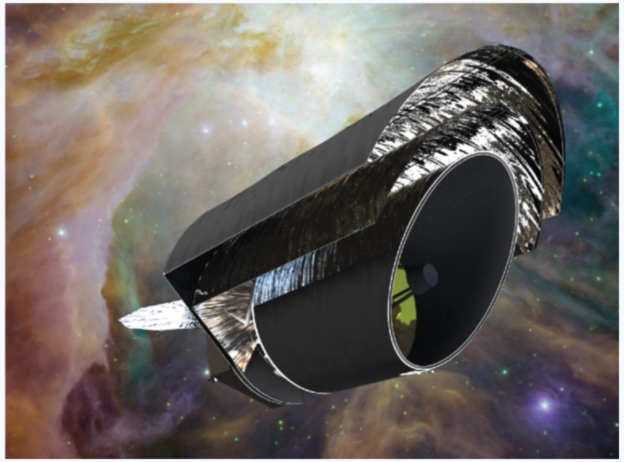


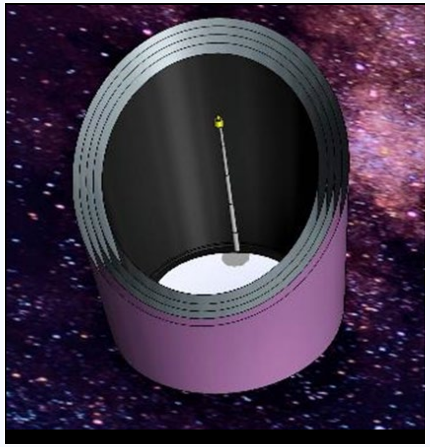
Credits: F. Merid PCC/Caltech

- SIMPLEx mission, PI Bethany Ehlman, Caltech

NBT: ASTROPHYSICS PROBES







FIRSST – PI. A. Coorey (U.C. Irvine)

- *Spitzer*-like 1.8-m telescope cooled to 4.7 K
- Direct detection and heterodyne spectroscopy instruments (35 – 600 μm)
- Science themes
  - Origin and evolution of planet forming disks
  - Trail of water from molecular clouds to oceans
  - Galaxy assembly

PRIMA – PI. J. Glenn (NASA/GSFC)

- 1.8-m telescope cooled to 4.5 K
- Direct detection grating spectrometer, FTS (24 – 235 μm)
- Hyperspectral imager (24 – 80 μm) with polarimetric capabilities (80 – 235 μm)
- Science themes
  - Evolution of galactic systems
  - Formation of planets
  - Rise of dust and metals

SALTUS – PI. C. Walker (U. Arizona)

- 20-m off-axis telescope, 45 K optics, adaptive optics
- Coherent and incoherent spectroscopy/imaging
- Science themes
  - Formation and evolution of planetary systems
  - Galaxy evolution
  - Nature of supermassive black holes

Solar System studies are not a driver, but all these missions would enable such studies!
Example: PRIMA would measure D/H ratio in 30 comets in a 240 h per year program.

SOFIA LIVES THROUGH ITS ARCHIVE

Credits: SOFIA/USRA