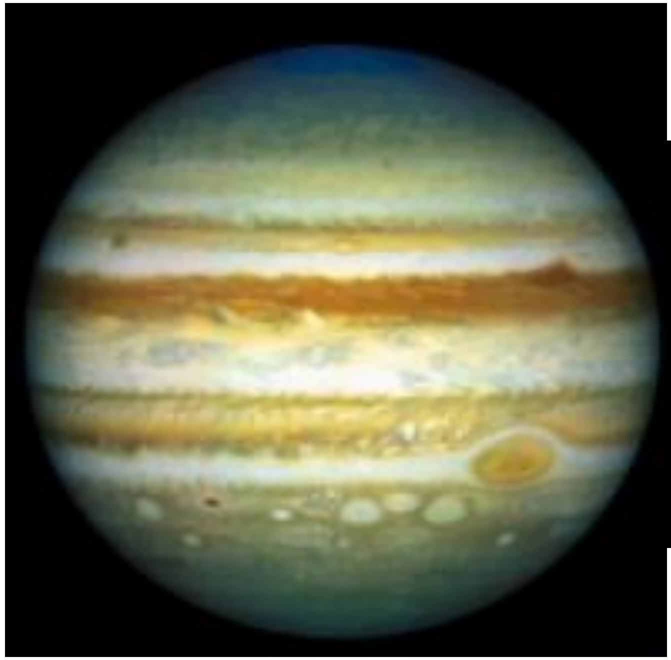
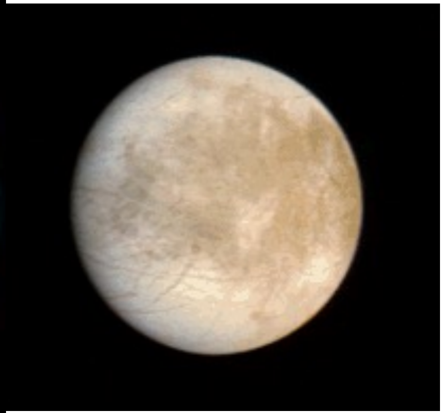
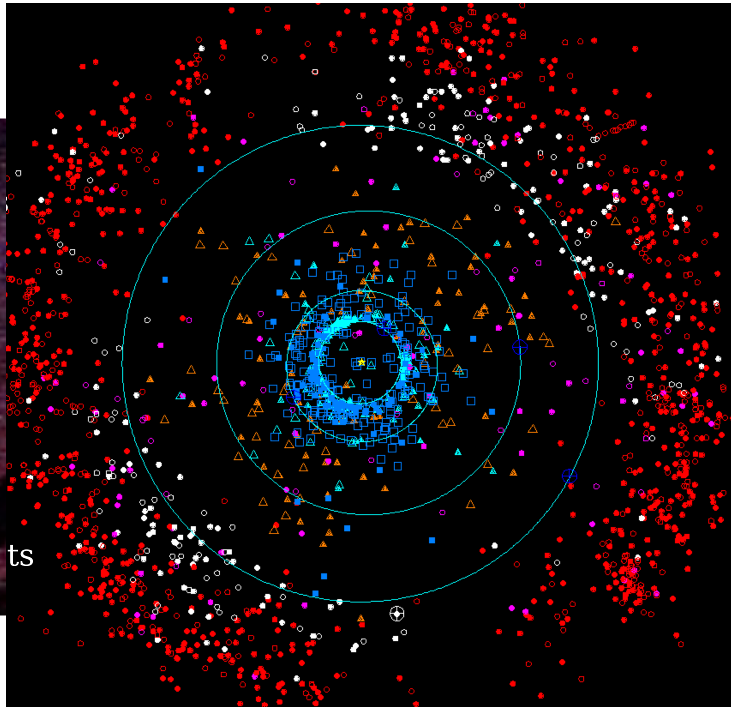
Solar system observations in the FIR/submm range : Past and future

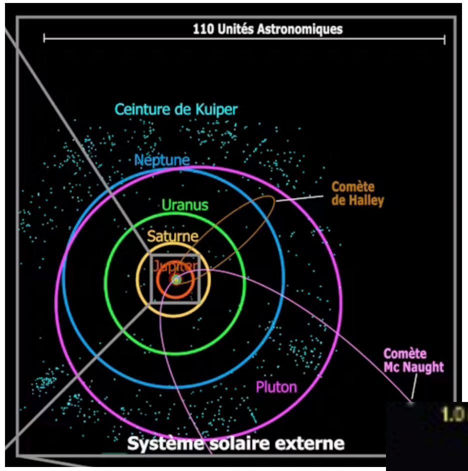


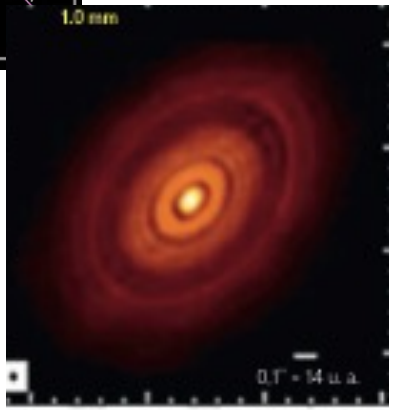
Thérèse Encrenaz

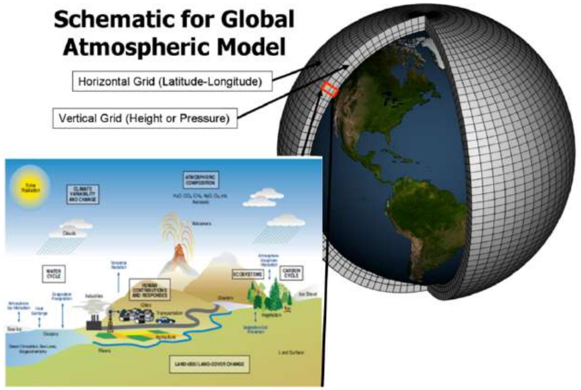
LIRA, Observatoire de Paris, CNRS

Workshop "Future Role of FIR-Submm Space Observations", Leiden, 2-4 April 2025

Six decades of planetary exploration

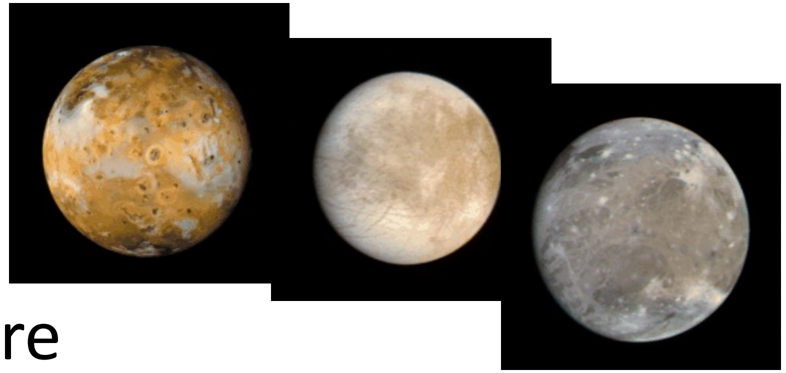




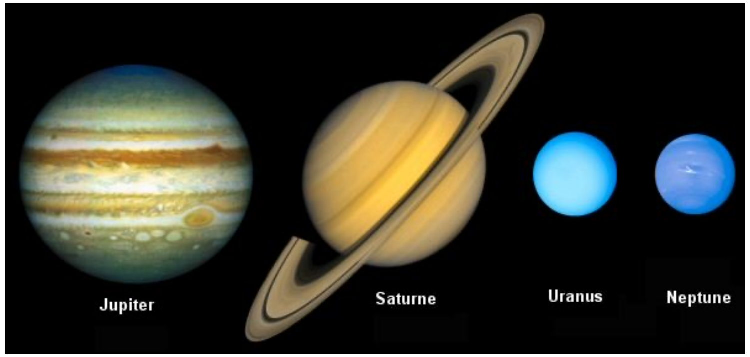


- Space missions to all planets & satellites, and several asteroids & comets
- Major achievements from ground-based observations
  - Discovery of trans-neptunian objects & the first exoplanets
- From numerical simulations -> dynamical history of the Solar system
  - Migration of the giant planets & Dynamical history of asteroid families
- Study of the Solar system as a benchmark for exoplanetary studies
  - Formation models (solar system/planetary disks)
  - Radiative transfer/photochemistry models & Global climate models

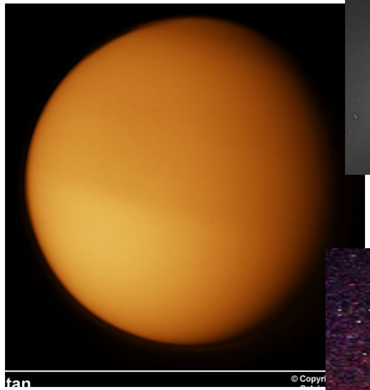
What is needed now ?

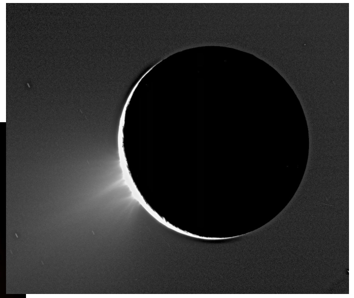


- <u>Study of planetary/satellite meteorology & climate</u>
  - Daily/seasonal variations in composition and structure
    - High spatial/spectral resolution, high dynamics
  - Wind measurements
    - High spectral resolution with mapping capabilities



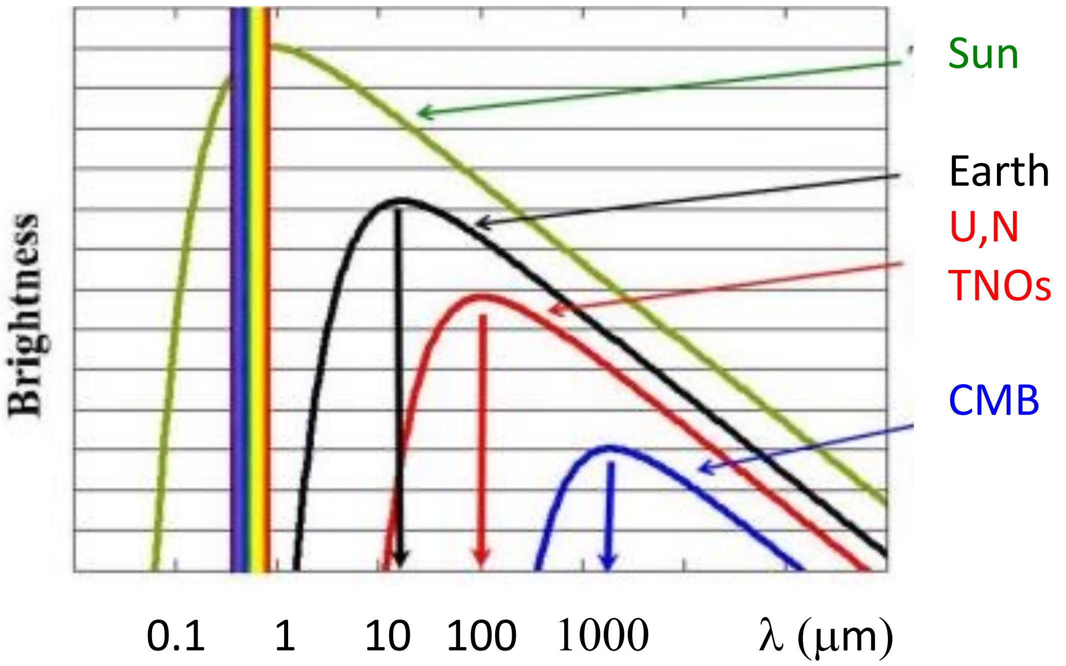
- <u>Composition of asteroids & comets</u>
  - Search for complex molecules (high spectral resolution)
  - Temporal evolution
    - Repeated observations on different timescales
  - **> Objective: understand the dynamical history of the small bodies**
  - **> Of special interest: ocean worlds (for exobiology)**



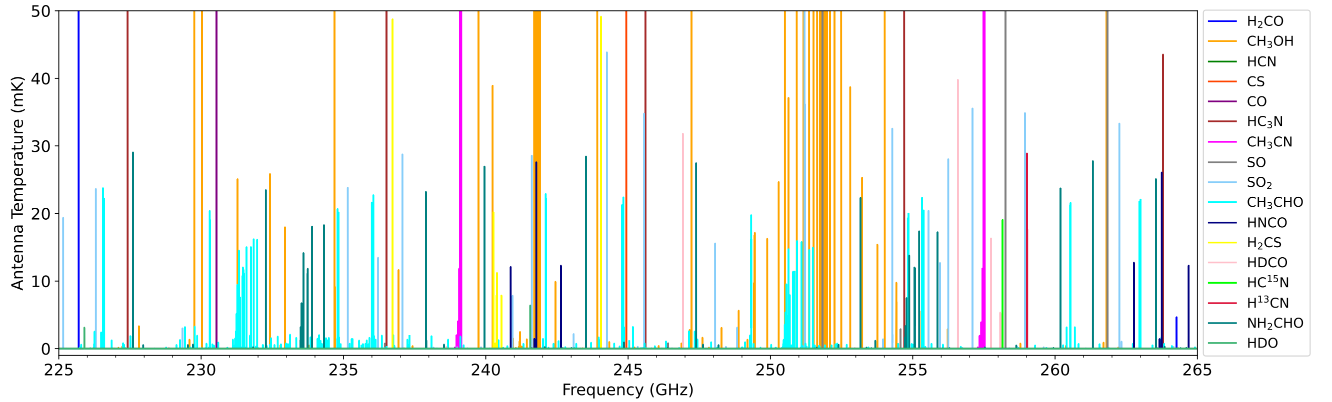


Thermal emission in the outer solar system is best observed by IR/submm remote sensing

- **Outer solar-system objects are cold**
  - Giant planets: λ_{max} from 25 μm (Jupiter) to 60 μm (U, N)
  - Outer satellites: 30 μm (Galilean sat.) > 70 μm (Triton)
- **In situ exploration is limited to a few targets**
  - Uranus and Neptune were only explored by Voyager in the 1980s
- **All strong molecular rotational transitions are found in the IR/submm range**

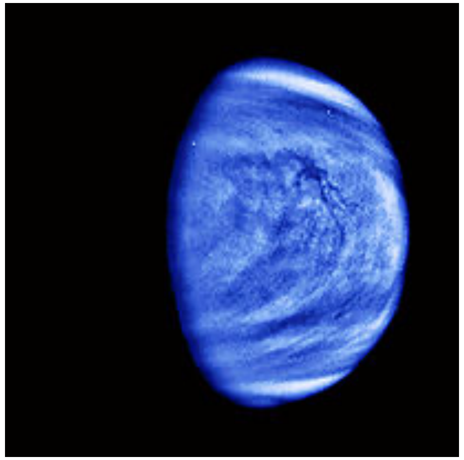


λ = 1.3 mm Cometary transitions λ = 1.1 mm

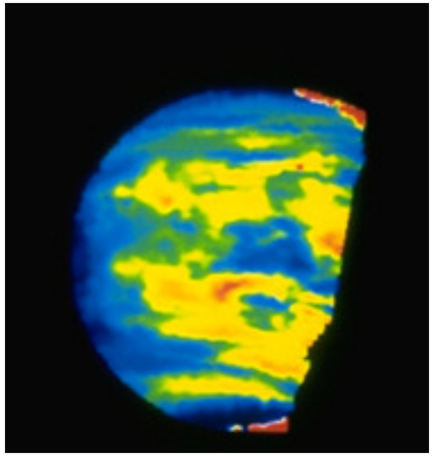


Planets look different at different wavelengths!

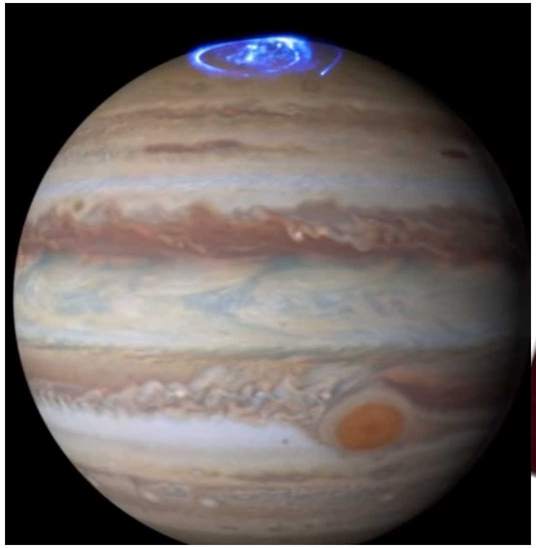
Venus in the UV (z = 70 km)



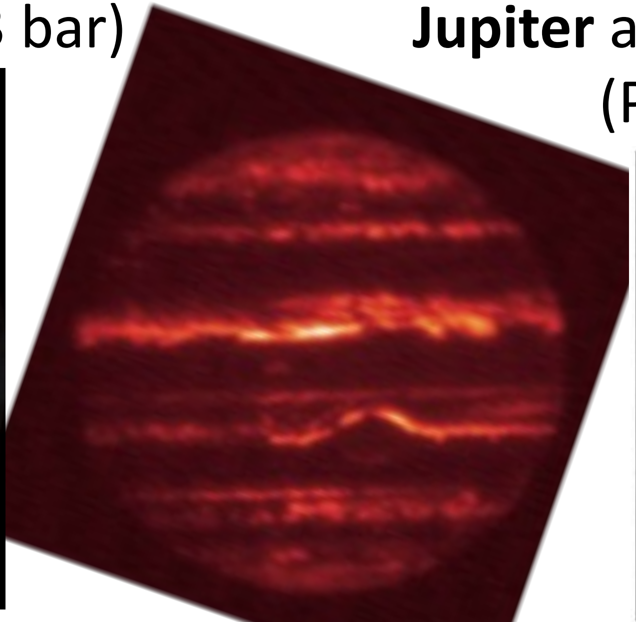
The night side of **Venus** at 2.3 μm (z = 30 km)

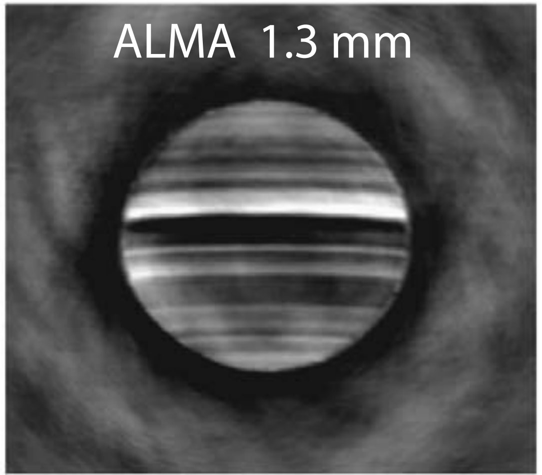


Jupiter in the UV (aurora, P = 1 μbar) + in the visible (P = 0.3 bar)

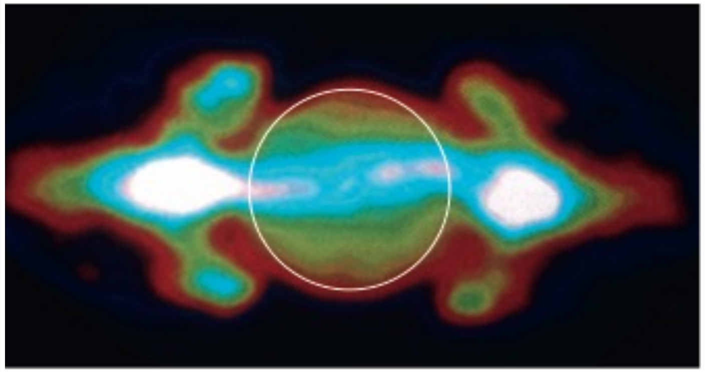


Jupiter at 5 μm & 1.3 mm (P = 1-5 bars)

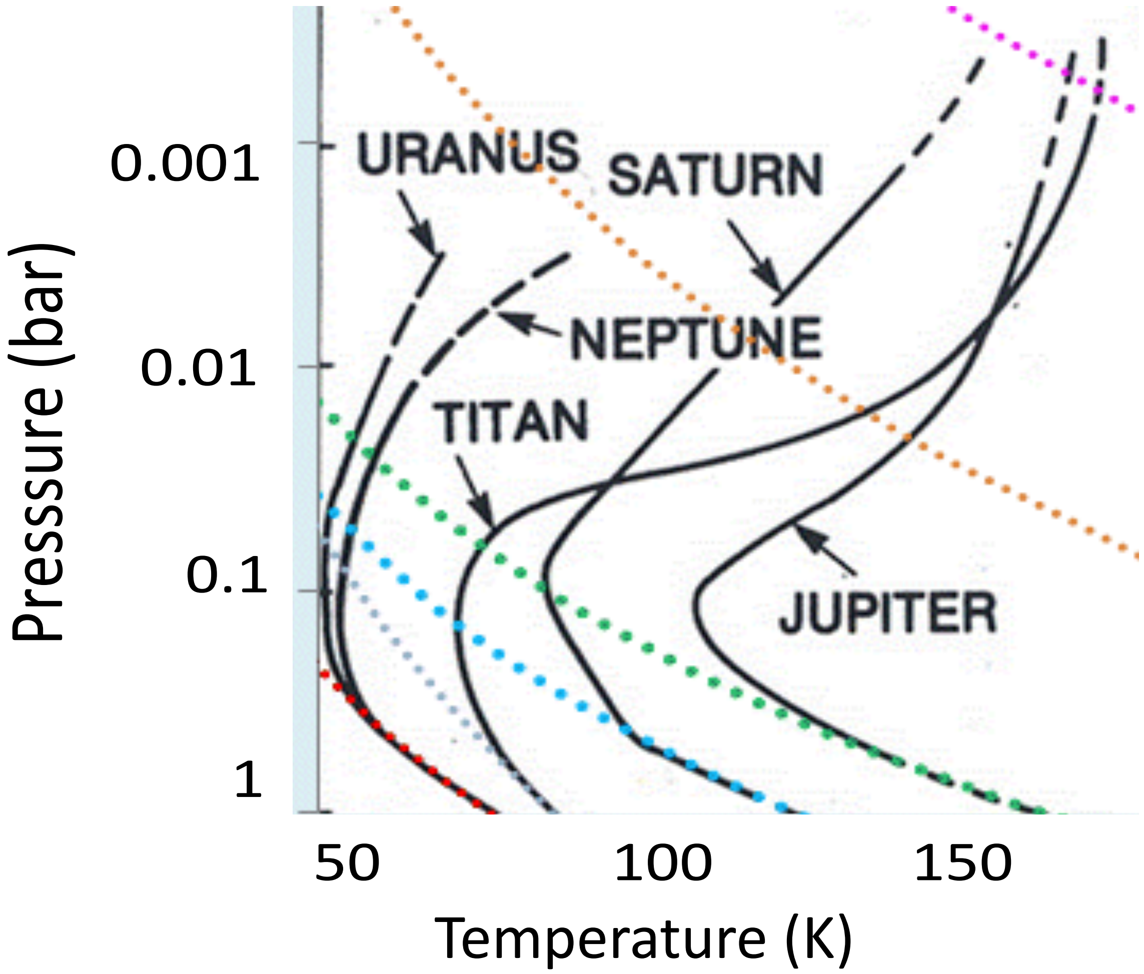




Jupiter at 2 cm (synchrotron emission)



Remote sensing of giant planets' atmospheres



P = 10^{-5}-10^{-7} bar :

UV + 3-5 μm range in the CH_4 (non-LTE) + H_3^+ emission lines (Aurorae)

P = 10^{-4} – 10^{-2} bar : UV + 12-13 μm range

CH_4 Photochemistry (C_2H_2, C_2H_6…)

P = 10^{-5} – 0.1 bar : mm/submm heterodyne spectroscopy

Stratospheric lines (hydrocarbons, oxygen species)

+ Exospheres of satellites, asteroids & comets

P = 0.1 – 1 bar : Visible + 8-12 μm + cm range

NH_3 cloud (Jupiter)

P = 1 -5 bars 5-μm window + cm range

- NH_4SH, H_2O clouds (Jupiter)
- H_2S cloud (Uranus?)

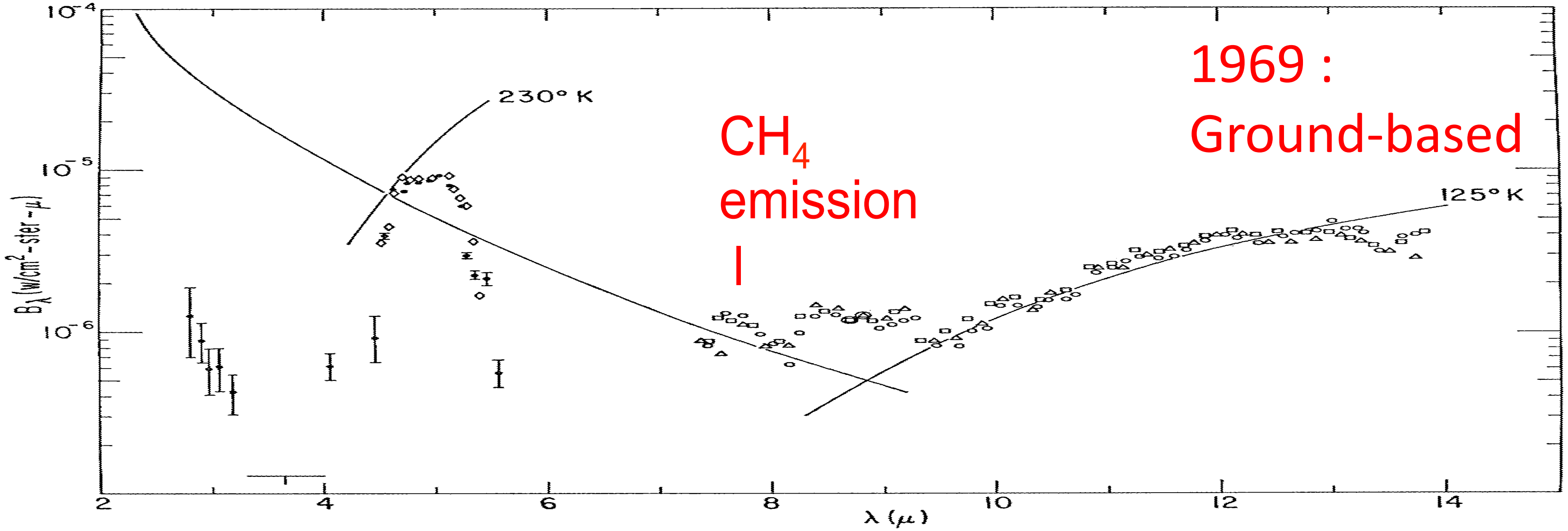
P > 10 bars

Radio range

- NH_3, H_2O in the deep troposphere

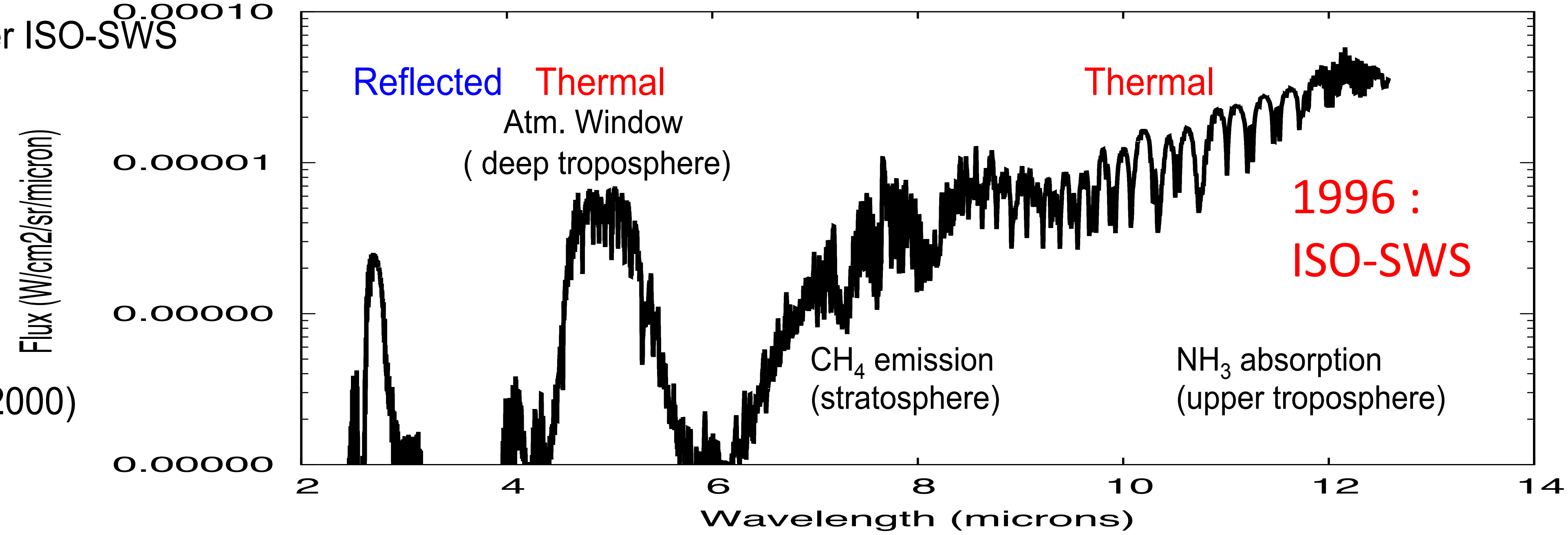
Planetary spectroscopy over ages : Jupiter in 1969 and 1996

Gillett et al.
ApJ 1969:
First evidence for a
thermal inversion



Jupiter ISO-SWS
1996

(R = 2000)

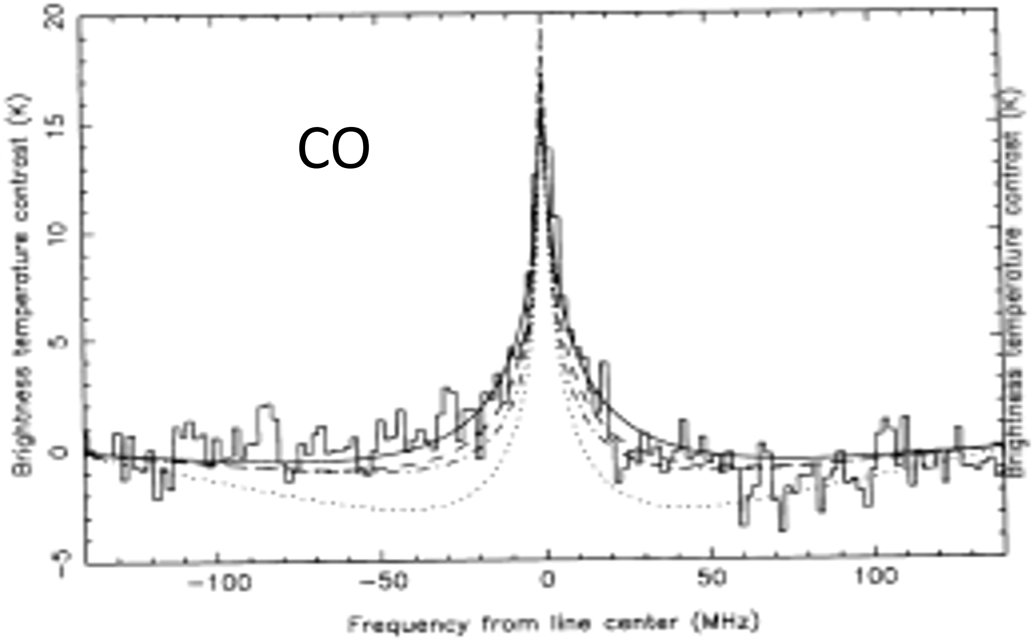


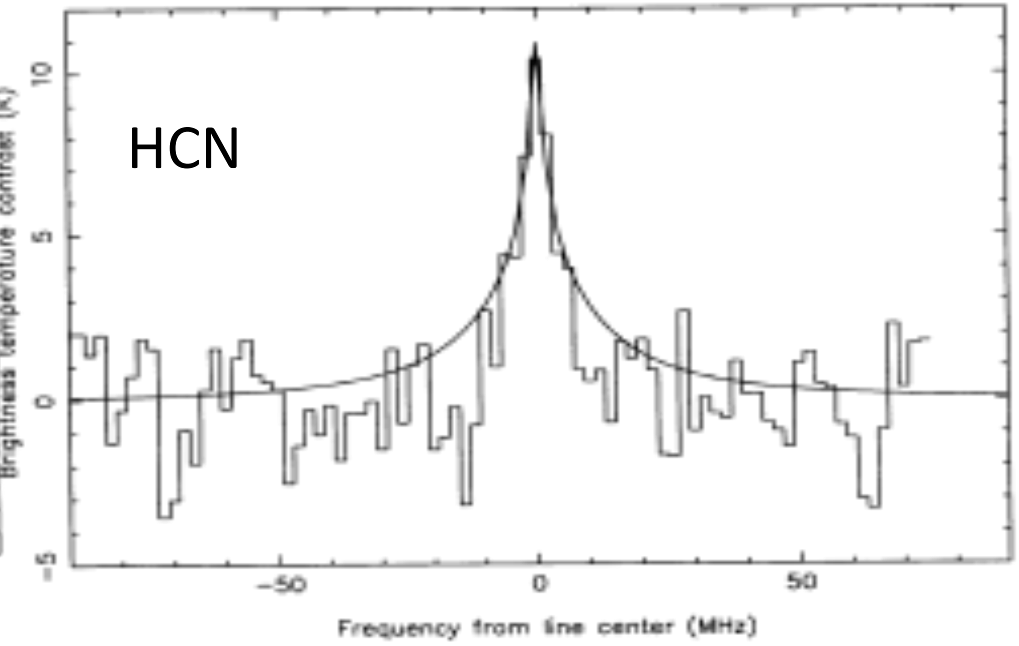
Planetary atmospheres:
A milestone in the millimeter range (IRAM-30m)

CO and HCN in Neptune (1992)

-> evidence for disequilibrium processes in Neptune

-> evidence for differences in the atmospheres of Uranus and Neptune





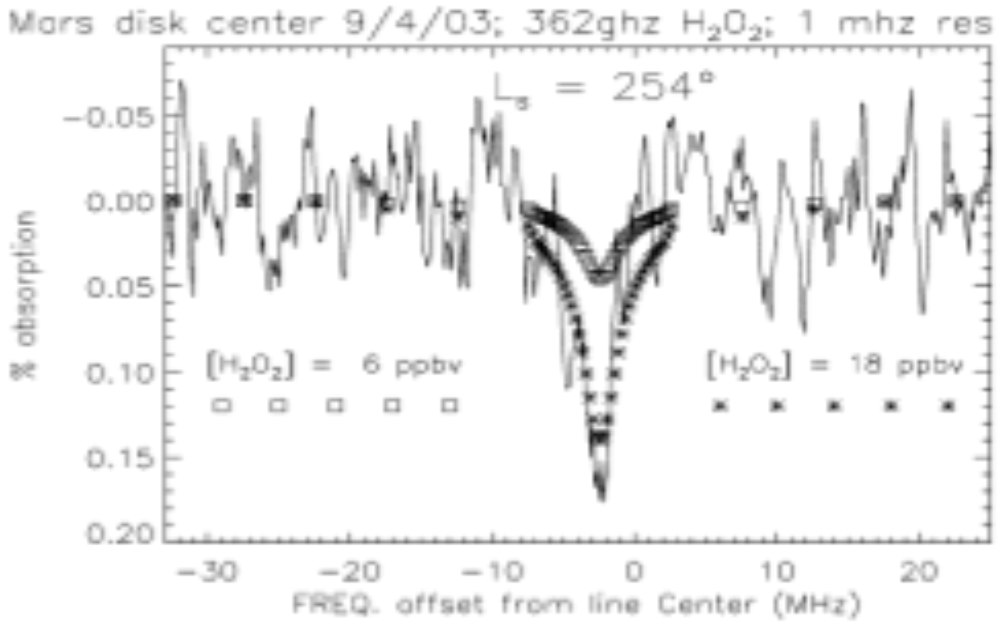
CO : 6 10^{-7} (expected: 10^{-9} from interior) in Neptune, < 4 10^{-8} in Uranus (internal/external?)

HCN: 3 10^{-10} in Neptune, < 8 10^{-10} in Uranus (external)

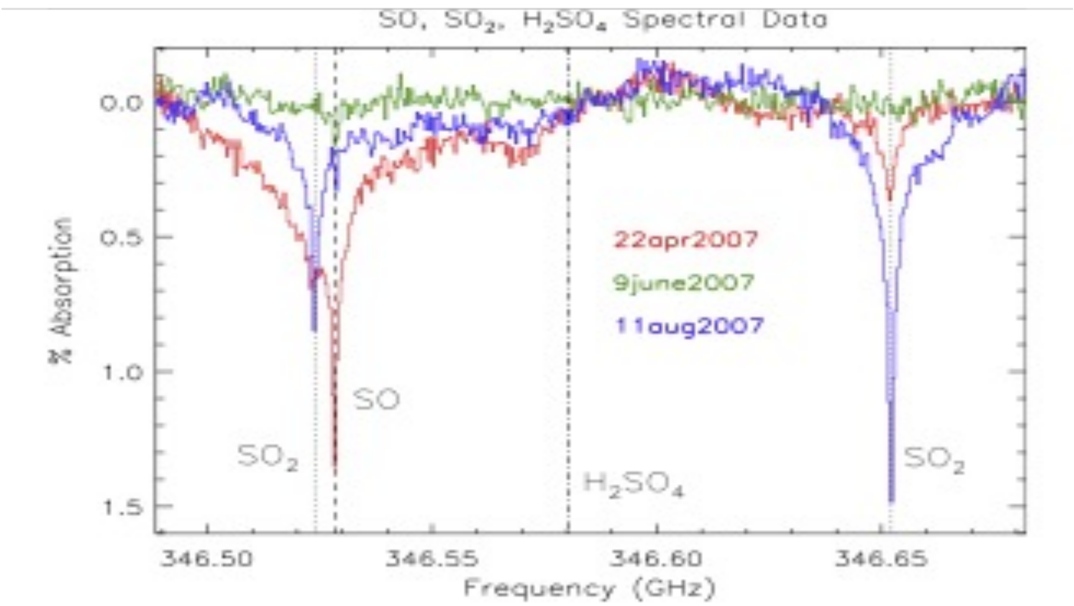
Marten + 92, 93, Rosenqvist + 92

Planetary atmospheres: Milestones in the submillimeter range (JCMT)

- H_2O_2 on Mars (2004)
- Mesospheric sufur species and HCl on Venus (2010, 2012)



H_2O_2 on Mars (Clancy et al. 2004)



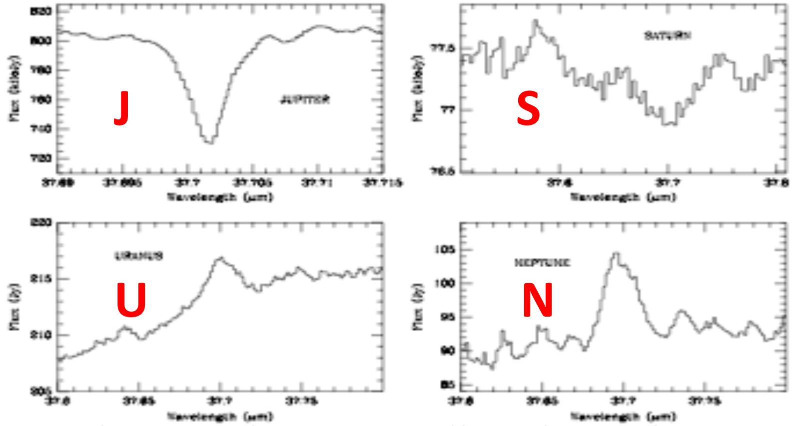
SO_2 & SO in the mesosphere of Venus
(Sandor et al. 2010, 2012)

ISO Highlights on Giant Planets (SWS)

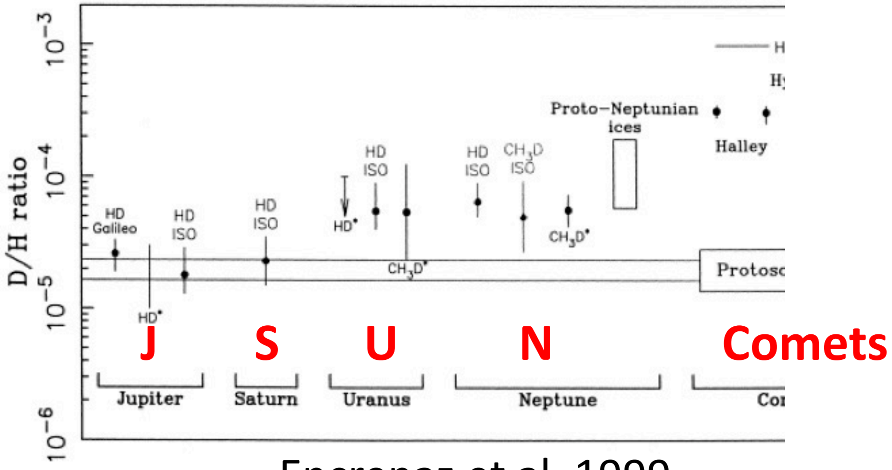
Origins: D/H from H_2

Deuterium enriched in icy giants

-> Support to nucleation model



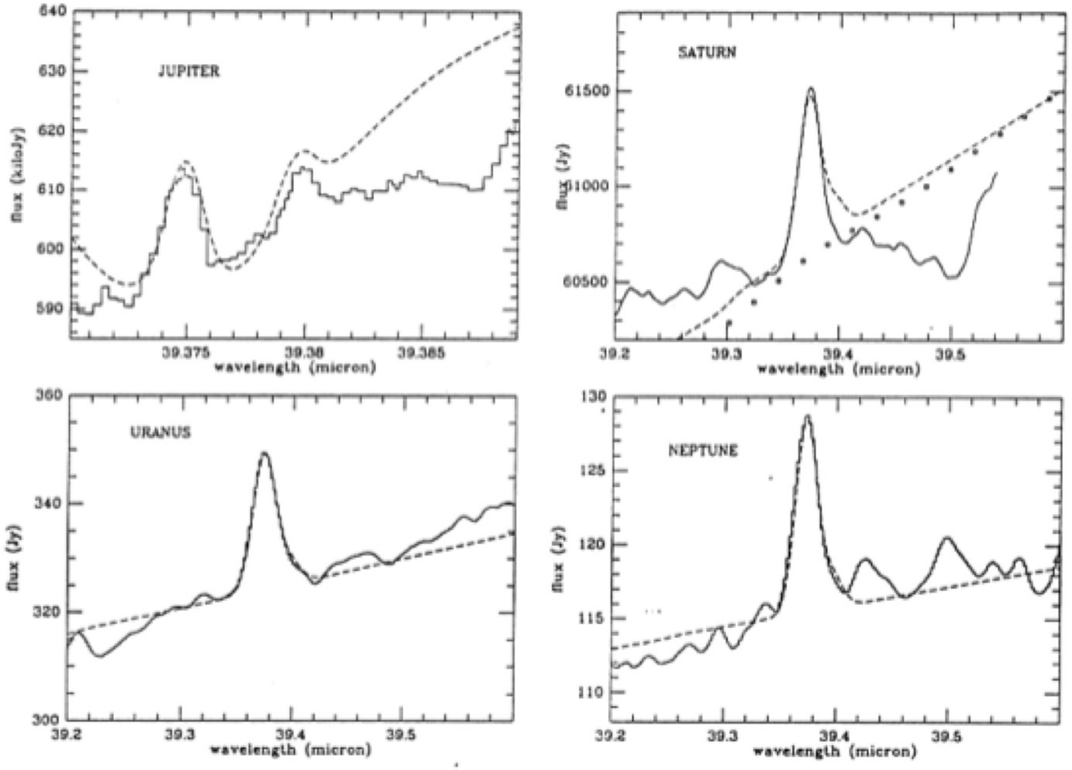
Feuchtgruber et al. 1999; Lellouch et al. 2002



Encrenaz et al. 1999

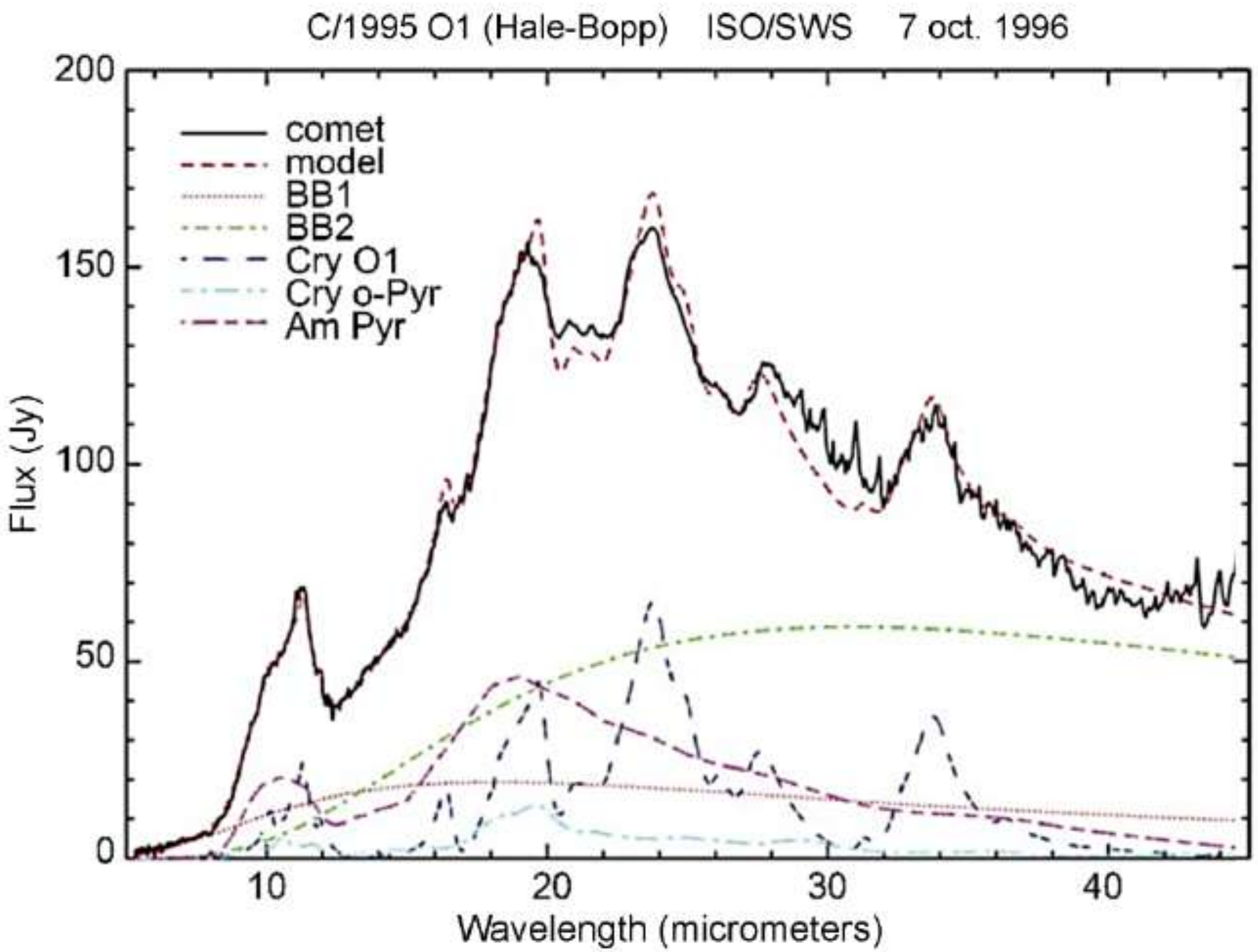
External oxygen flux: source?

- Local source (satellites, rings)
- Interplanetary source
    - flux of meteoroids
    - comets (Jupiter: SL9?)



Feuchtgruber et al. 1997

ISO Highlights on comets: Hale-Bopp (SWS)



Crovisier + 97

First thermal spectrum of cometary dust : a mixture of silicates (forsterite Mg_2SiO_4 and pyroxene (Mg,Fe) SiO_3 – Strong analogy with interstellar dust

Herschel Highlights

Giant planets

- D/H in Uranus and Neptune
- Stratospheric water in Jupiter, Saturn and Titan
- CO in Uranus (Cavalié + 14)

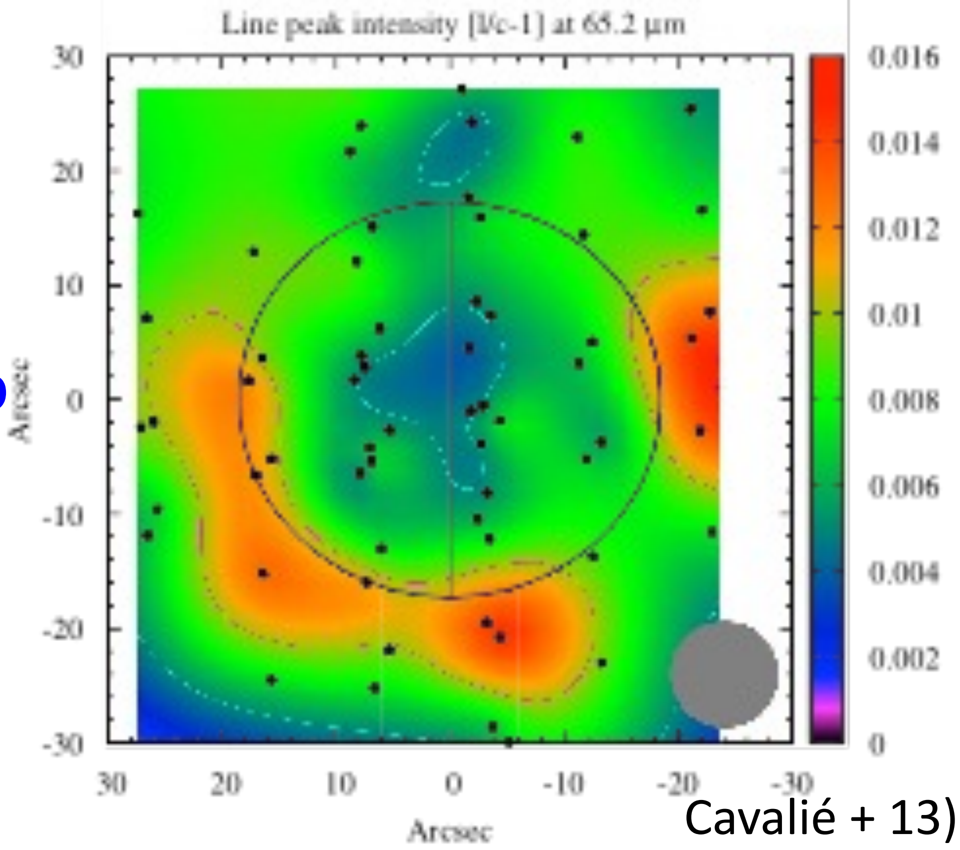
Outer satellites

- Atmospheric composition of Titan

  (Moreno + 11, 12; Courtin + 11
- Water torus of Enceladus (Hartogh + 11)
- H_2O atmosphere around Ganymede and Callisto (Marconi + 07)

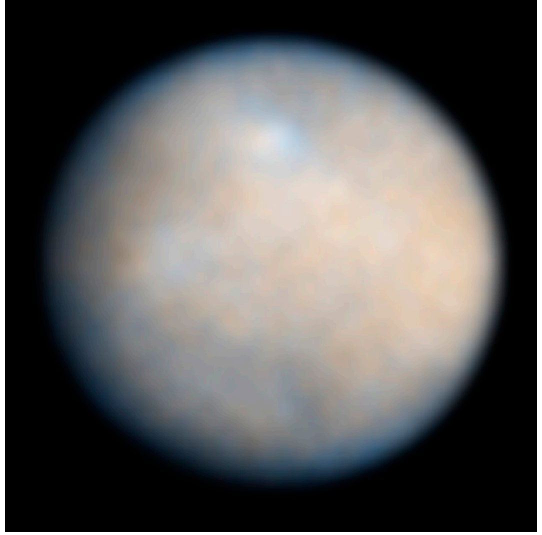
Asteroids

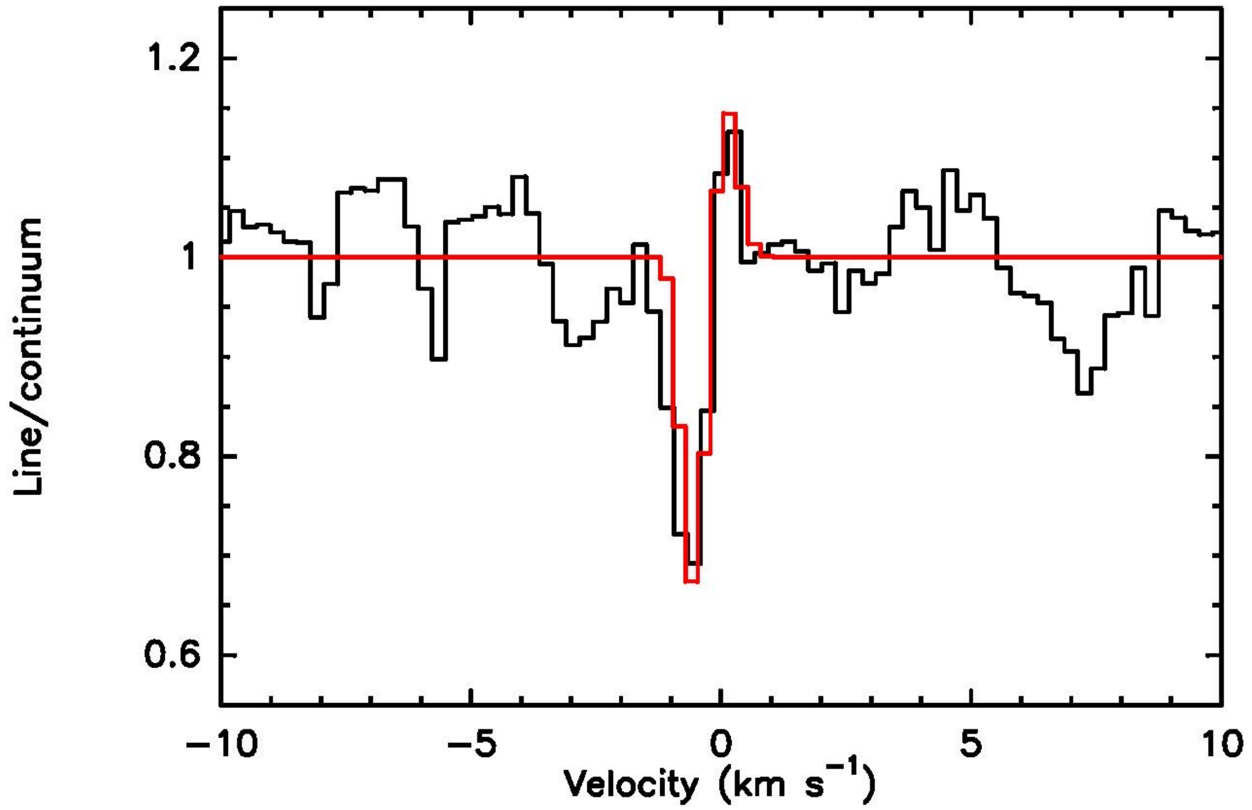
- Detection of H_2O around Ceres (Kueppers + 04)
- TNO Survey -> Size, albedo (Müller +12)

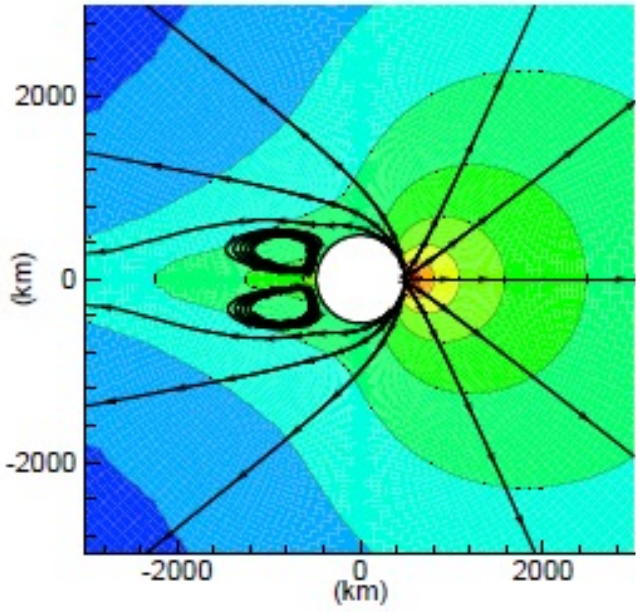


Cavalié + 13)

An unexpected discovery:
The detection of water vapor around Ceres



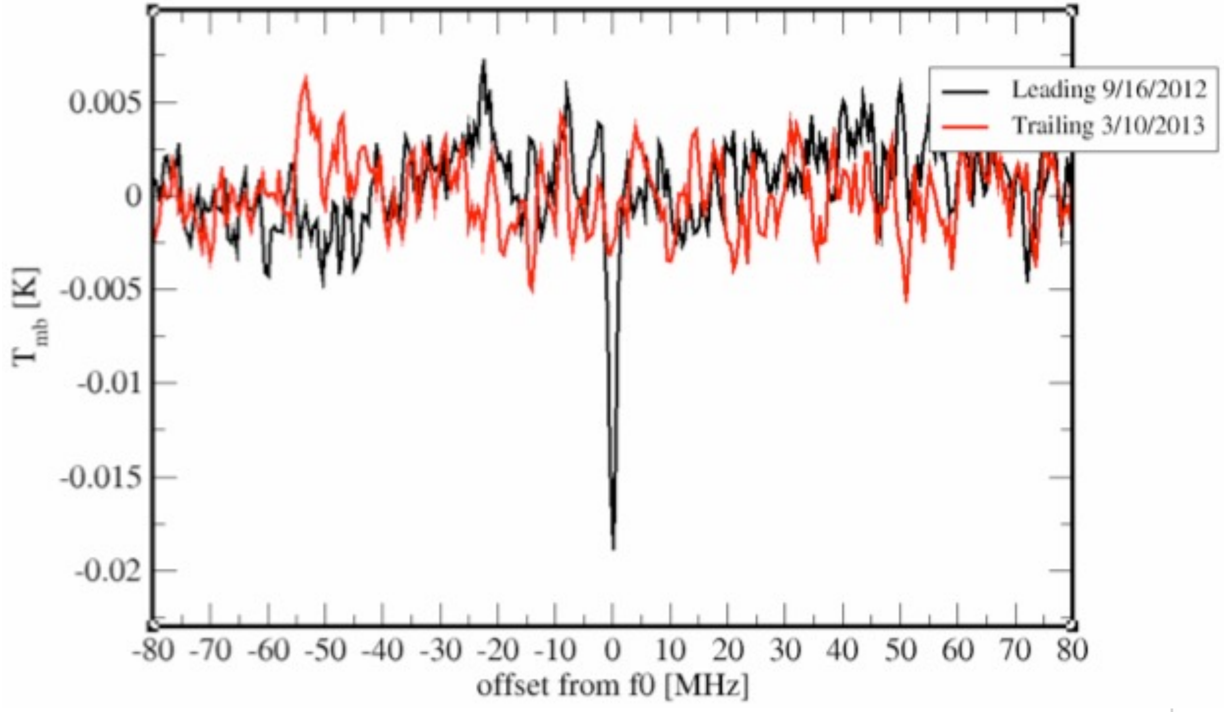




557 GHz H_2O line detected with HIFI (Kueppers + 14)

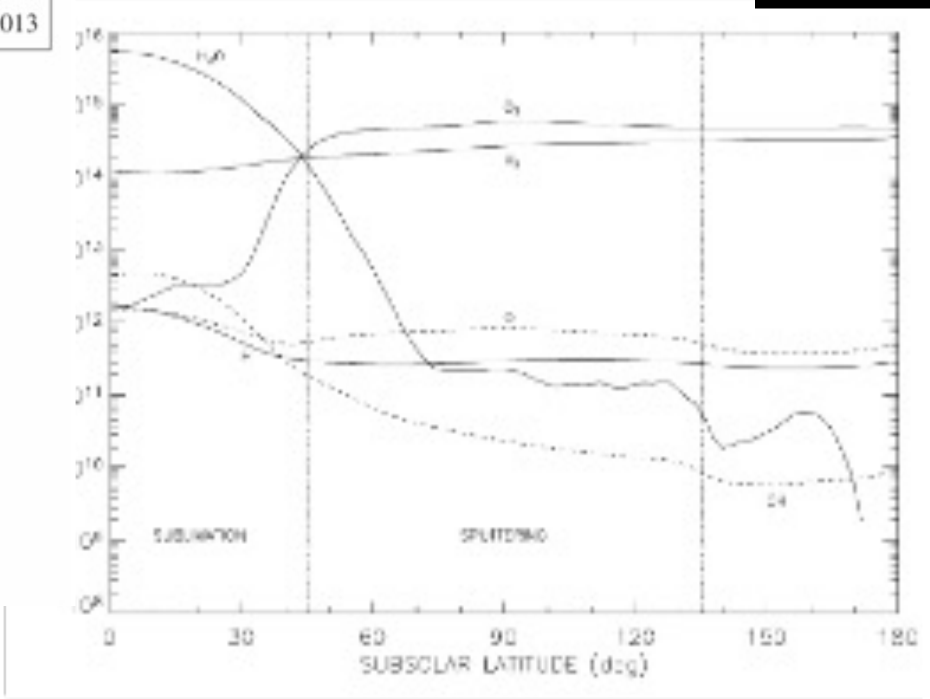
Ceres might host an internal water ocean (origin: Kuiper Belt?)

Another surprise from Herschel/HIFI: Water vapor on Ganymede and Callisto (557 GHz)



H_2O @ 557 GHz on Ganymede, Sept. 2012 (HIFI)

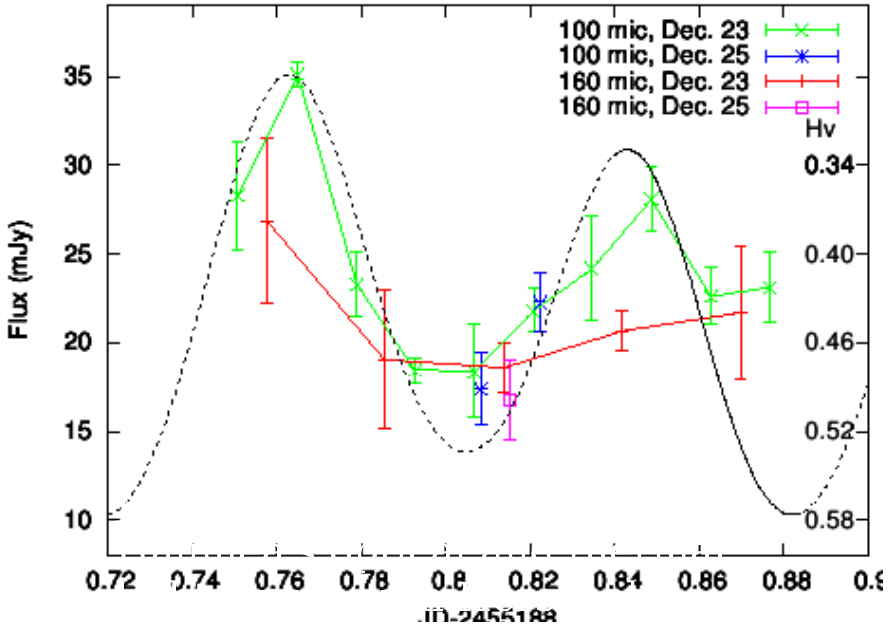
P. Hartogh, Herschel Conference, Oct. 2013



Distribution of H_2O and other species as a function of subsolar latitude in Ganymede's atmosphere (Marconi + 07)

The Herschel Key-Program: « TNOs are Cool »

- Continuum measurements are important too!
- FIR flux at # λ: -> Thermal properties, sizes, albedos (140 targets)
- Binaries -> Masses, densities, phase curves (25 targets)
- Objectives:
  - – Size distribution
  - – Orbital/physical correlations
  - – New collisional families

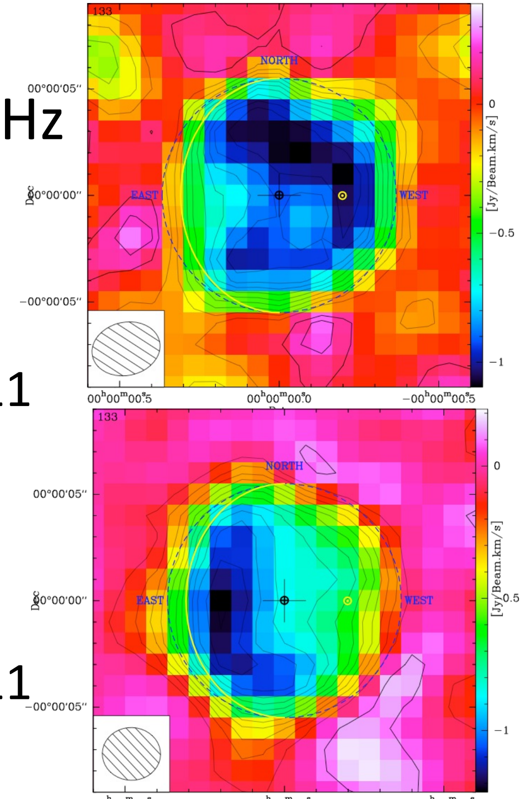


Haumea :
Optical and thermal
Lightcurves
(Lellouch +10)

Alma Highlights

- Mapping of planets and satellites
  - Origin of oxygen source on giant planets
  - SO, SO_2 on Venus
  - Winds and meteorology
  - CS on Neptune
  - Nitriles on Titan
- Composition of distant objects (Centaurs, TNOs)
  - CO, HCN, HNC on Pluto
- Cometary activity

Venus
SO @ 346.5 GHz



Nov. 14, 2011

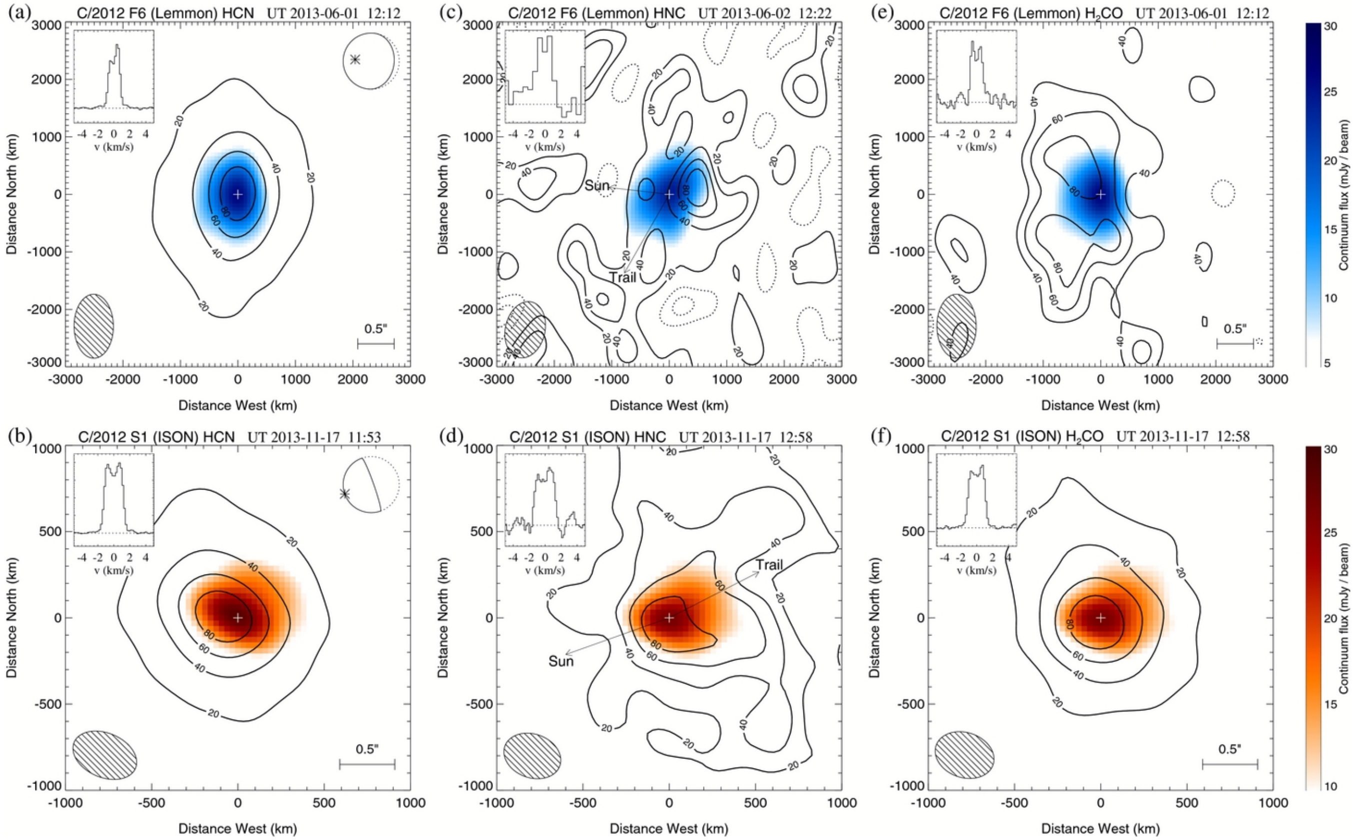
Nov. 15, 2011

Encrenaz +15

Comets with Alma

- Detection of minor species (C_2H_5OH and CH_2OHCHO in C/2014 Q_2 Lovejoy
- Mapping of gas and dust -> jets, active regions on the nucleus

HCN HNC H_2CO

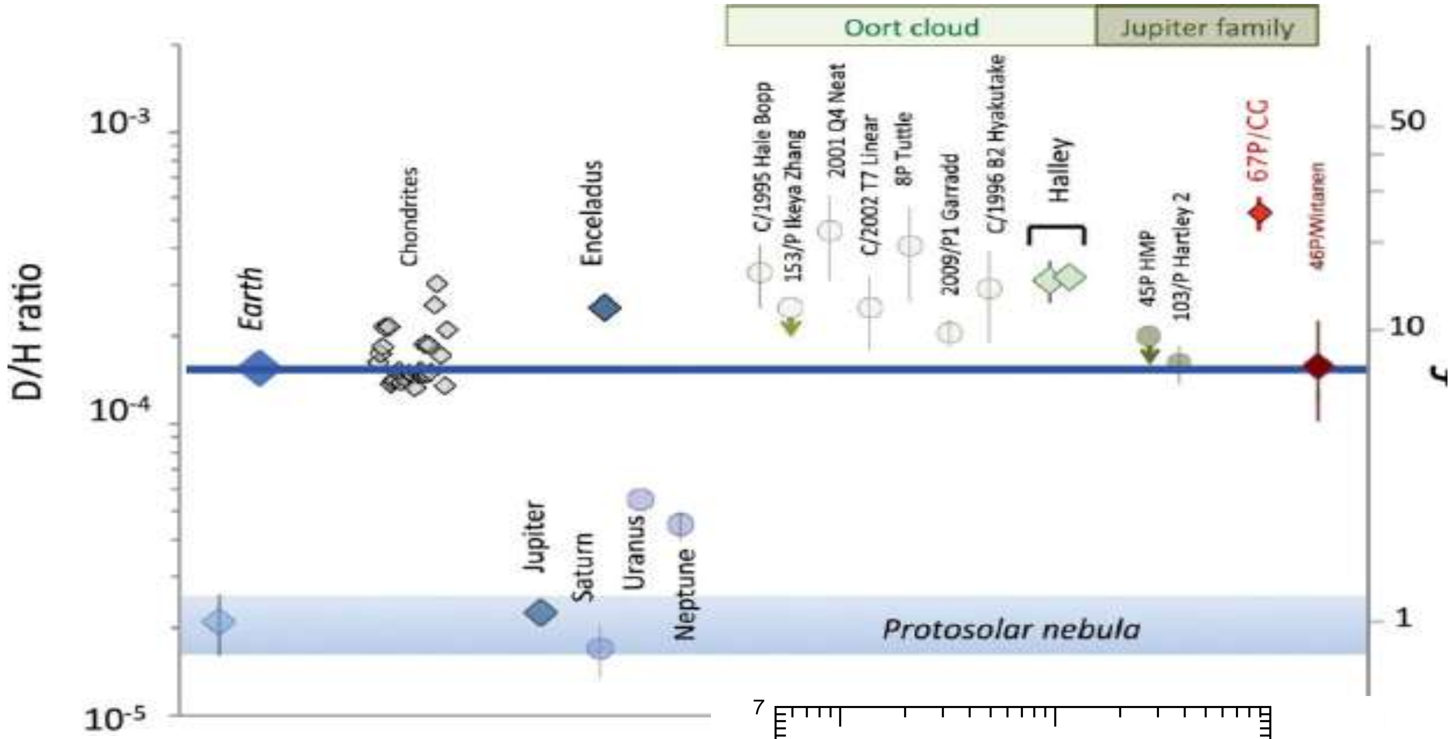


C/2012 F6 (Lemmon)

C/2012 S1 (ISON)

Crovisier + 16

D/H ratio in comets: A diagnostic of the origin of terrestrial water?



$[D/H]_{Earth}$ = 0.3 -1 x $[D/H]_{Comets}$

$[D/H]_{Earth}$ = 1 x $[D/H]_{C\text{-}Chondrites}$

-> **Origin of oceans:**

- D-type Main-Belt Asteroids?
- Hyperactive comets? (Lis +19)
- A mixture asteroids-comets?

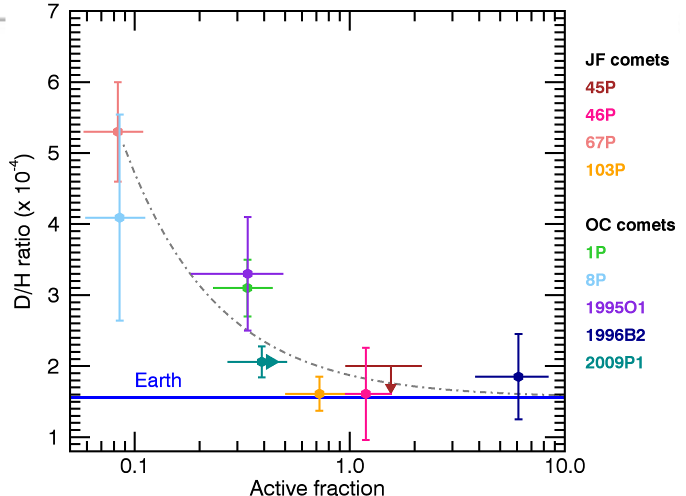
-> **Mechanism:**

- Meteoritic bombardment?
- Or: Disk of gaseous H_2O coming fromD-type MBA, generated by early solar outburst? (Kral + 24)

Diversity in cometary D/H:

D/H appears to be anticorrelated with cometary activity (Lis + 19)

-> Possible fractionation at the surface?

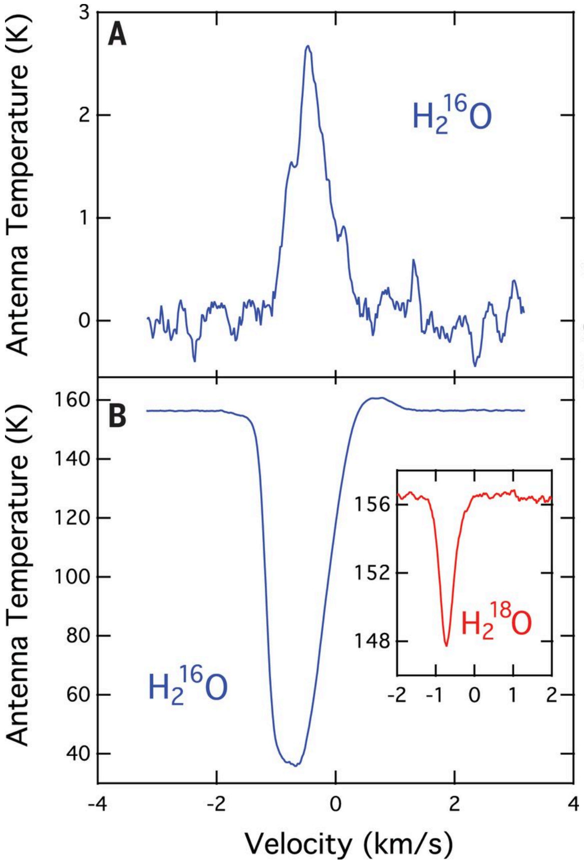


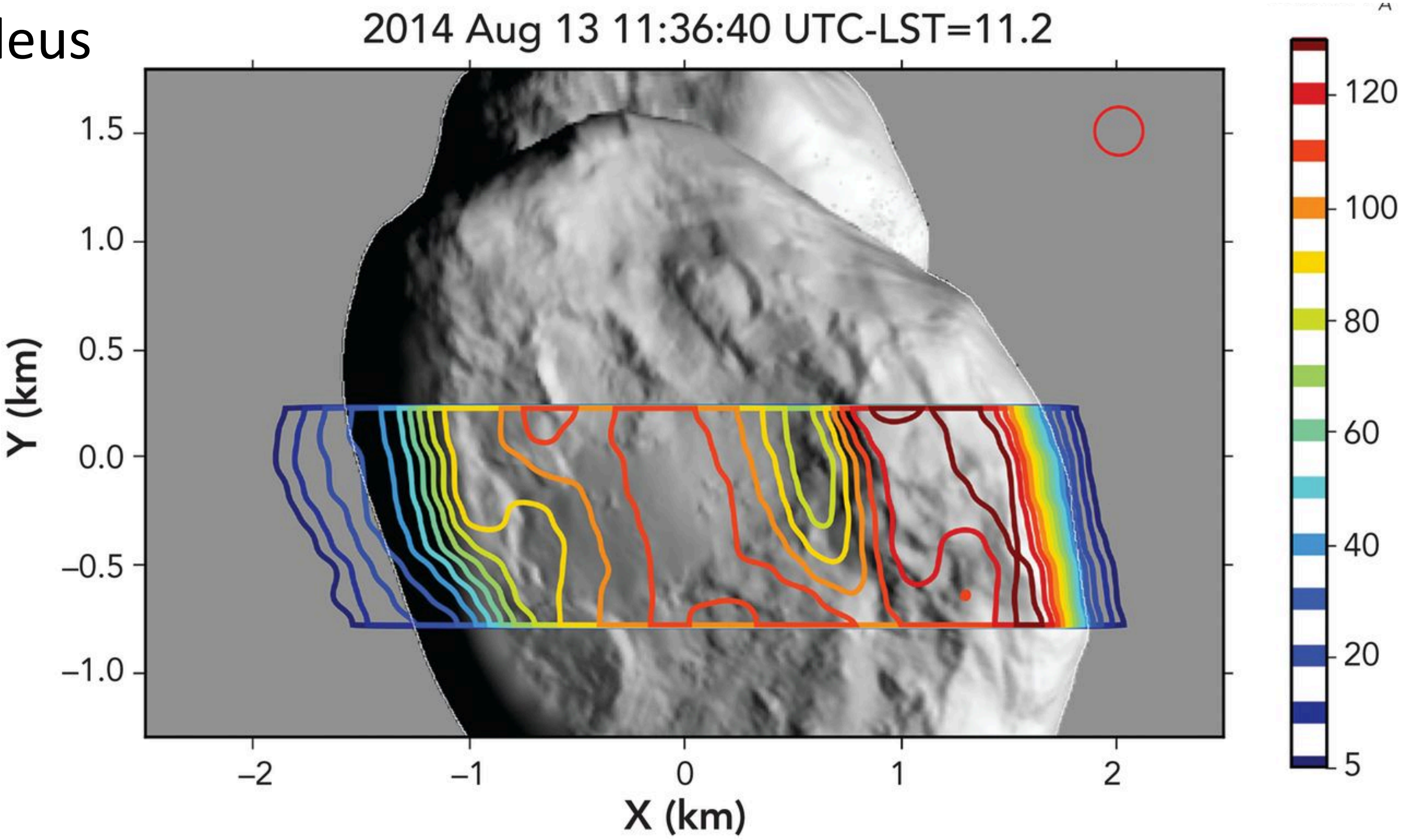
Mapping of 67P/Churyumov-Gerasimenko with MIRO aboard Rosetta

- MIRO : first heterodyne instrument on a planetary space mission
- Heterodyne spectroscopy, 2 channels (0.5 and 1.6 mm wavelength)
- H_2O + isotopes, CO, NH_3, CH_3OH
- Thermal emission of the nucleus

H_2O 557 GHz
D = 128000 km
23 June 2014

H_2O 557 GHz
D = 81 km
19 August 2014





Surface temperature at λ = 0.5 mm, 13 August 2014

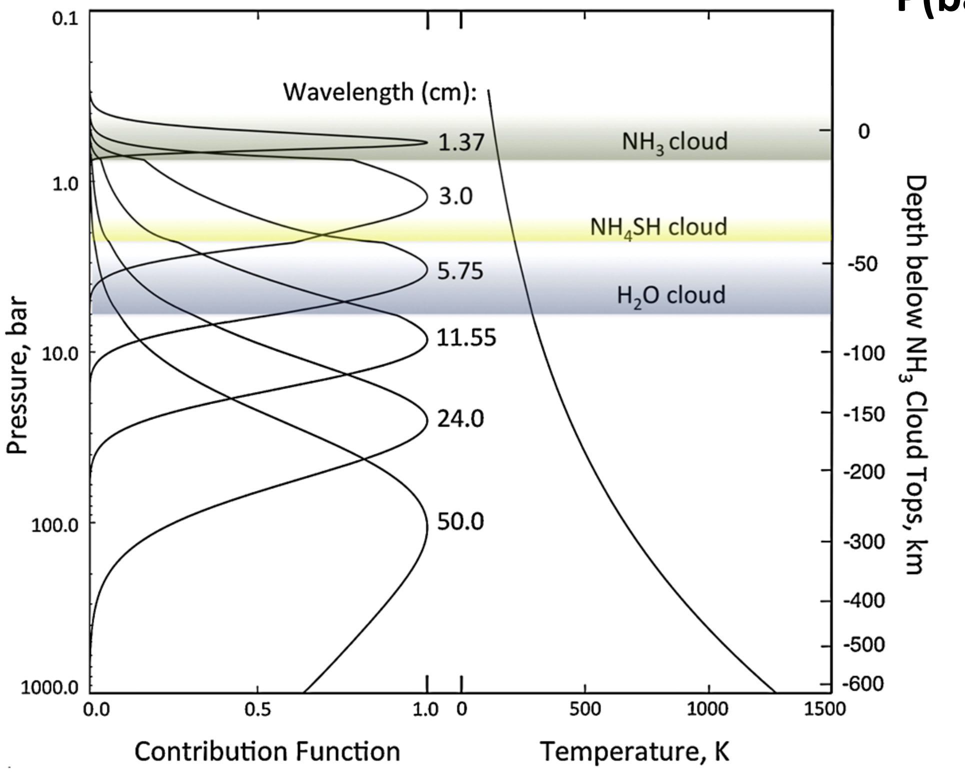
Crovisier + 16

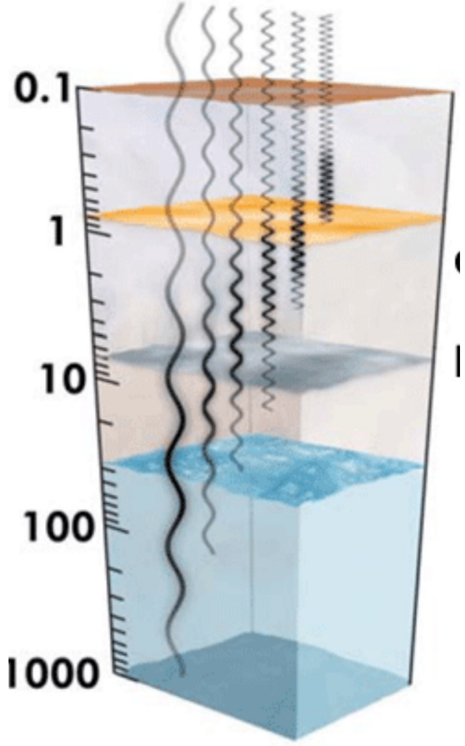
Probing the interior of Jupiter using JUNO/MWI (NASA)

Launch : 2011 – Expected end: 09/2025
PI: S. Bolton
Objectives :

- Constrain the internal structure and measure O/H
- Study atmospheric dynamics & aurorae

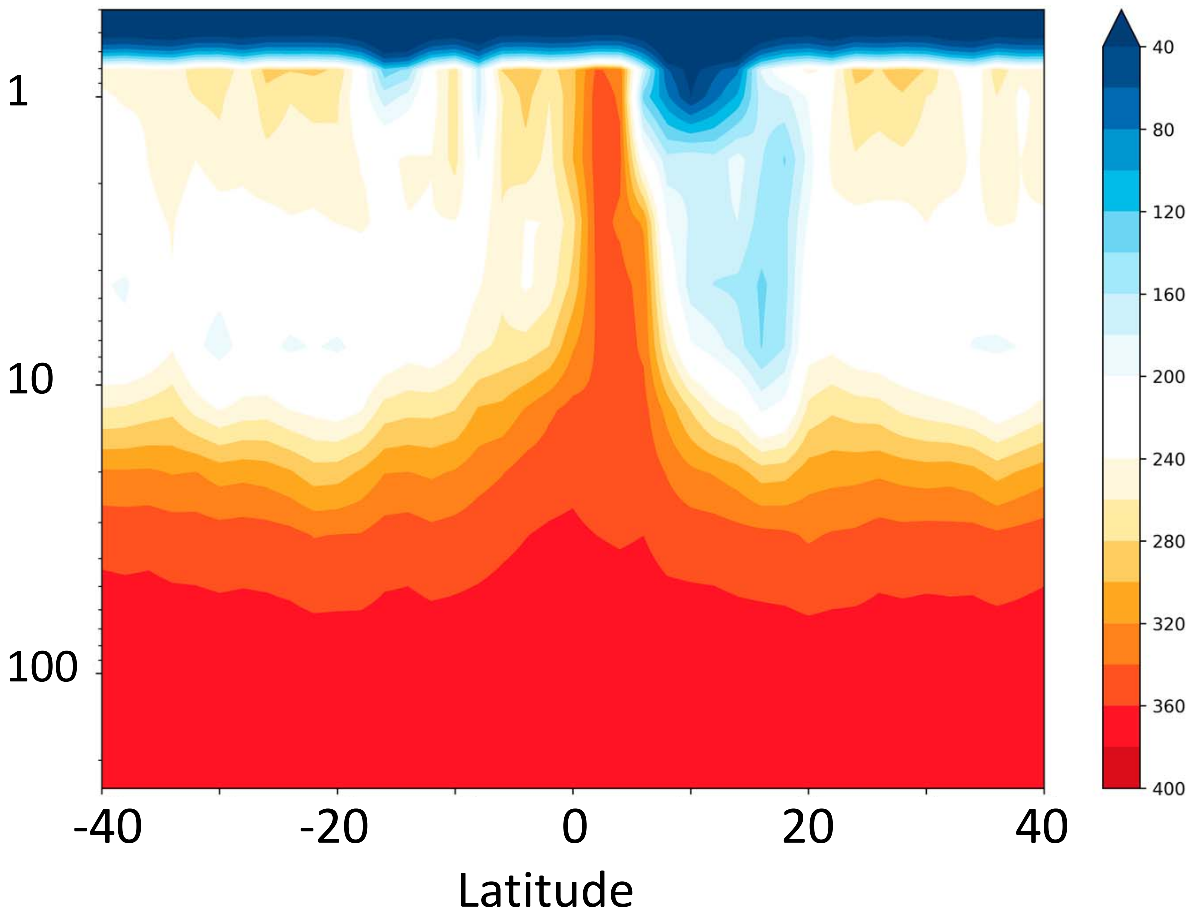
MWI (Janssen +17) : Microwave sounder, λ = 1.3 -> 50 cm
Objective : probe the deep troposphere & determine the NH_3 and H_2O vertical distributions



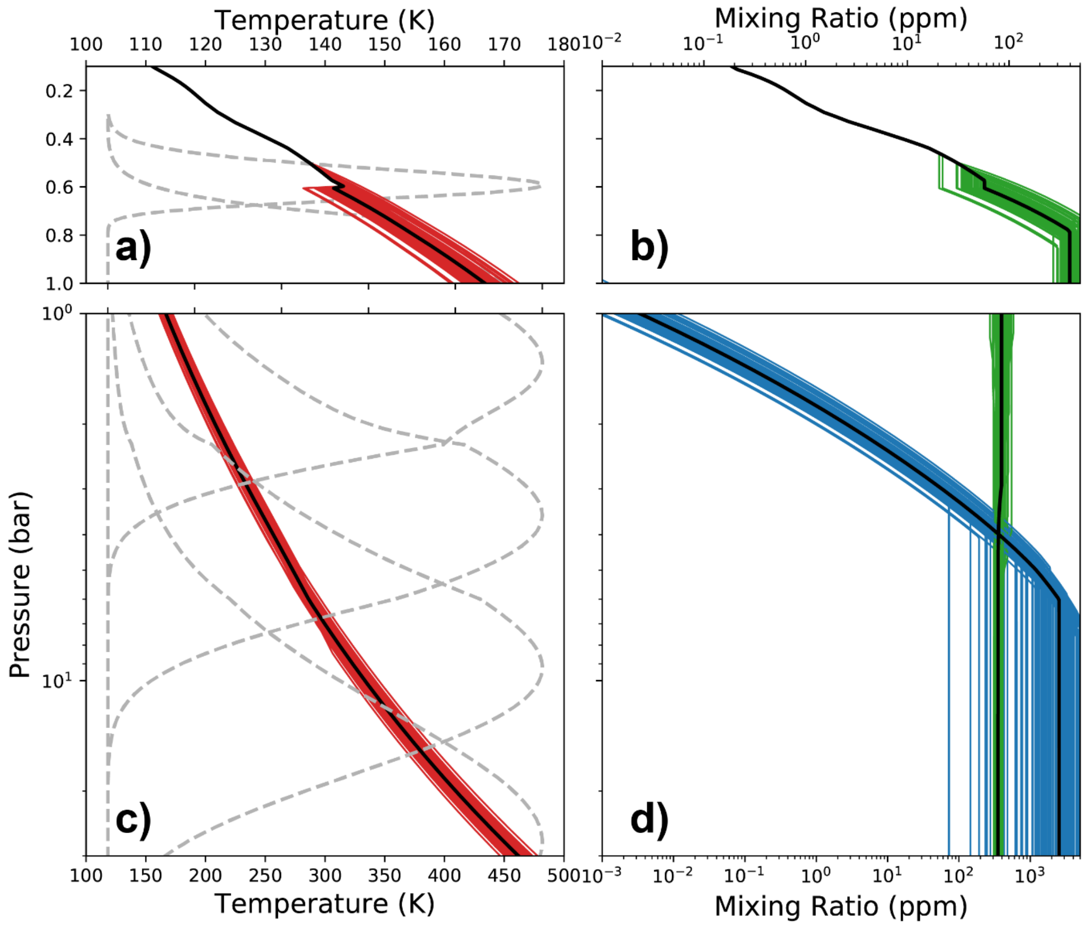


MWI/JUNO : Results

A very surprising NH_3 distribution in the deep troposphere, with strong depletion around the NEB (Li +17)



At the equator : O/H = 2.7 (+2.4,-1.7) x solar (Li +20)
- consistent with C/H, N/H, S/H from Galileo Owen +97)
- consistent with solar-composition icy planetesimals

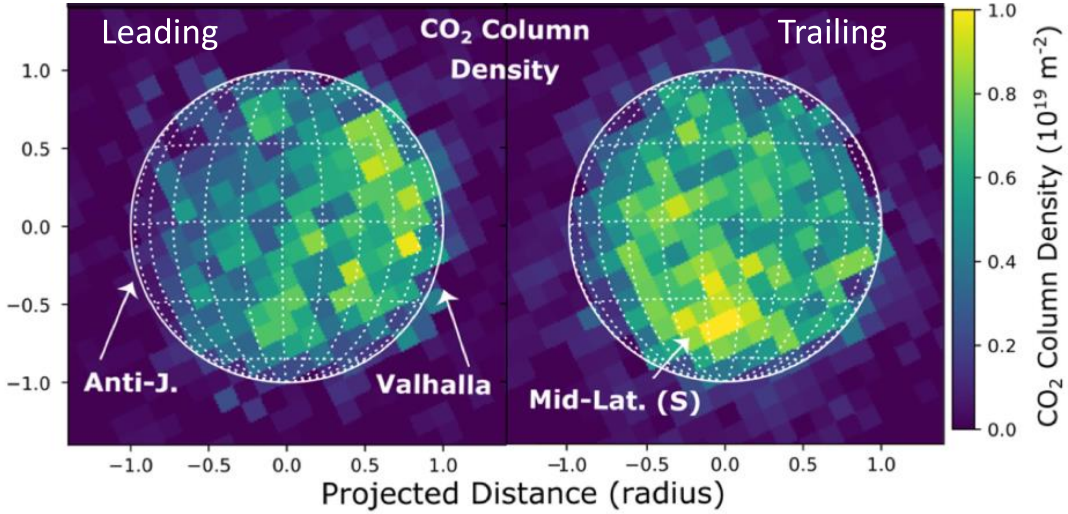


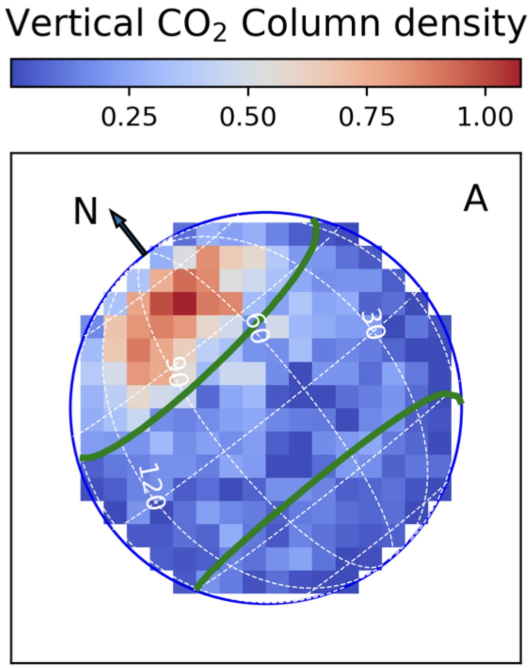
JWST Highlights

- Meteorology on planets
  - Jupiter : south pole, Great Red Spot (Fouchet, de Pater +24)
  - Saturn: Structure & dynamics of the Northern hemisphere (Fletcher + 24)
  - Uranus and Neptune (Roman + 24)
- Exospheres on satellites and distant small bodies
  - SO on Io (de Pater +24)
  - H_2O, CO, CO_2 on Galilean satellites (Cartwright +24, Bockelée-Morvan +24)
  - Activity on Centaurs (Faggi + 24)
  - Uranus rings (de Pater + 24)

[redacted]

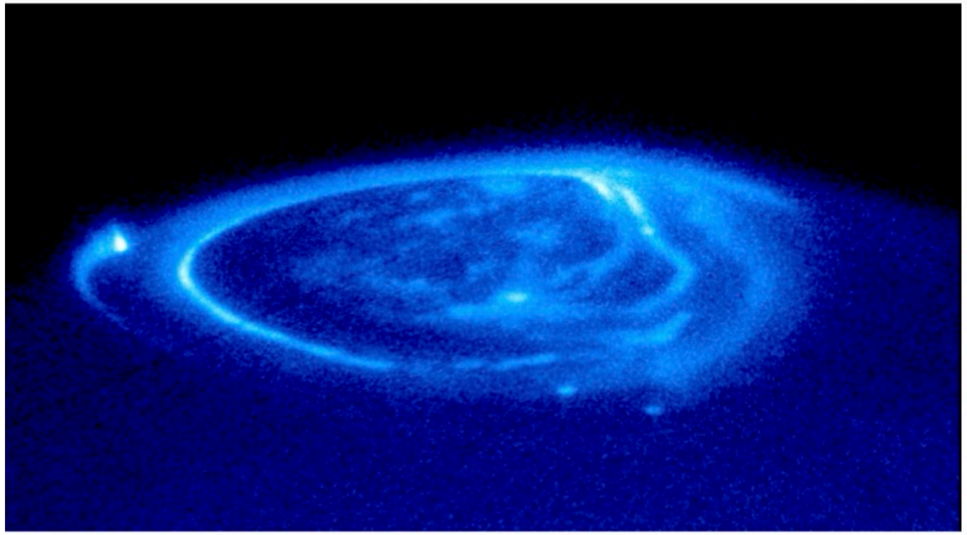
Gaseous CO_2 on Callisto (Cartwright + 24)

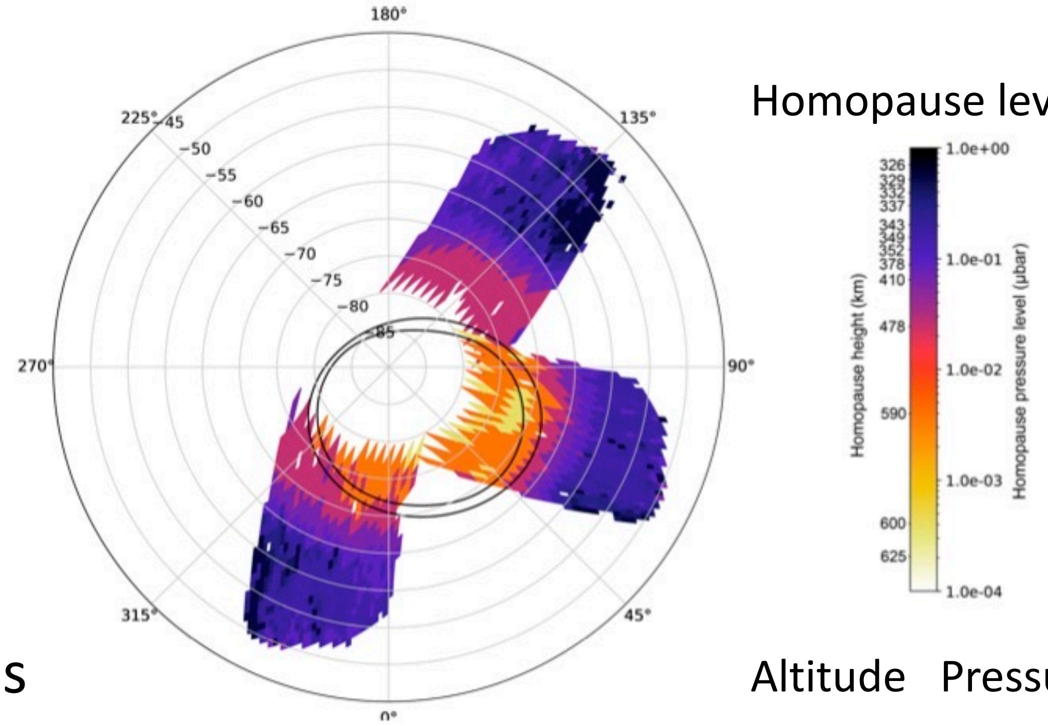




Gaseous CO_2 on Ganymede (Bockelée-Morvan + 24)

The South Pole of Jupiter as seen by JWST/MIRI





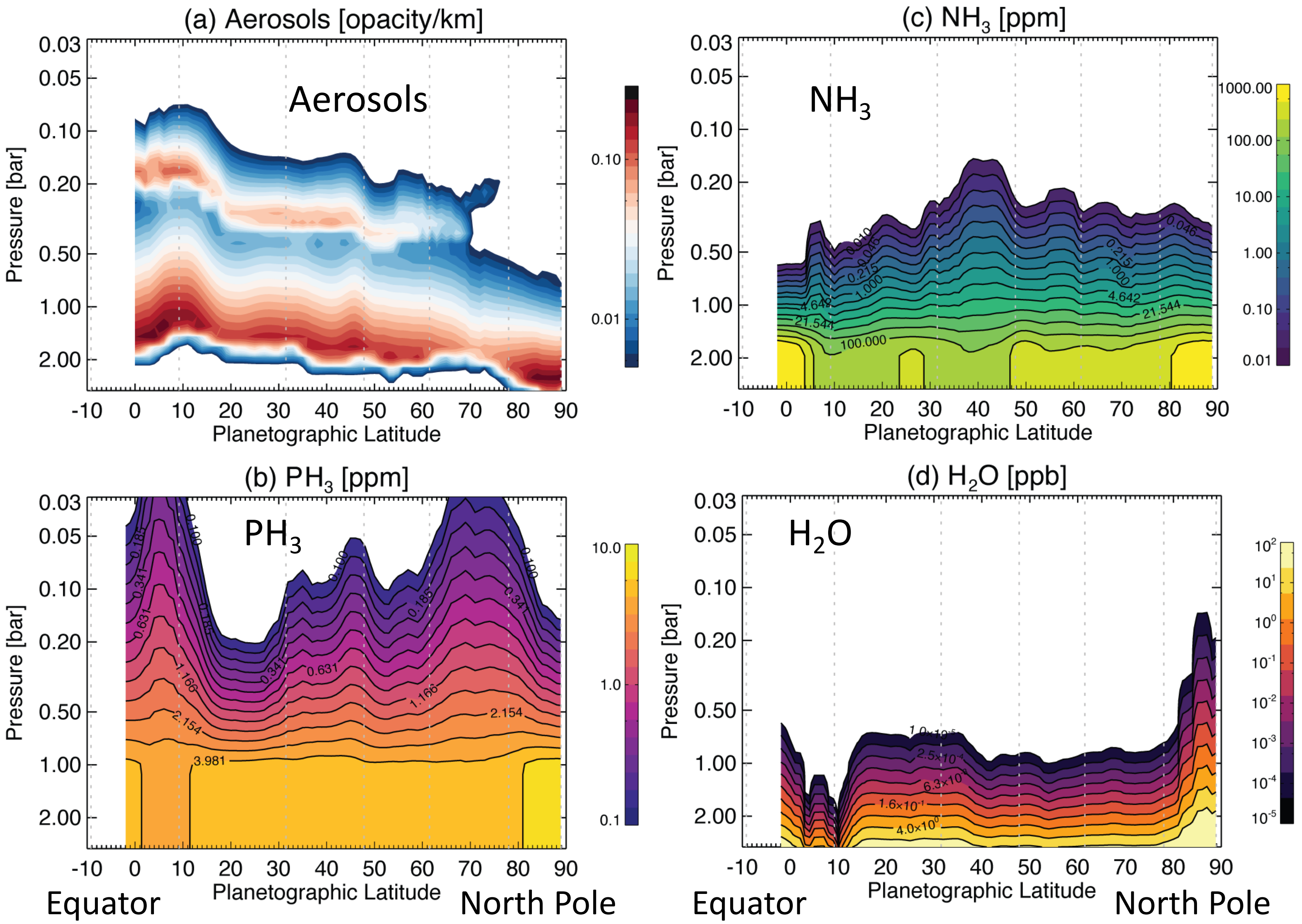
Homopause level

Altitude Pressure

Mapping of the auroral region with MIRI
-> Detection of benzene C_6H_6 & many hydrocarbons
-> Retrieval of T(z) and the altitude of the homopause
-> Detection of stratospheric photochemical haze
➔Results: The homopause is higher by 140 km in the auroral region and
stratospheric temperatures are higher
Aerosols are produced from C_6H_6 through the formation of PAHs

Rodriguez-Ovalle + 24

Composition, structure & dynamics of Saturn's atmosphere



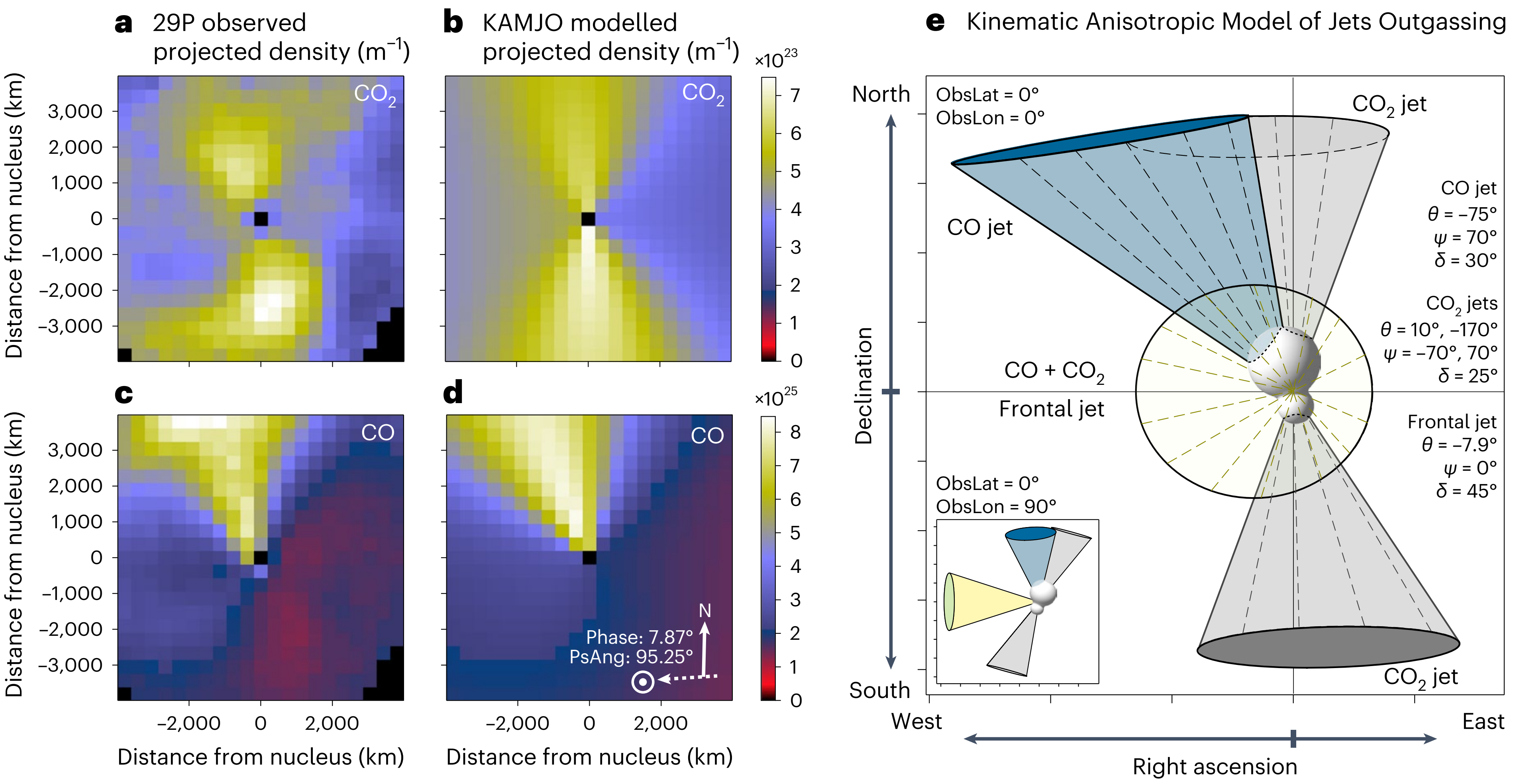
- Evidence for seasonal changes since Cassini in temperatures and winds (from N-winter to N-summer)

- Evidence for two aerosol layers around 1-2 bar (NH_3?) and 0.2-0.3 bar (photochemical haze?)

- No correlation between PH_3, NH_3 and H_2O

Fletcher +23

JWST/MIRI mapping of 29P/Schwassman-Wachman 1 in CO & CO_2



Faggy + 24

The nucleus of 29P/SW1 is a bilobed object (1 CO + CO_2-rich and 1 CO_2 rich) with two distinct origins

Solar system studies in the FIR : The future

Present limitations:

- **Interferometers (Alma/Noema…):** Absence of flexibility, presence of ripples in the case of bright sources
- **JWST:** Limited spectral range & resolution, absence of flexibility, no heterodyne spectroscopy available

What to do next:

(1) Ground-based facility: a large single dish with heterodyne spectroscopy

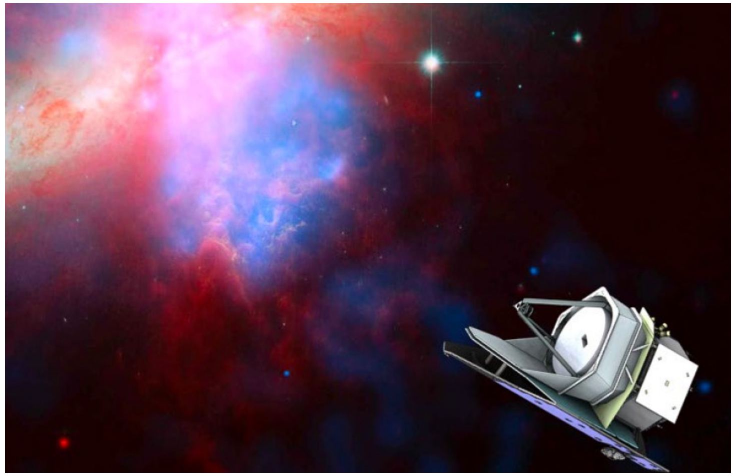
- High dynamical range
- High spectral resolution on large banswidths

- > the European AtLAST project

(2) Space observatory: a 2-m cryogenic telescope between 25 and 300 μm (imaging, spectoscopy, polarimetry)

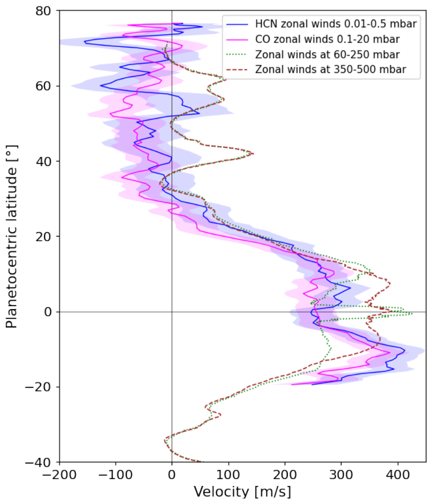
- Fills the gap between the JWST and ALMA with unprecedented sensitivity

- > the PRIMA project, under Phase A at NASA



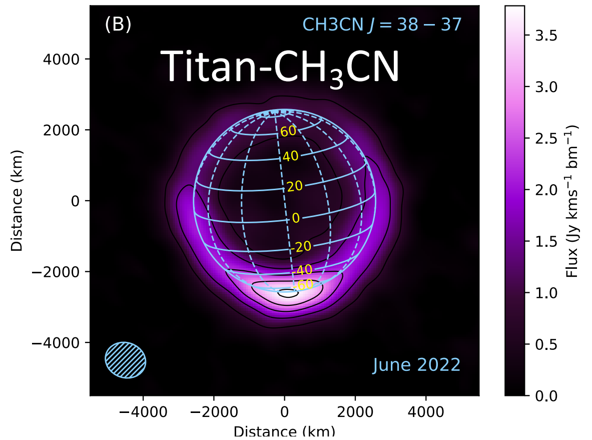
Solar system studies with AtLAST

Access to the monitoring of transient/seasonal phenomena (Cordiner +24)

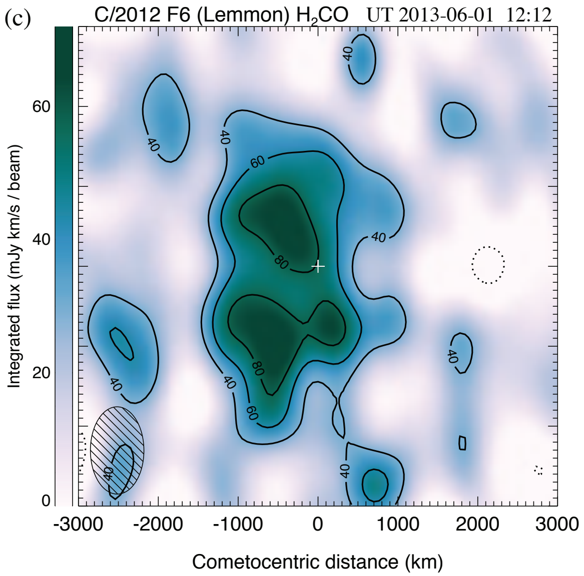


Saturn's winds (Benmahi +22)

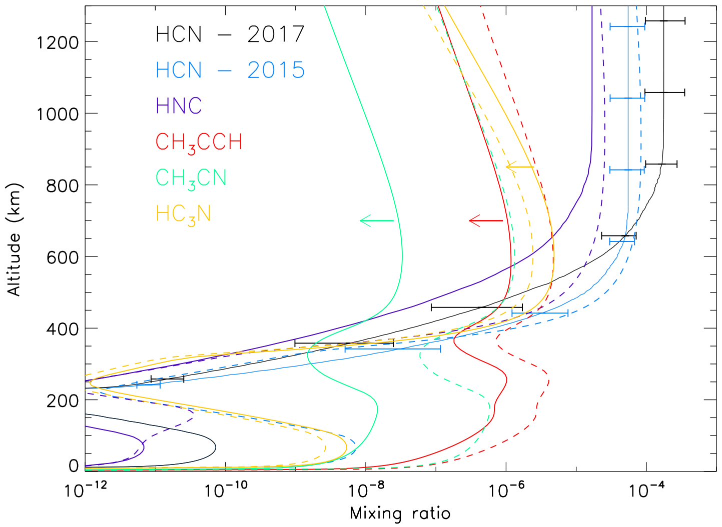
- 3-D atmospheric dynamics on large planets
- Wind fields on planets and satellites
- Composition of exospheres on distant objects
- Mapping of comets
- Albedos and sizes of TNOs



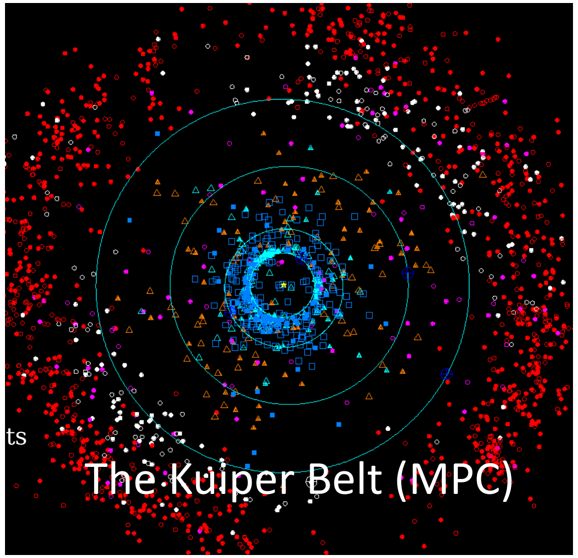
CH_3CN on Titan (Thielen +23)



H_2CO in Comet Lemmon (Cordiner +14)



HCN & HNC on Pluto (Lellouch +22)



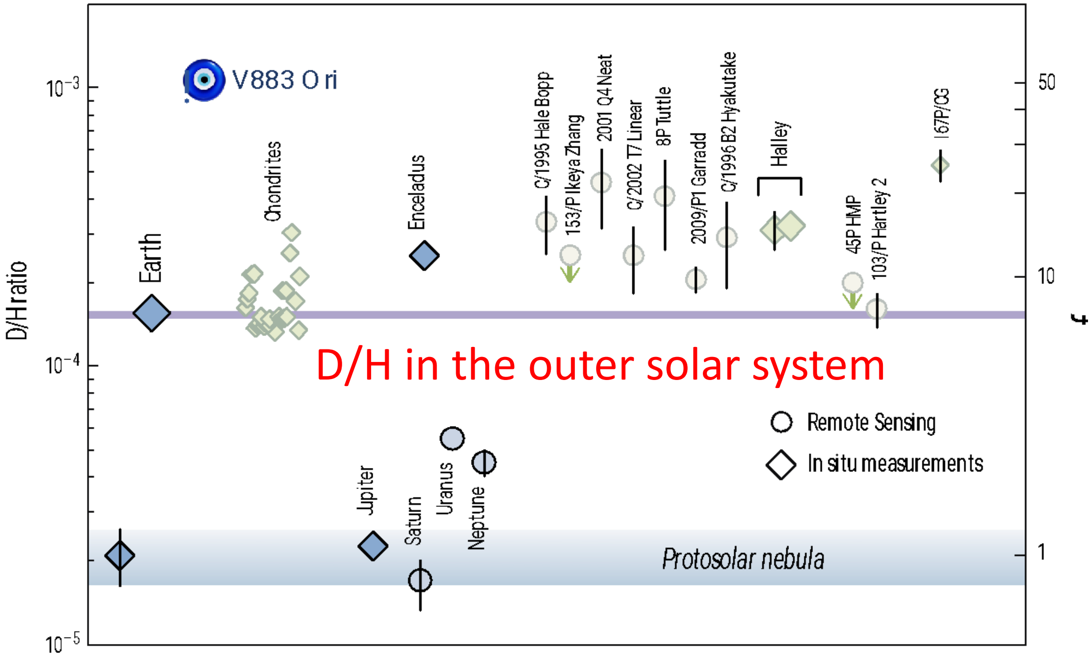
Solar system studies with PRIMA

Comets and the origin of terrestrial water (Lis +23)

Objective: to measure D/H in a large sample of comets to understand the D/H distribution among different types of comets and better constrain the link to the origin of terrestrial water

Method: Observation of optically thin HDO & $H_2^{18}O$ lines

Large program, 30 comets, FIRESS, R = 4400 @ 112μm

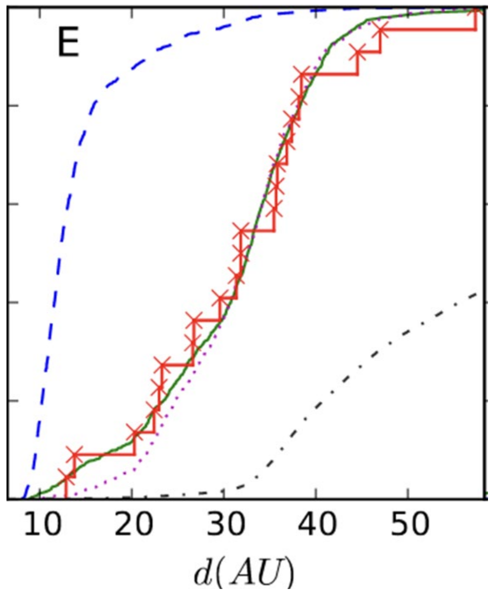


Size distribution in the Kuiper Belt (Moullet +23)

Objective: constrain the destruction & accretion mechanims in the Kuiper belt formation

Method: thermal survey of KBOs at 100 μm to determine the size+albedo of about 200 objects in the 35-80 μm range

Large program, PRIMAger maps in hyperspectral band 2A

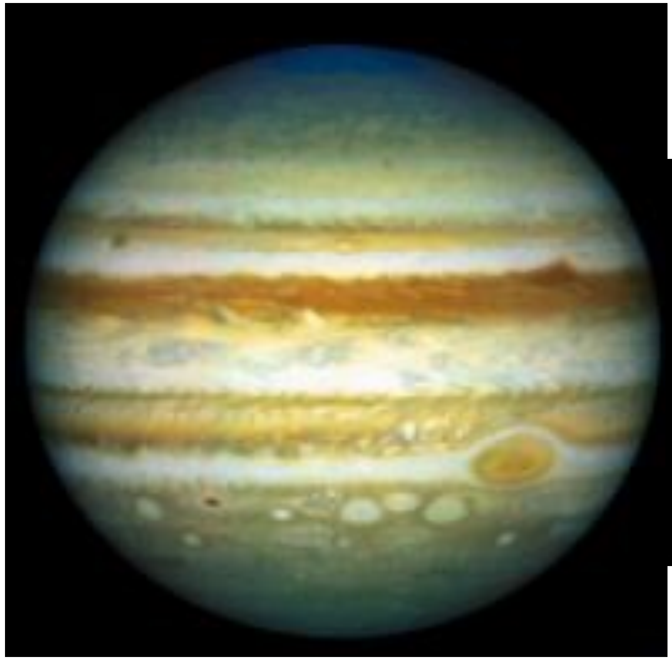


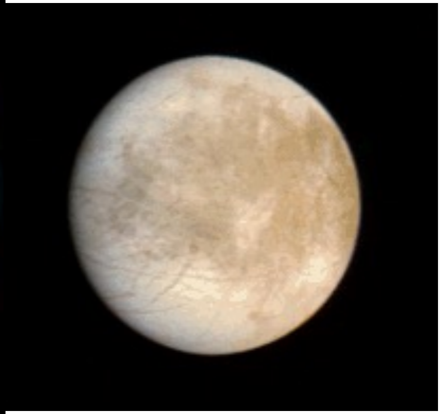
Cumulative distribution of scattered KBOs from optical measurements (assumed albedo, 0.05)

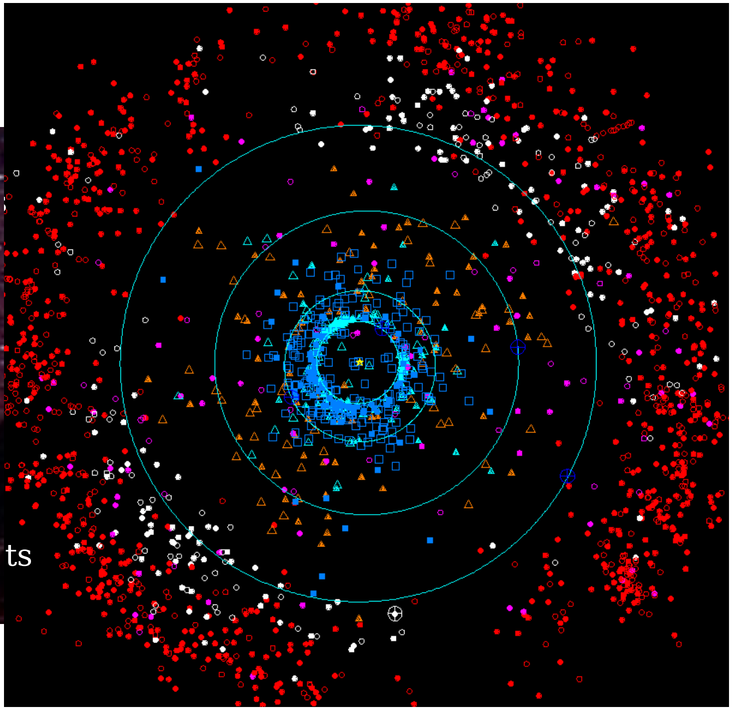
Preferred capabilities for the future

(1) Ground-based facility: a large single dish with heterodyne spectroscopy

(2) Space observatory: a 2-m cryogenic telescope between 25 and 300 μm (imaging, spectoscopy) : FIRESS, R= 4400 @ 112 μm ; PRIMAger, 2A band







Thank you for your attention!