SOLAR SYSTEM SCIENCE – RECENT HIGHLIGHTS FROM SOFIA AND ALMA

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LAKE ARROWHEAD, FEBRUARY 28, 2022

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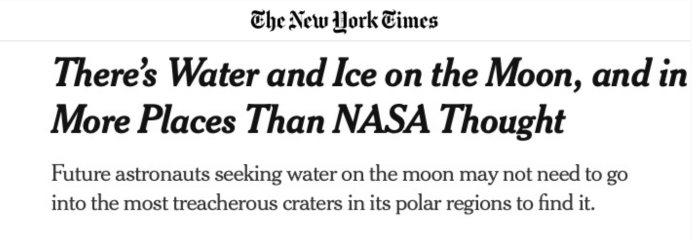
California Institute of Technology

OUTLINE

Demonstrate current observational capabilities

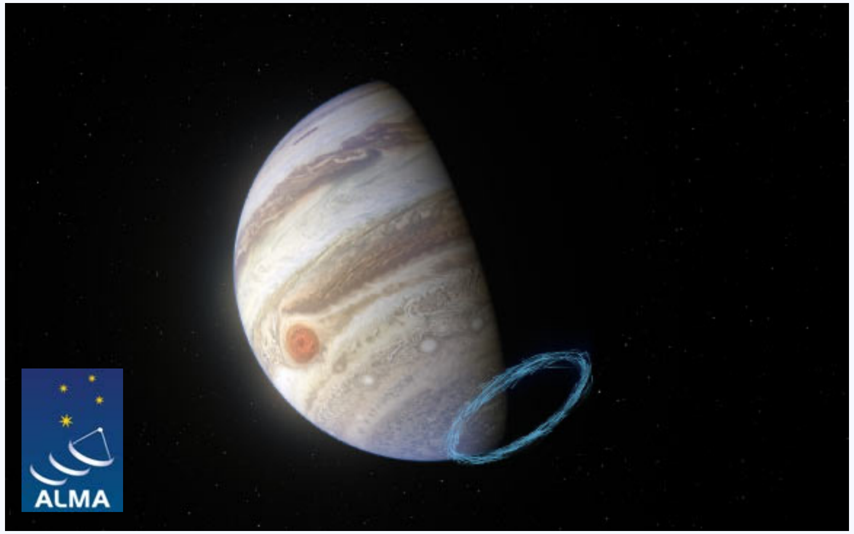
Selected recent results:

- Lunar water
- Winds on Jupiter
- Phosphine on Venus
- Comets
- Occultations


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.



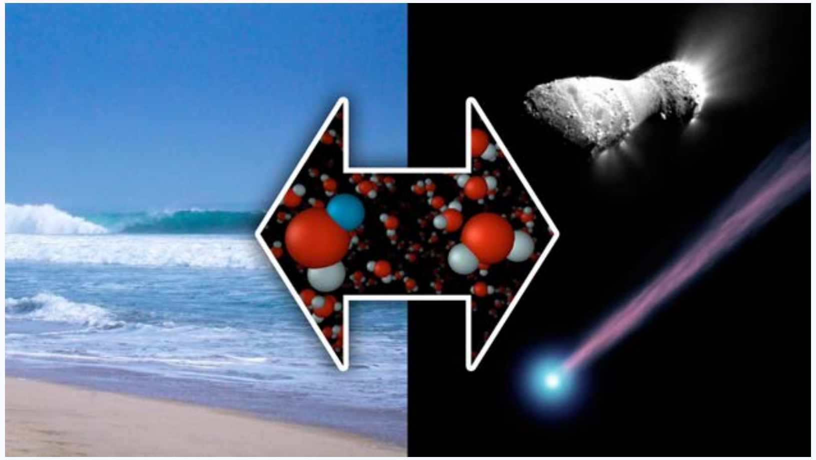

SPACE

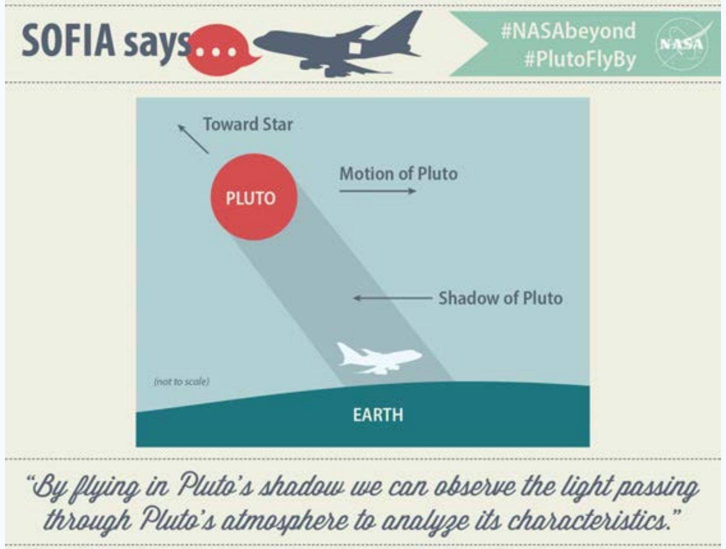
Hyperactive Comets Hint at Origins of Earth's Oceans

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

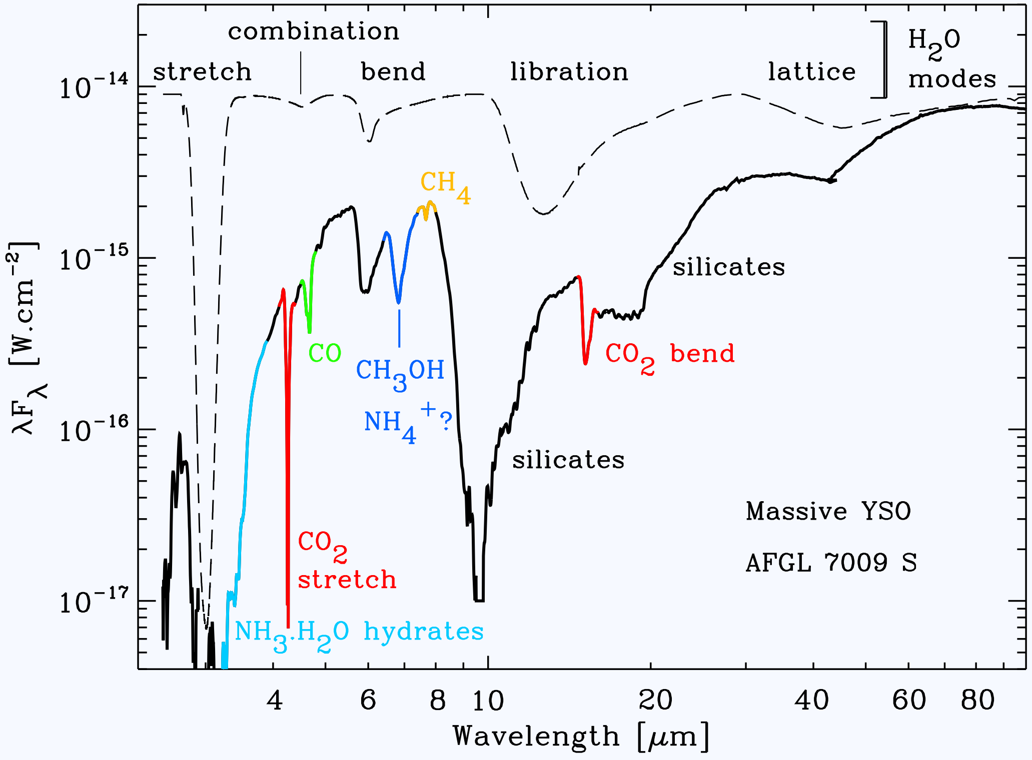
By Nola Taylor Redd on May 9, 2019

SCIENTIFIC AMERICAN 175





LUNAR HYDRATION



Boogert et al. 2015, ARAA

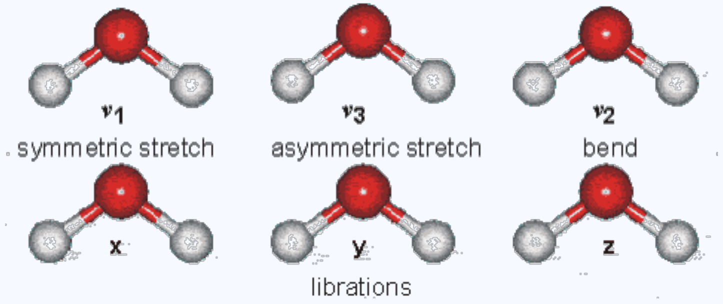
Apollo samples:
- Initial analysis showed no minerals containing water
- Advances in instrumentation 4 – 46 ppm H_2O

2009: Independent detections of the 3 μm hydration band by Chandrayaan-1, Deep Impact, and Cassini – widespread, shows variations with latitude, temperature, and lunar time

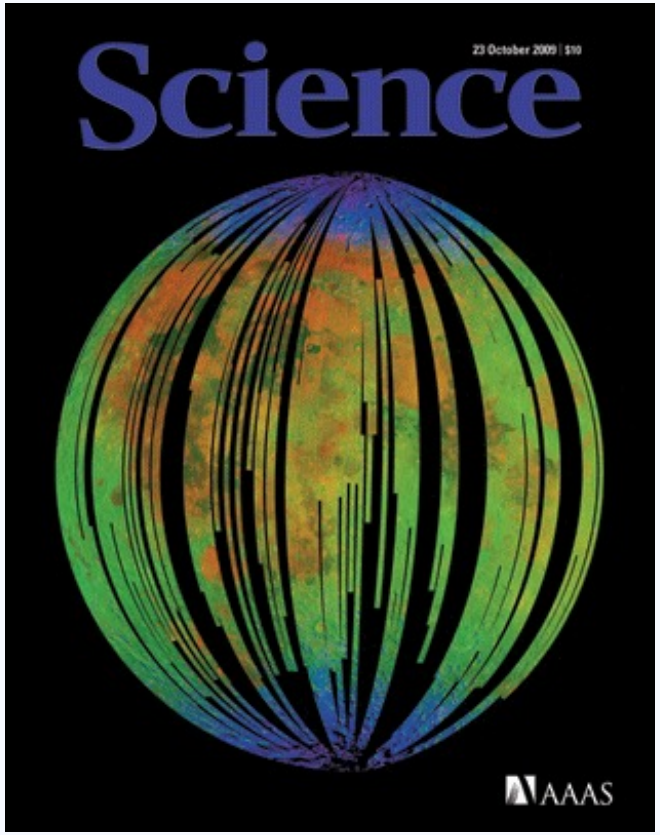
The 3 μm band (symmetric and asymmetric stretch of the OH bond) cannot distinguish between water and hydroxyl

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



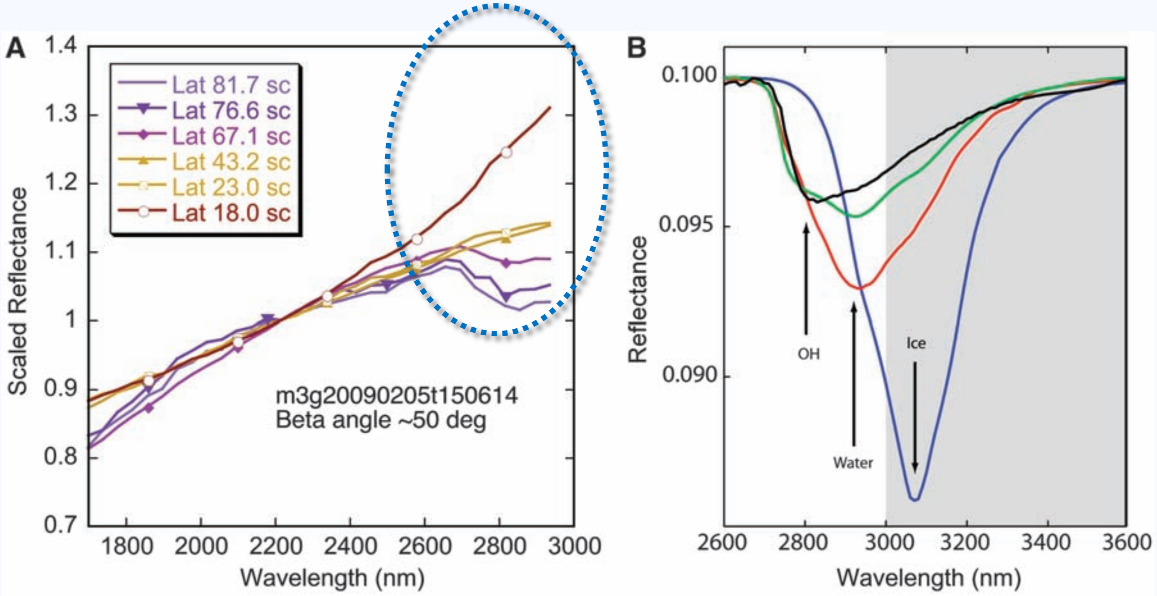
CHANDRAYAAN-1 -- MOON MINERALOGY MAPPER (M^3)



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

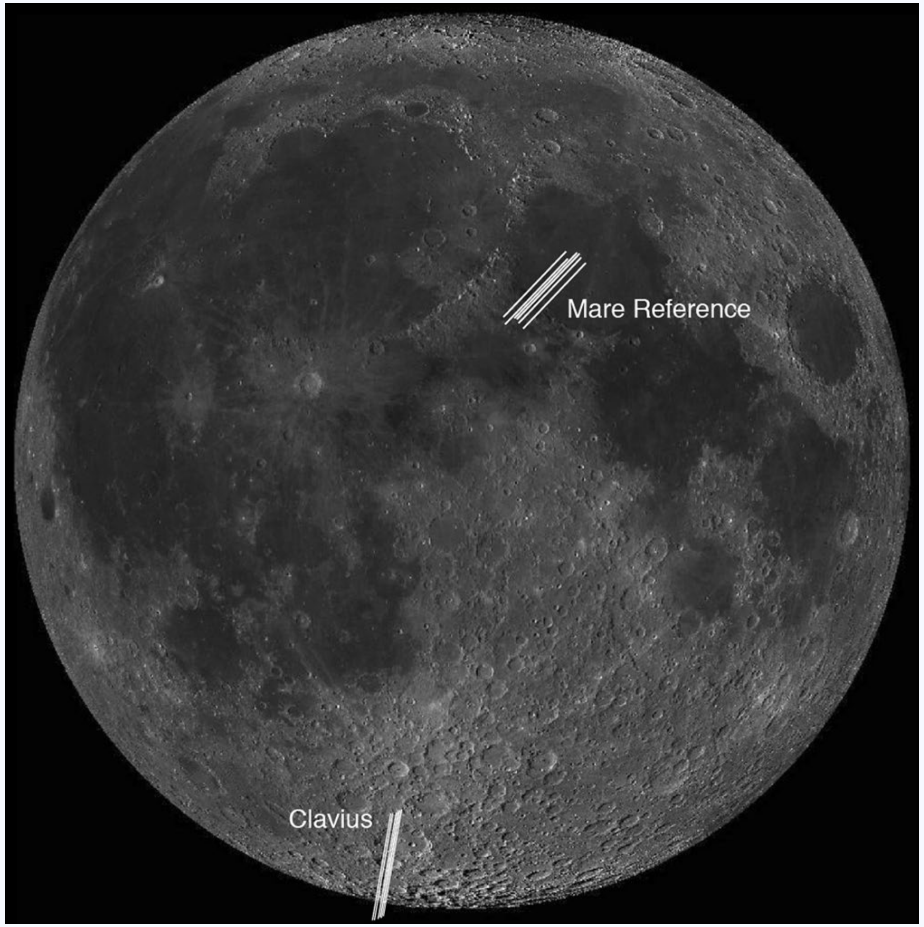
Visible and NIR imaging spectrometer (JPL), 0.43–3 μm, 260 channels; 70 m resolution

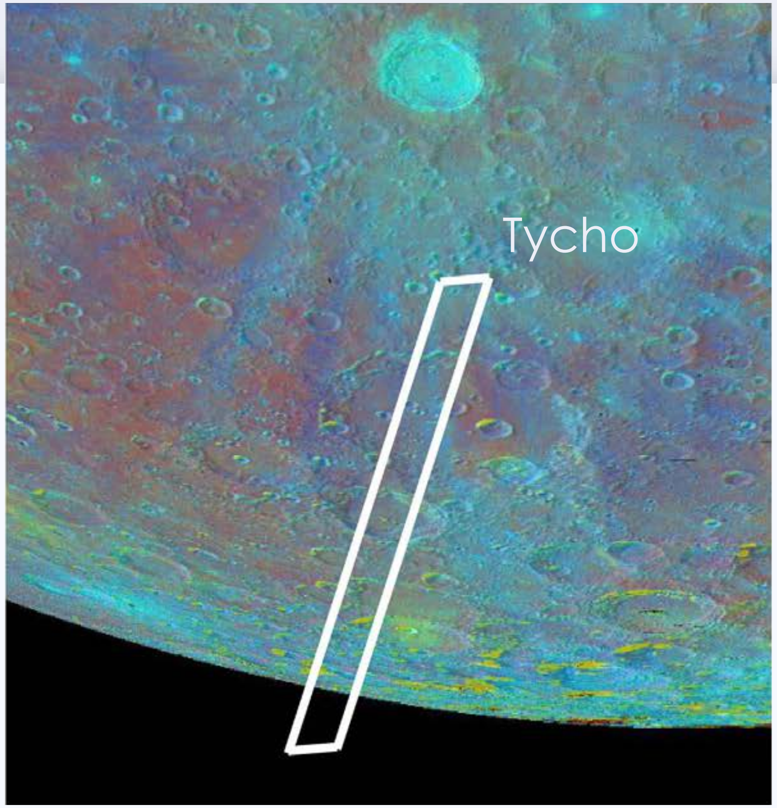
Absorption features at 2.8 – 3 μm, near the poles, attributed to hydroxyl or water-bearing materials



Pieters et al. 2009

SOFIA OBSERVATIONS



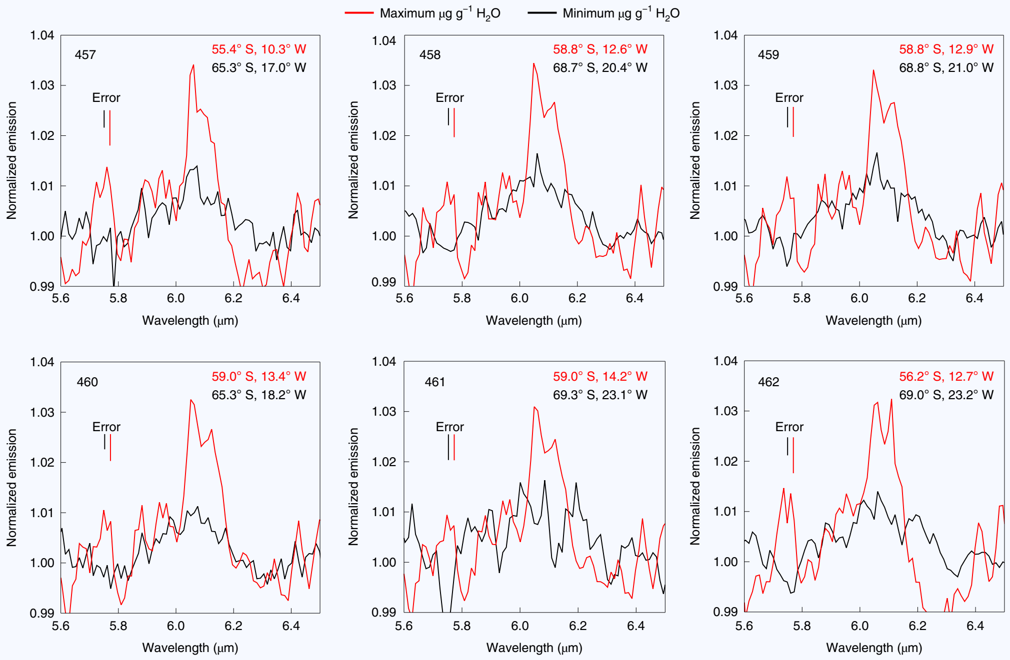


FORCAST targets: two sunlit locations

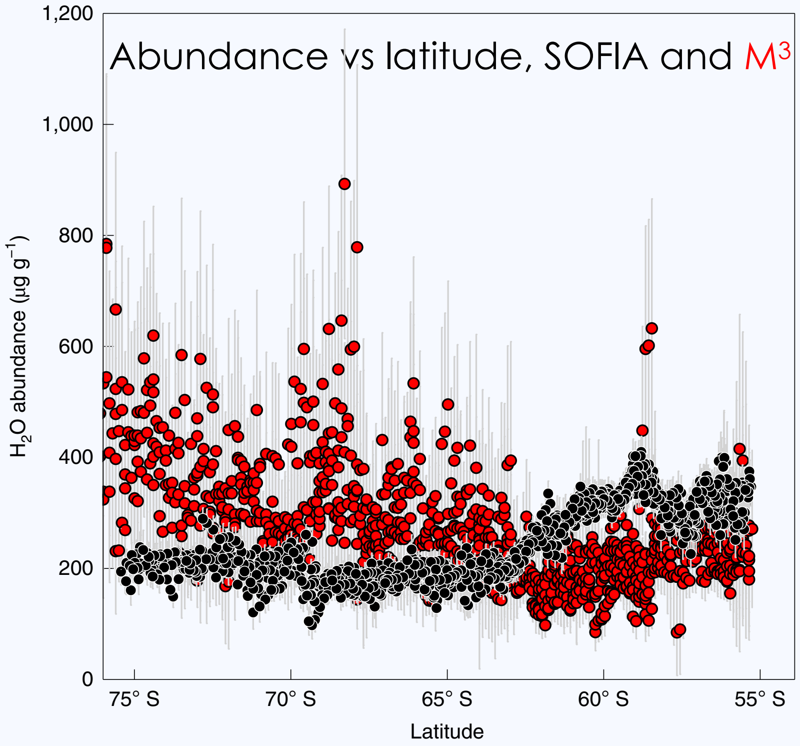
- A high southern latitude region near Clavius crater (high total water abundance in the M^3 data)
- A low-latitude portion of Mare Serenitalis (control region with little or no water)

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

Honnibal 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

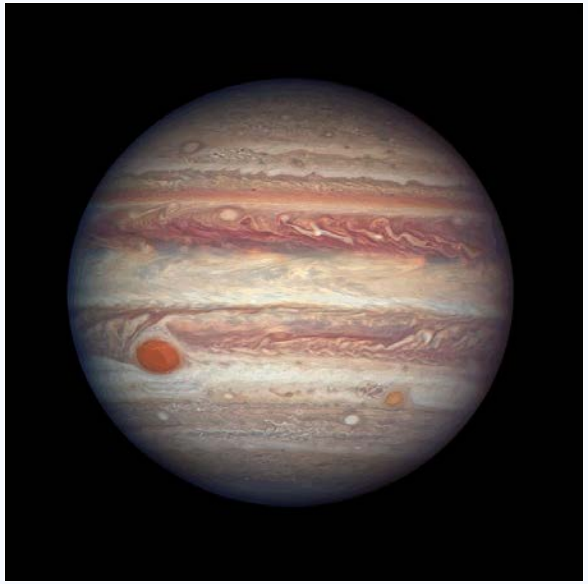
The measured water abundance implies 300 to 1300 µg g^{-1} H_2O in impact glasses – within the range of laboratory measurements

Water entrained in impact glass explains the 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 impact from pre-existing lunar material than impact delivered water

A follow-up SOFIA Legacy Program currently under way

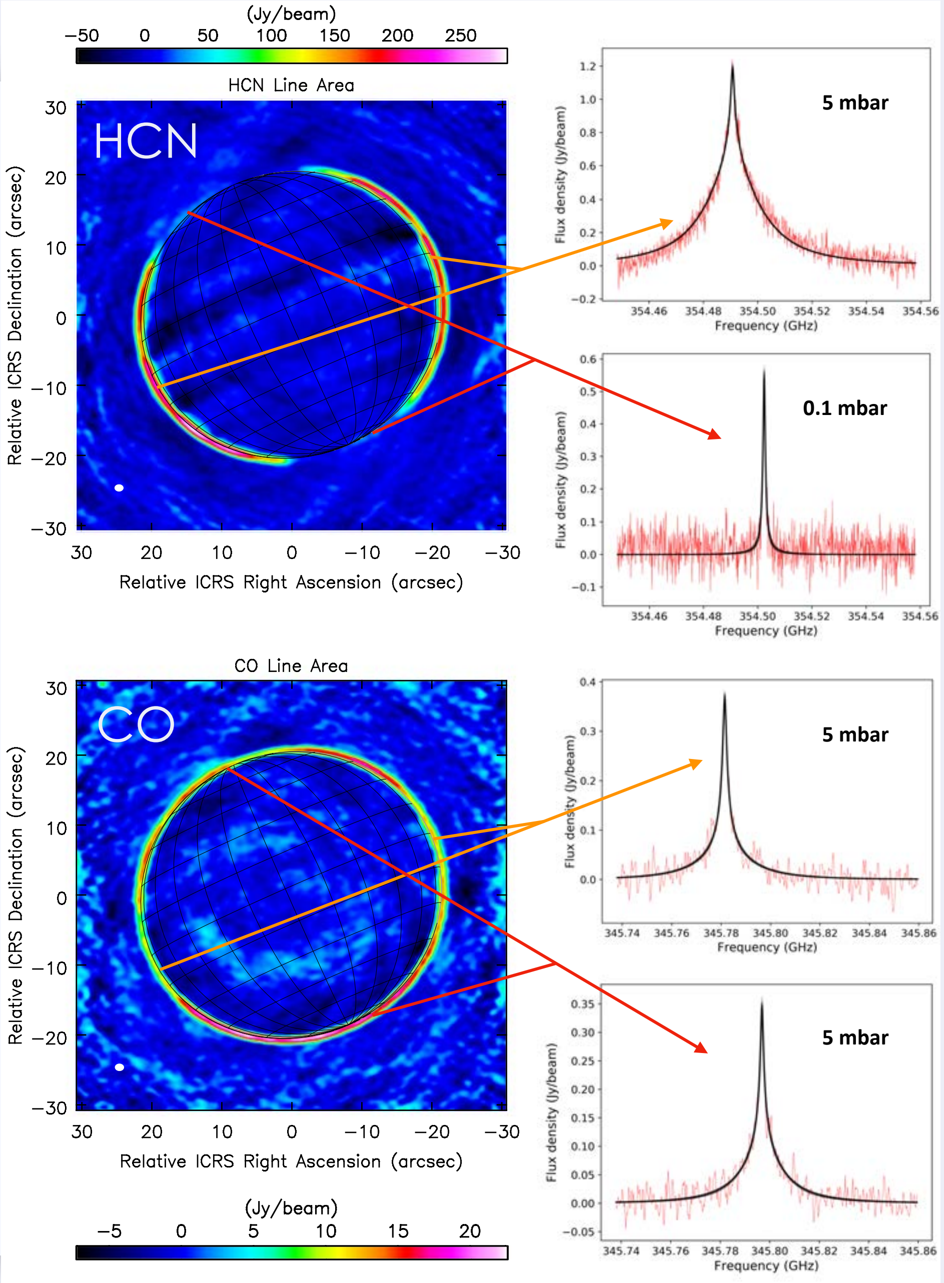
AURORAL AND EQUATORIAL JETS IN JUPITER'S STRATOSPHERE



Tropospheric wind pattern: alternating prograde and retrograde zonal jets (up to 100 m s^{-1})

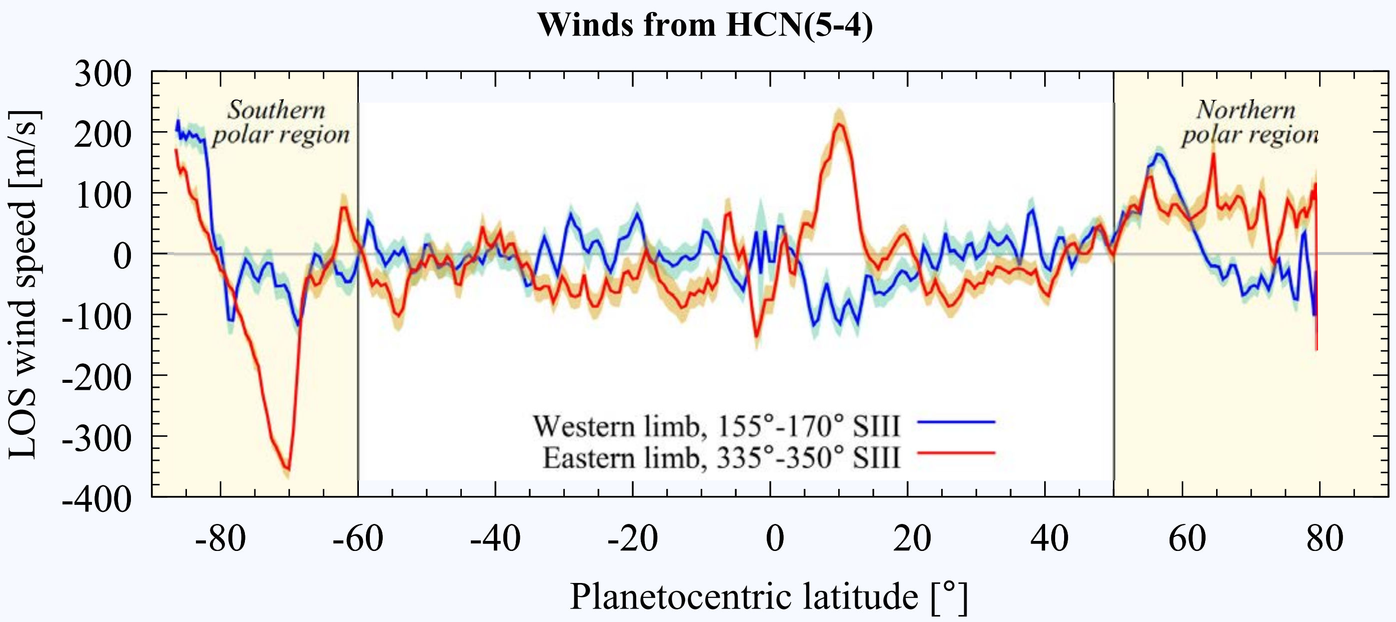
Above the tropopause, no tracers to infer the wind pattern from visible

HCN and CO, two species delivered by the SL9 impact, can be studied using ALMA at exquisite spatial and spectral resolution (100 m s^{-1} winds superposed on 12.5 km s^{-1} Jovian rotation at the equator)



Cavalié et al. 2021

AURORAL AND EQUATORIAL JETS IN JUPITER'S STRATOSPHERE



Zonal winds at low-to-mid latitudes

Strong and broad prograde jet at 9 – 11° N at 1 mbar (E limb +215 m s^{-1}, W limb -115 m s^{-1})

Nonzonal winds in the N and S polar regions at 0.1 mbar (300 – 400 m s^{-1})

Counter-rotating velocities, 100s of km below the ionospheric auroral winds (lower tails)

May help increase the efficiency of chemical complexification

Cavalié et al. 2021

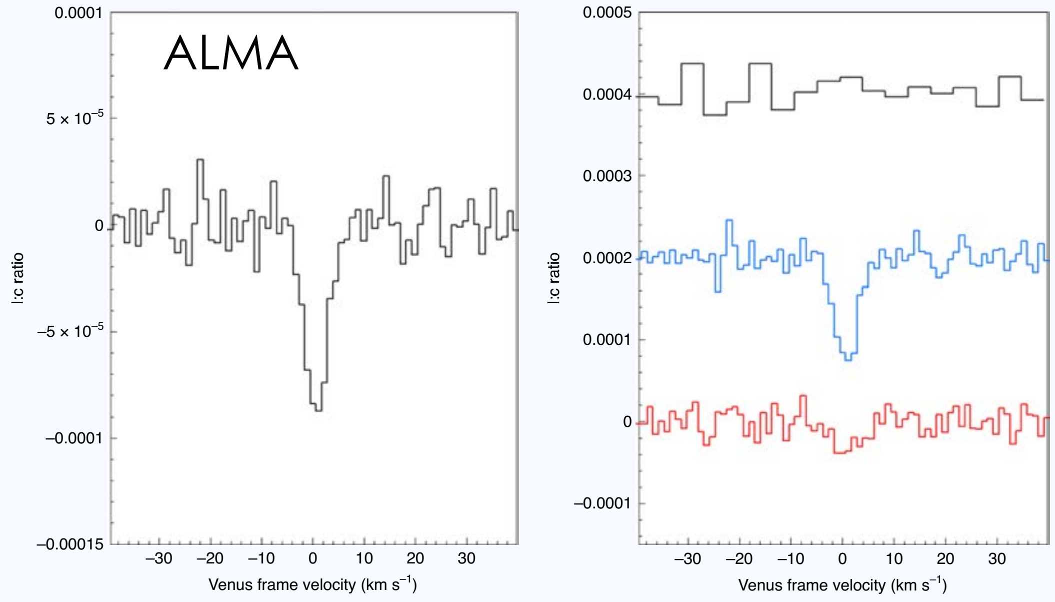
PHOSPHINE ON VENUS

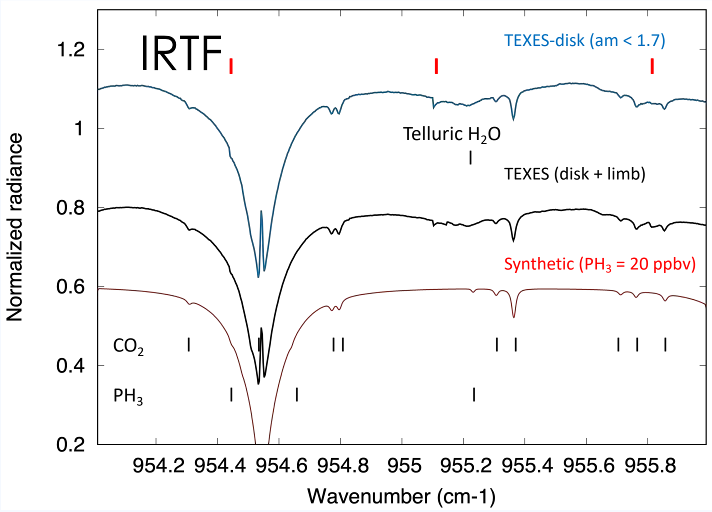
Submm detection of PH_3 at ~20 ppb in the atmosphere of Venus (ALMA+JCMT).

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).

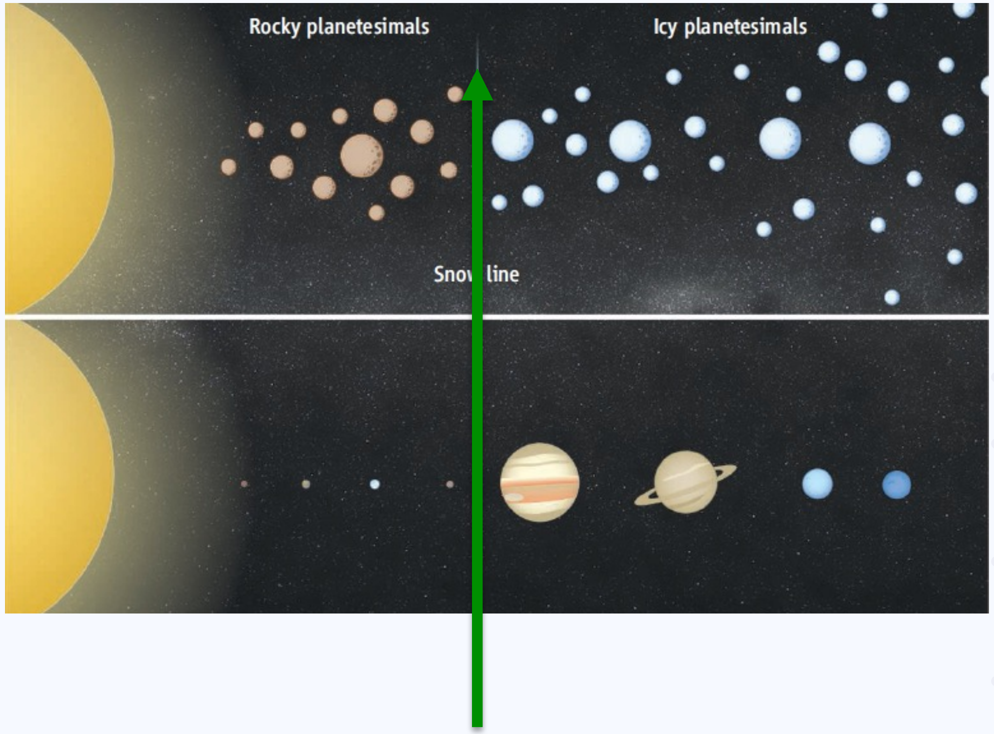
Also, availability of water in the Venus cloud deck, as quantified by the “water activity” parameter, is 2 orders of magnitude below the limit for known extremophiles.



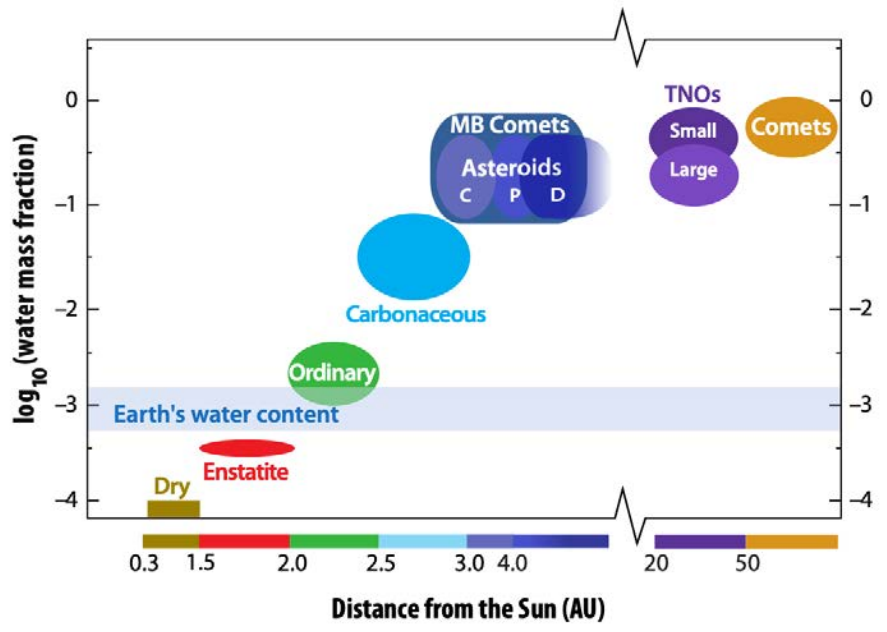


Greaves et al. 2020 — Encrenaz et al. 2000 — Hallsworth et al. 2021 +32 ADS papers

THE ORIGIN OF EARTH'S WATER

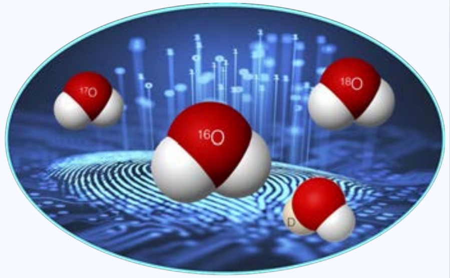


Snow Line



- Water mass fraction increases with distance from the Sun
- "Textbook model": temperature in the terrestrial planet zone too high for water ice to exist
- Water and organics were most likely delivered later by comet or asteroid-like bodies
- Alternative: water could have survived, incorporated into olivine grains or through oxidation of an early H atmosphere by FeO in the magma ocean

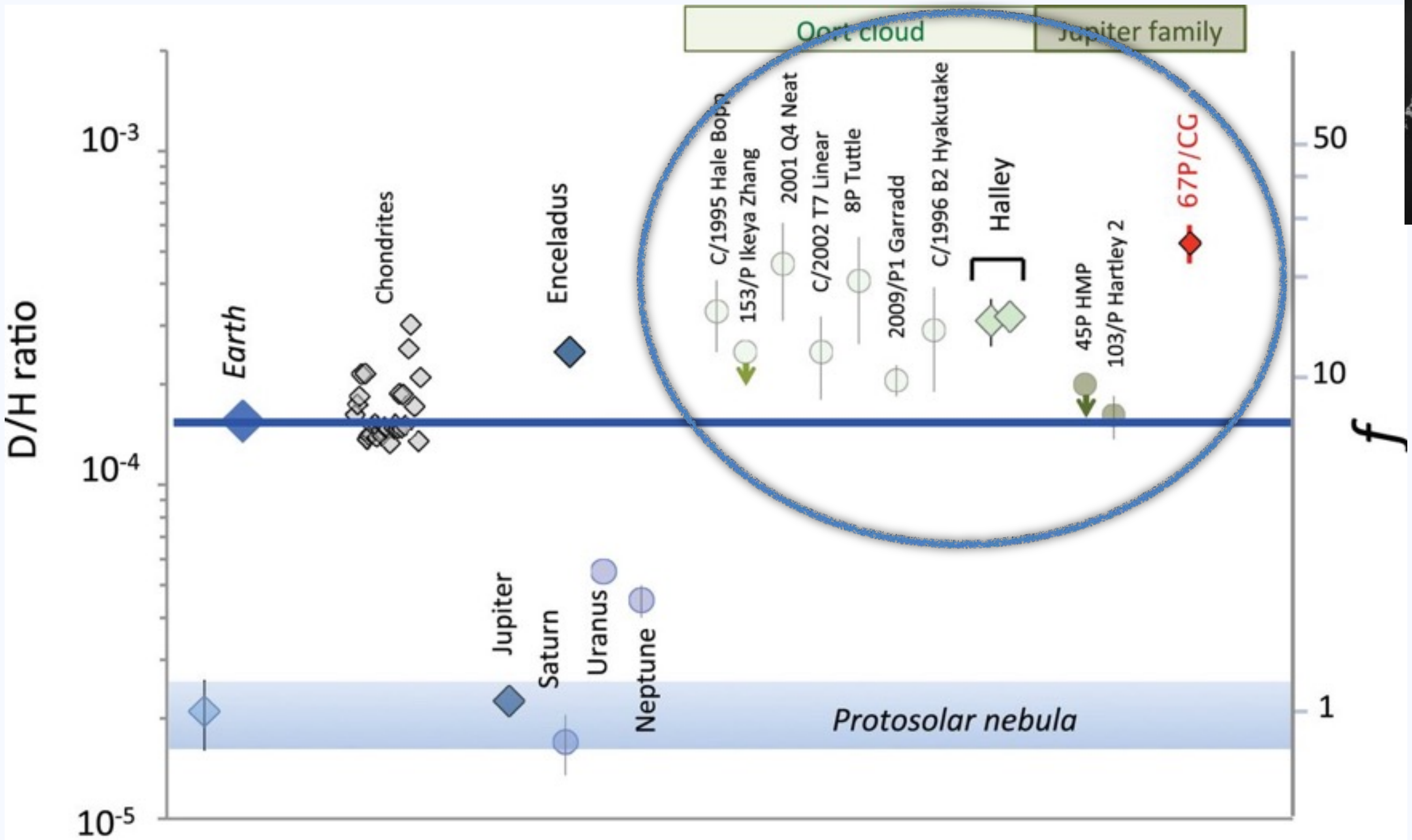
ISOTOPIC MEASUREMENTS

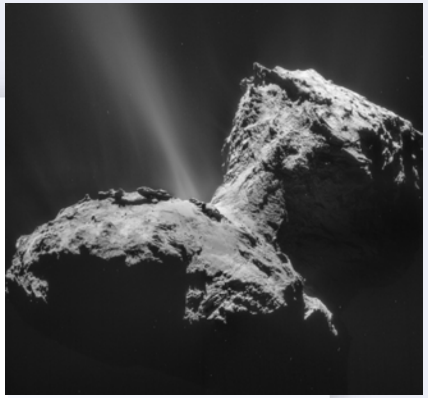


Sample return or in-situ — detailed studies of individual objects

Remote sensing — statistical studies of objects that have atmospheres

D/H RATIO

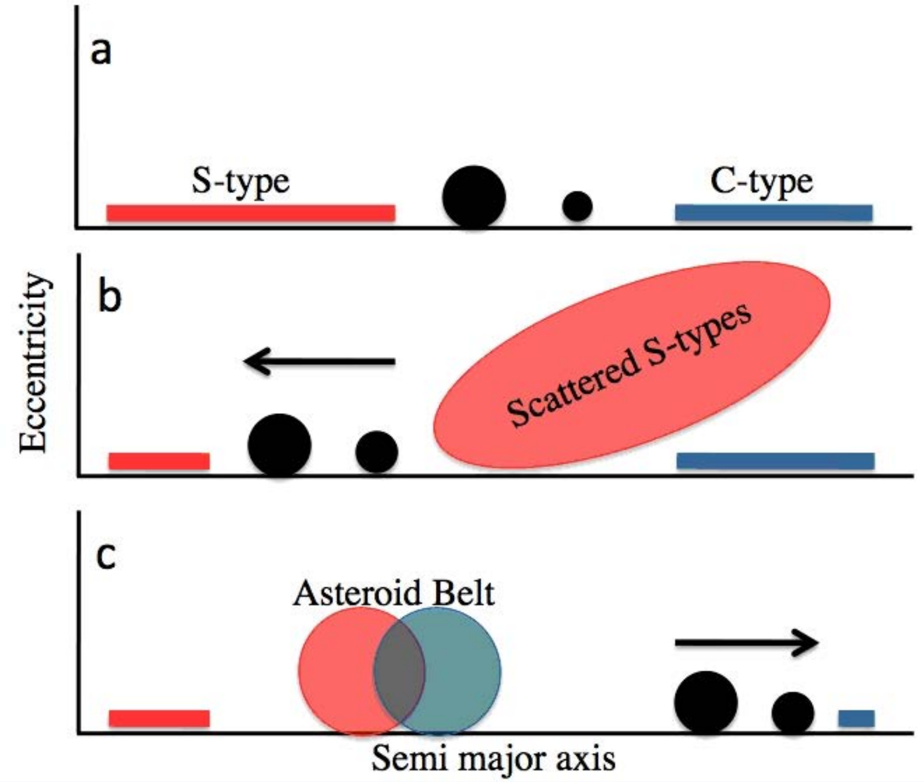


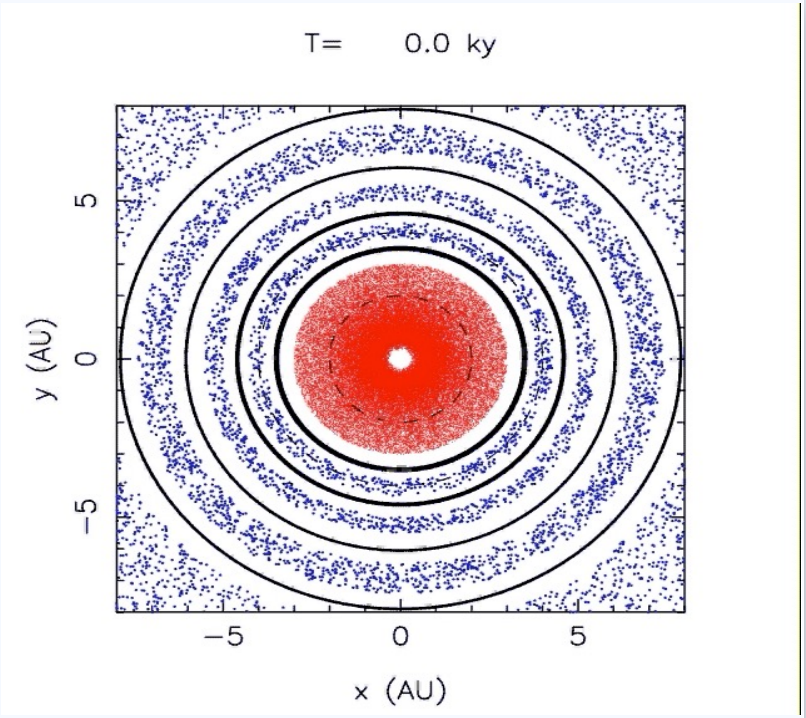


- Comets: variations between one and three times terrestrial value
- No trends with physical or dynamical parameters

ORIGINS Space Telescope

COMPLEX SOLAR SYSTEM DYNAMICS

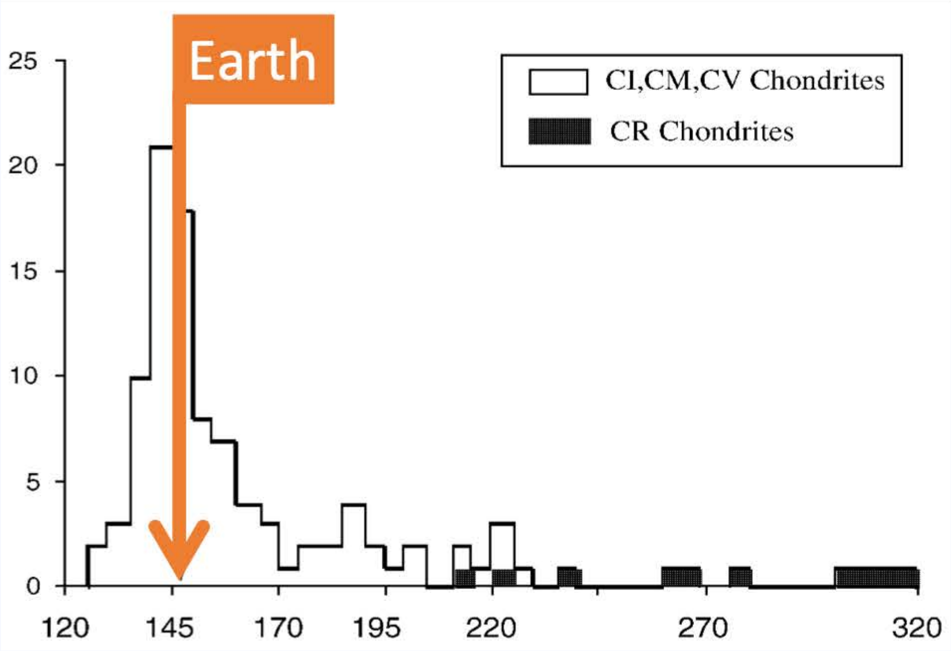




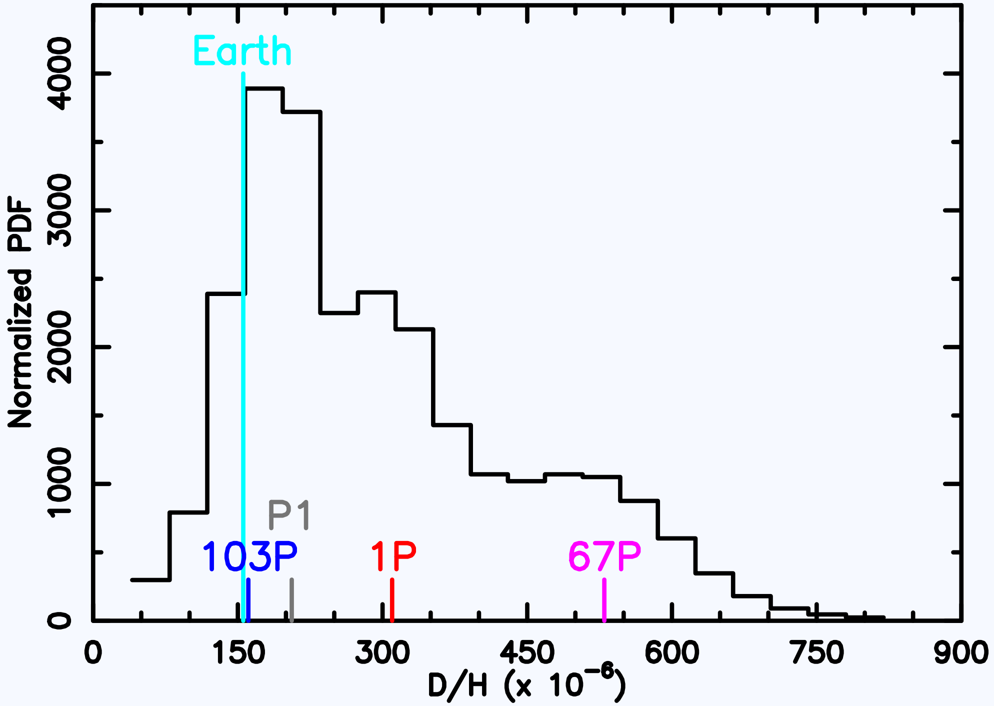
- Grand Tack Model: inward then outward migration of Jupiter and Saturn (~5 Myr)
- Nice Model: Saturn migration into 1:2 orbital resonance with Jupiter — Late Heavy Bombardment (~500 Myr)

Walsh et al. 2011 — Gomes et al. 2005 — Tsiganis et al. 2005 — Morbidelli et al. 2005

D/H DISTRIBUTION: INNER VS. OUTER SOLAR SYSTEM



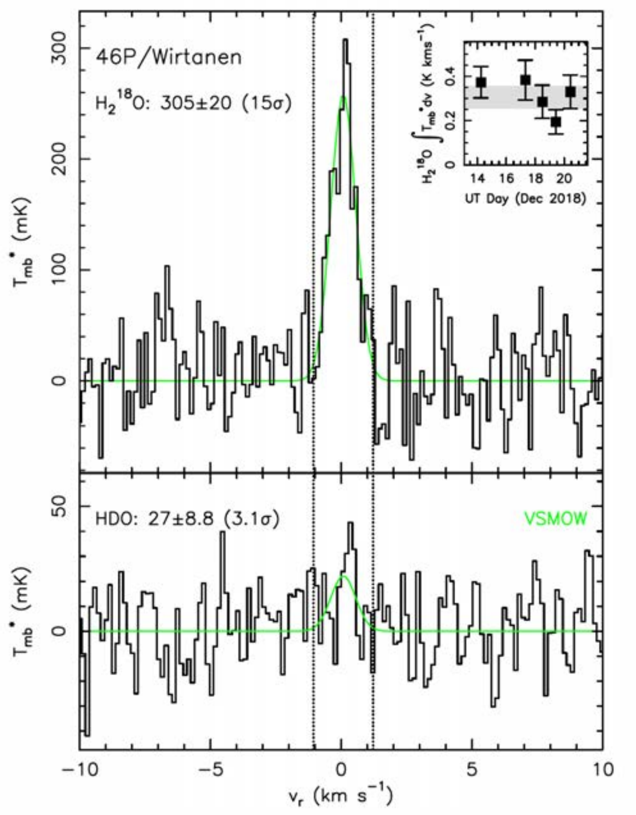
D/H in the inner Solar System relatively well constrained by measurements in meteorites (100+ measurements)



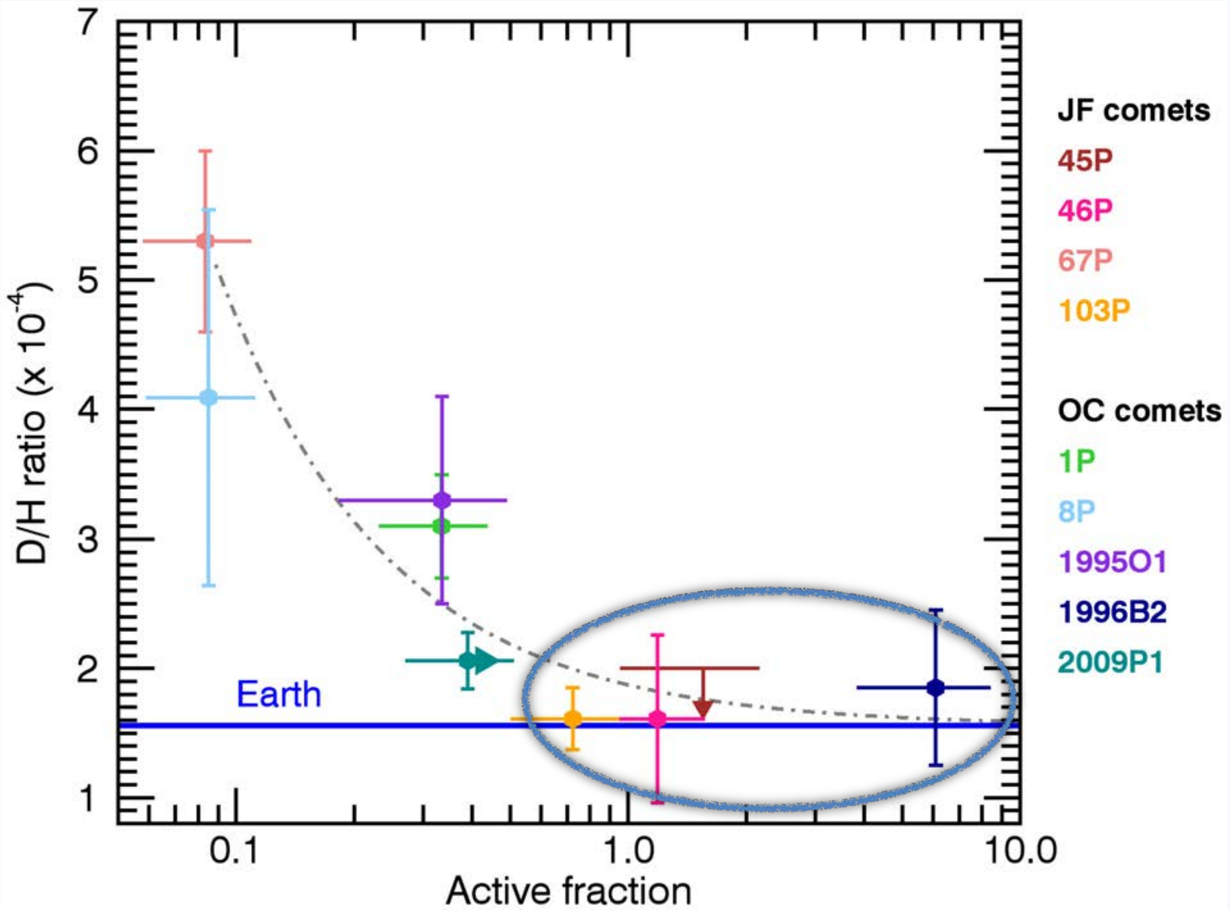
D/H in the outer Solar System poorly constrained – a few measurements in comets with large uncertainties

Alexander 2006

HYPERACTIVE COMETS



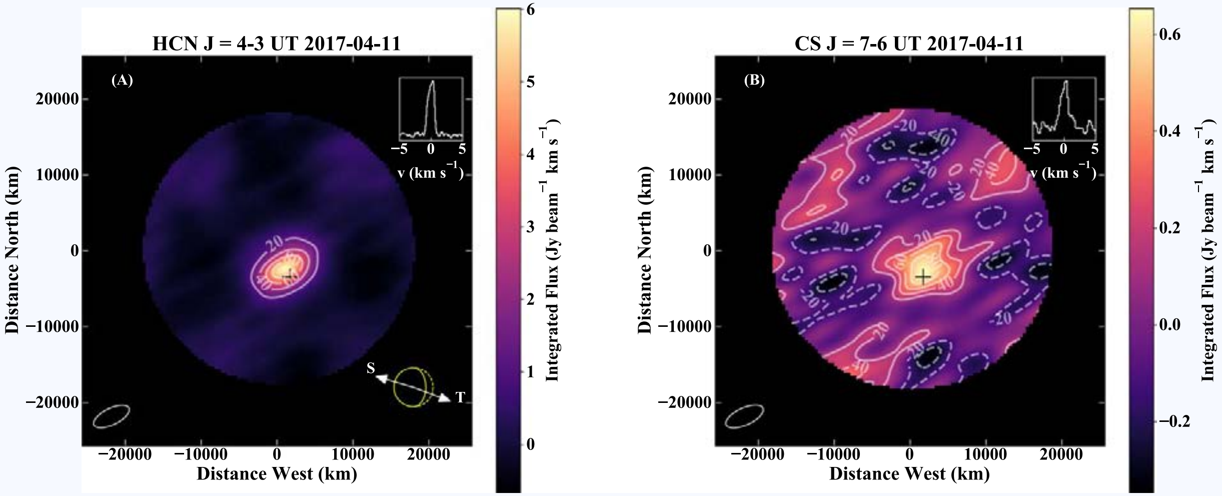
SOFIA Comet Wirtanen
D/H= (1.61±0.65) × 10^{-4}



Comets with high active fractions typically have terrestrial D/H ratios
Water release from sublimating icy grains in the coma

Lis et al. 2019

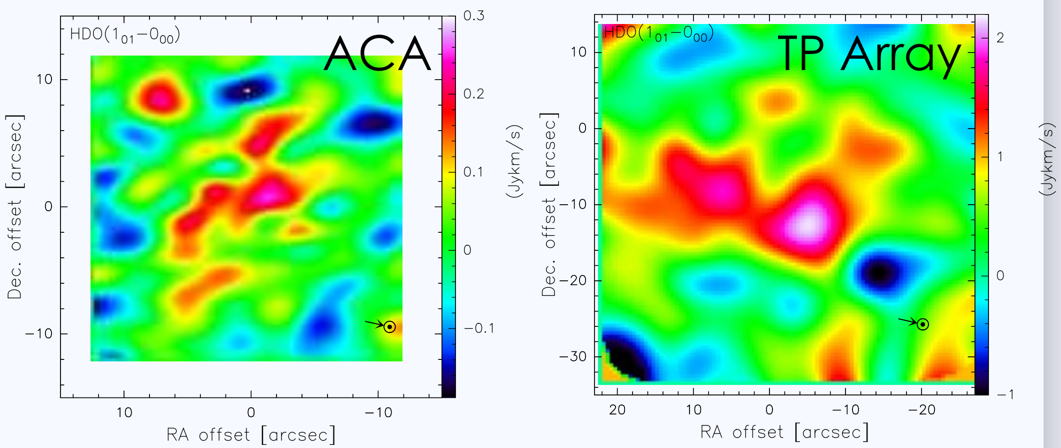
COMETS WITH ALMA



ALMA imaging observations allow discerning parent(HCN) from daughter/distributed source species (e.g., CS, H_2CO, HNC, possibly CH_3OH)

ACA and ALMA autocorrelation spectroscopy

Comet Wirtanen – HDO 464 GHz



Preliminary D/H = 1.5 × VSMOW

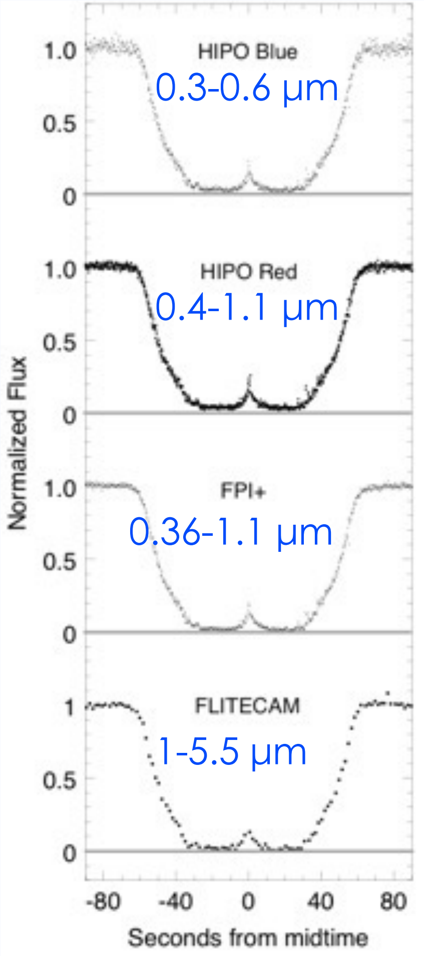
Consistent with the SOFIA measurement within the error bars

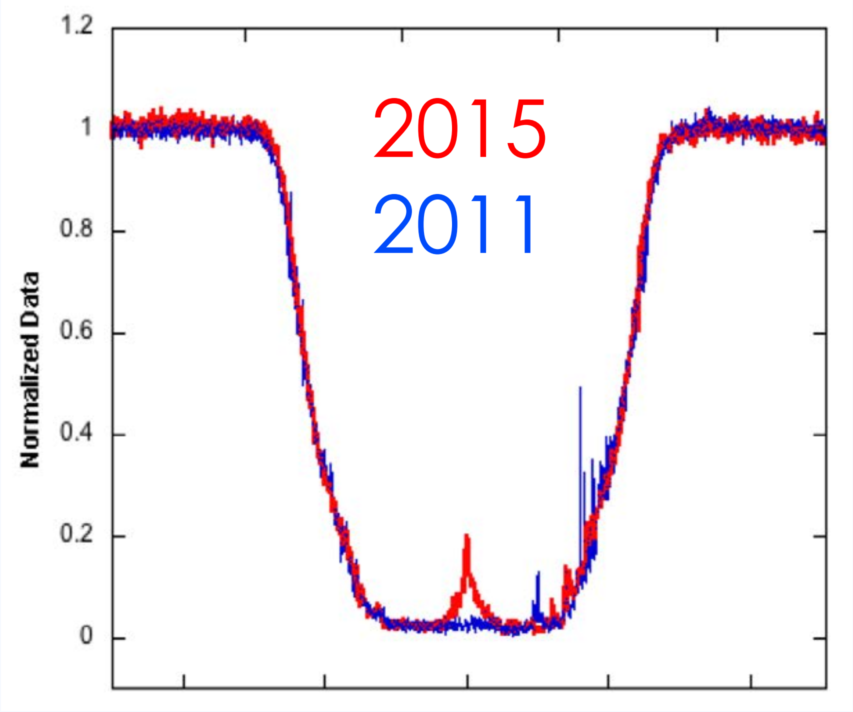
May indicate variations in the D/H within the FoV (direct release vs. icy grains)

ALMA and SOFIA observations are very complementary!

Roth et al. 2021 — Cordiner et al. 2019 — Biver et al. 2022

PLUTO OCCULTATIONS

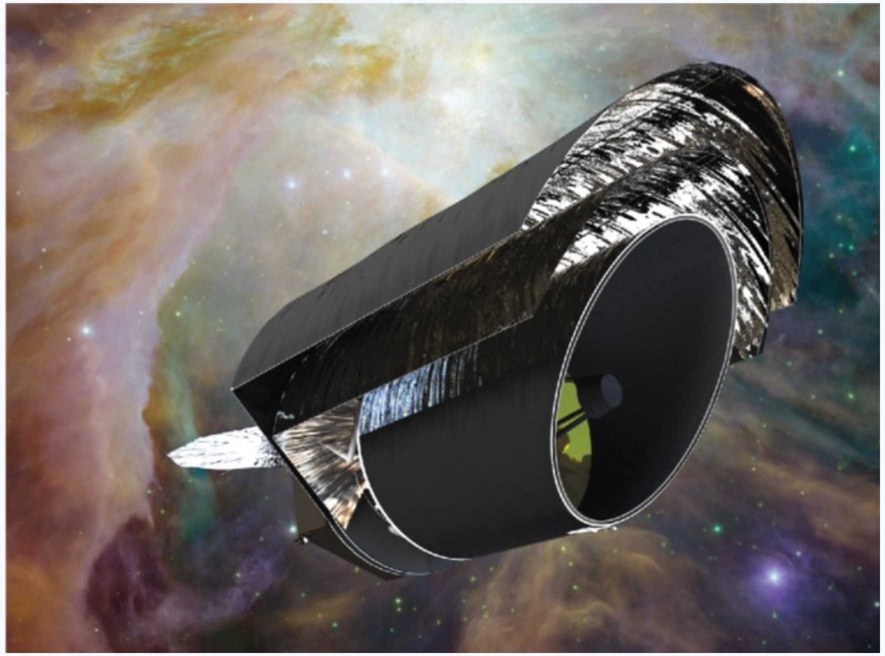




- Early KAO highlights — detection of the Uranian ring system and the atmosphere of Pluto
- "Central flash" provides constraints on *haze densities* and thermal gradients in lower atmosphere, bounds on haze-particle sizes
- Multi-wavelength observations allow analysis of atmospheric profiles and aerosol 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

LOOKING INTO THE FUTURE



Astro2020 Report Published and Planetary Decadal Report expected in April

FIR Flagship – *Origins* – would provide measurements of the D/H ratio in 100s comets – 2040

FIR Probe would allow first statistical studied – 2030

It is critically important to take full advantage of the complementarity of the existing FIR/submm facilities

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