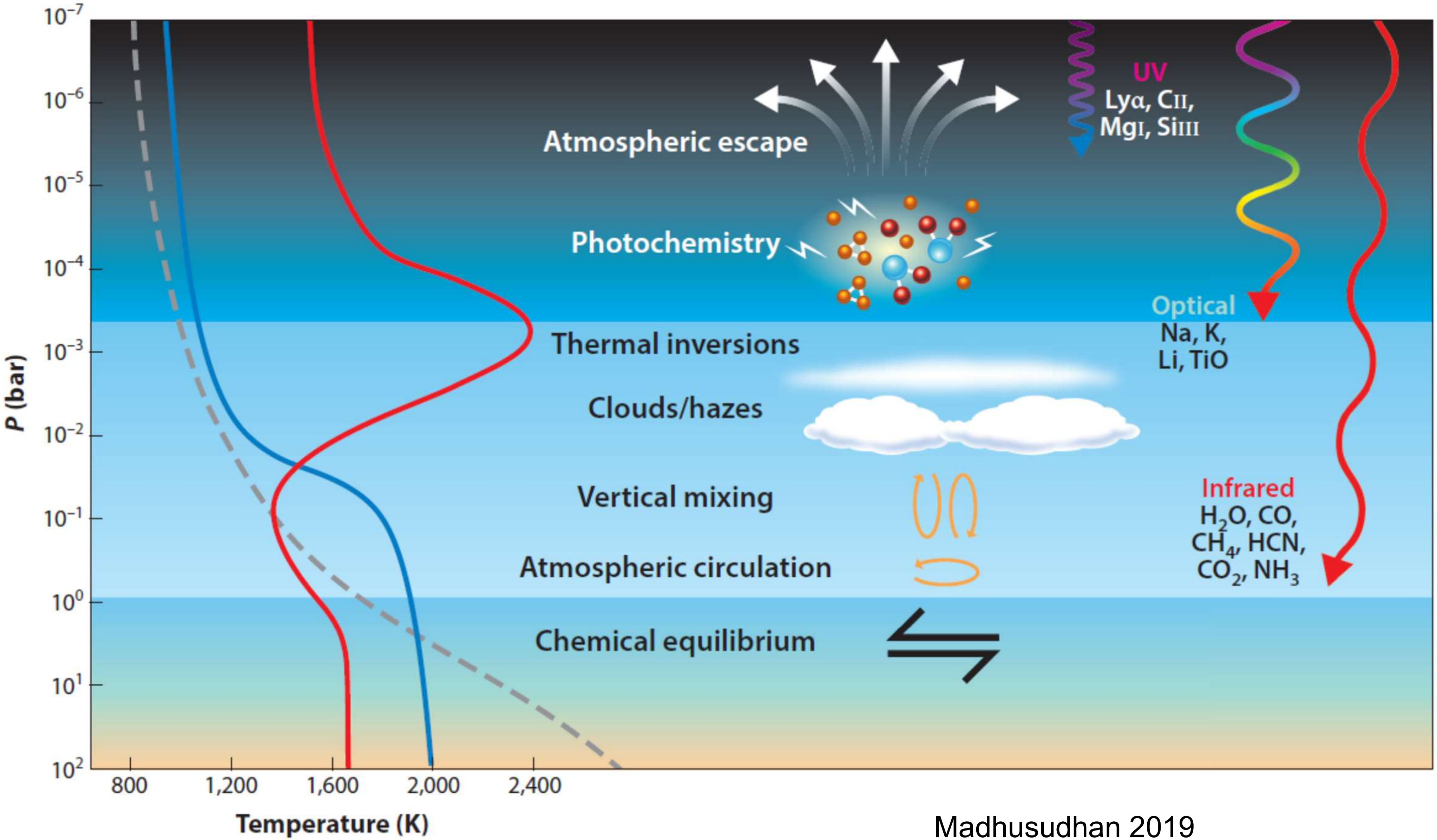
Solar System atmospheres in the near-IR (1-5 μm) at high spectral resolution

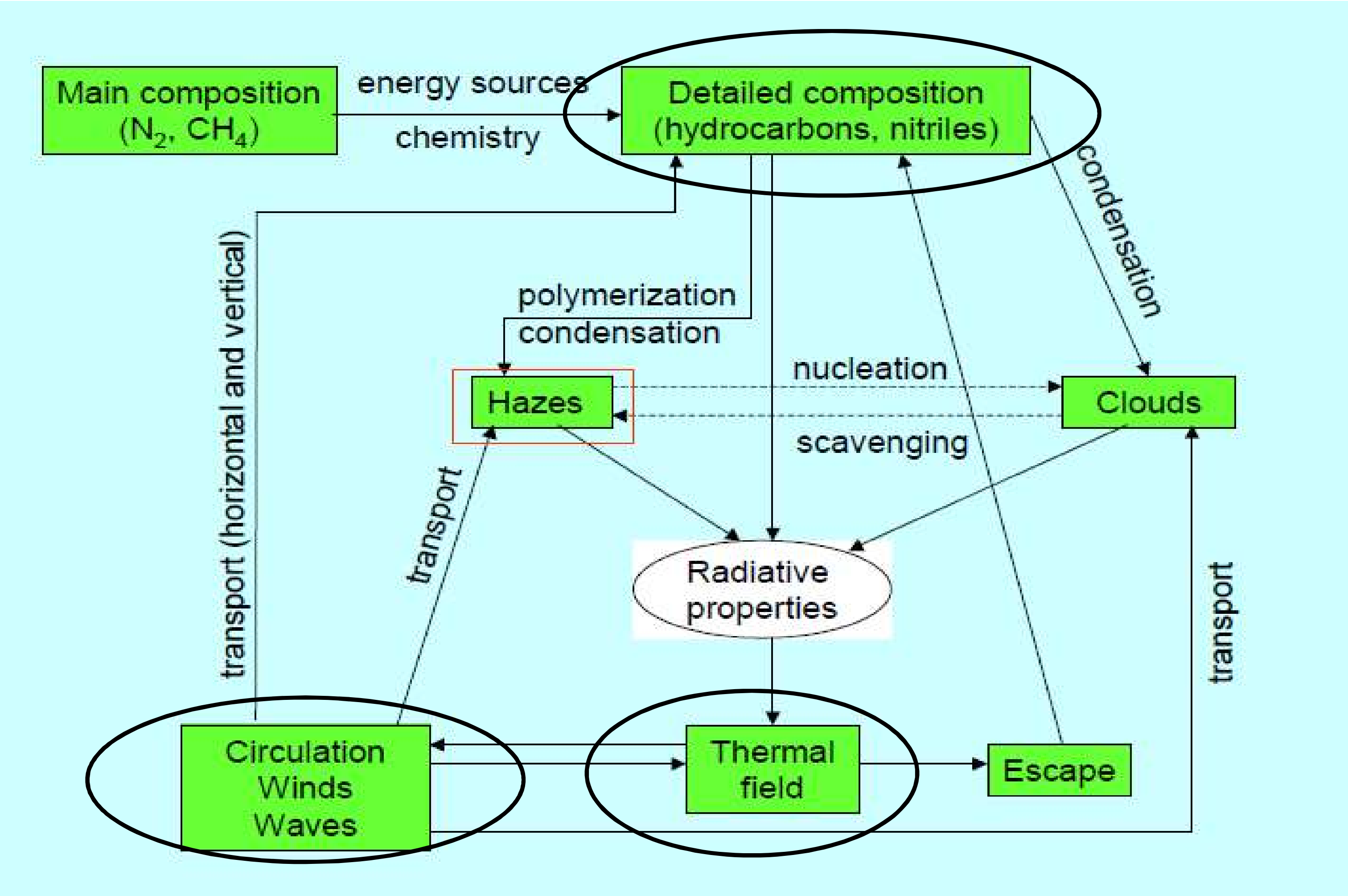
Emmanuel Lellouch

Observatoire de Paris



Madhusudhan 2019

Couplings in planetary atmospheres: Titan example



Need to characterize 3D fields

- Composition (gas, condensates)
- Temperature
- Winds

Coustenis et al. 2009
TANDEM mission proposal

The need for high resolution

- 1. Disentangling lines from different species in crowded spectral regions → molecular identification and abundance measurements

- 2. Spectral separation of the ro-vibrational lines of a given species → temperature information from line rotational distribution or from thermal profile retrieval with vertically resolved information (in thermal range, for species with known abundance)

- 3. Resolving line profiles → gas vertical profiles
  - Typically Lorenz halfwidth ~ 0.1 cm^{-1} / bar. At 5 μm = 2000 cm^{-1} , a resolving power R = 100,000 enables to resolve lines formed at 0.2 bar and deeper
  - Doppler halfwidth $\Delta\nu = 4.3 \times 10^{-7} \nu \, \mathrm{sqrt}(T(K)/M(g))$. With T=200 K, M=28 (CO), $\Delta\nu / \nu = 1.1 \, 10^{-6}$, hence $R = 10^6$ is needed to resolve Doppler lines. *In general*, requires heterodyne detection (not in near-IR)

- 4 .For unresolved lines, high resolving power enhances line contrast (proportional to R), facilitating detection (either in targetted or in serendipitous observations)

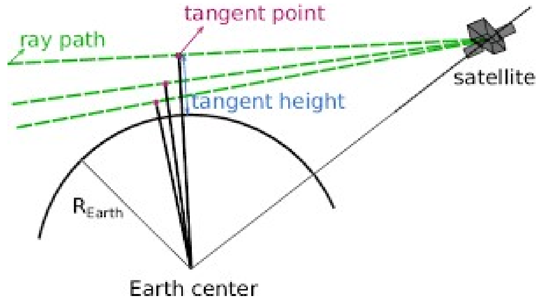
The need for high resolution

- 5. Direct wind measurements from Doppler shifts. E.g. R = 100,000 gives Δv = 3 km/s. But Doppler shifts can be detected to much lower levels…
  - Doppler precision on a single line ~ Δv / (S/N) , e.g. 30 m/s for S/N = 100
  - Simultaneous use of many lines (e.g. solar lines reflected off planet) → traditional velocimetry (motion of atmosphere with respect to observer)
  - May be limited by instrument stability, or by pointing uncertainties (esp. for rapidly rotating planets, e.g. v_{eq} (Jupiter) = 13 km/s)

- 6. For ground-based observations, high resolution considerably alleviates effects of telluric transmission (and of solar lines)

- 7. For spaceborne observations, limb sounding considerably

enhances sensitivity and vertical sounding capability

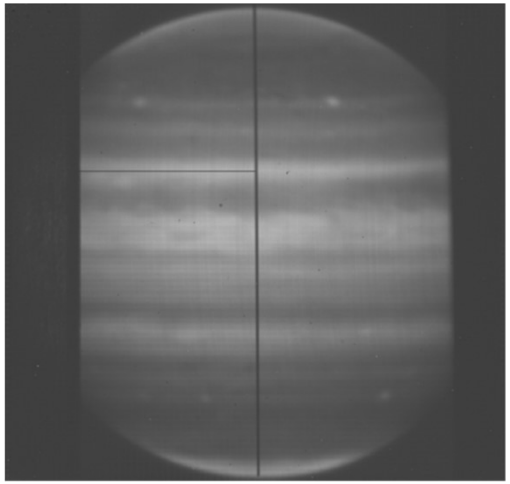


- 8. High-resolution observations, by « clearing the jungle », enable subsequent observations at lower resolution (e.g. from spacecraft)

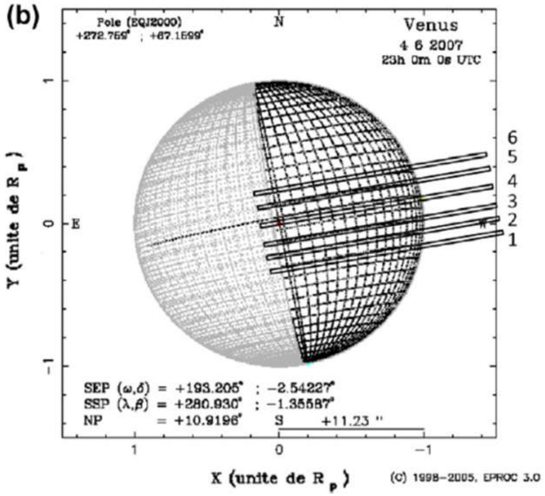
Mapping the planets

- Single-pixel instruments (e.g. CFHT/SPIRou, TNG/GIANO, Espadons (visible), HARPS (vis)…): require point-by-point observations.
- Long-slit spectrometers (IRTF/iSHELL, Keck/NIRSPEC, VLT/CRIRES, VLT/UVES (vis)…)
  - 1D instantaneous mapping, full 2D can be obtained by moving slit (or let planet rotate)
  - Interest for wind measurements: improving pointing knowledge (limb position) and yielding differential measurements
- 2-D imaging spectroscopy (former CFHT/ FTS-BEAR, CFHT/Sitelle (vis), VLT/MUSE (vis))

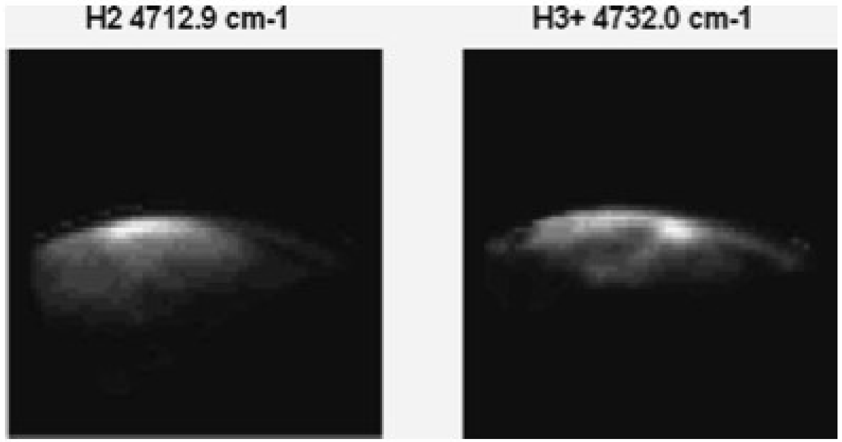
Jupiter with (old) CRIRES



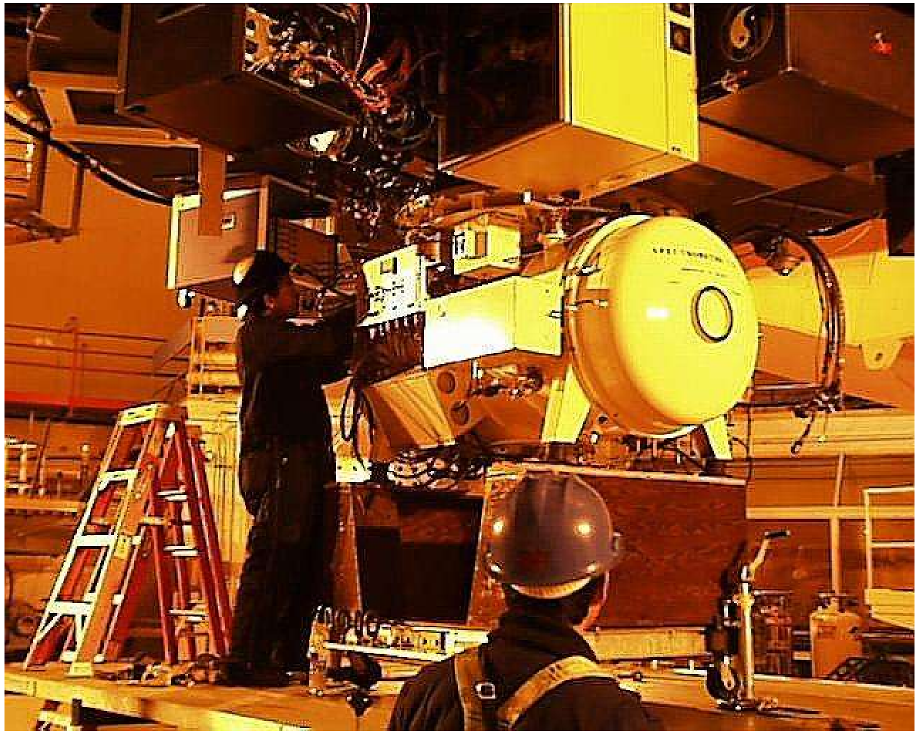
Venus with Espadons



Jupiter aurora with FTS-BEAR (R=20000)



The Fourier Transform spectrometer (FTS) at the CFHT (1983-2000)

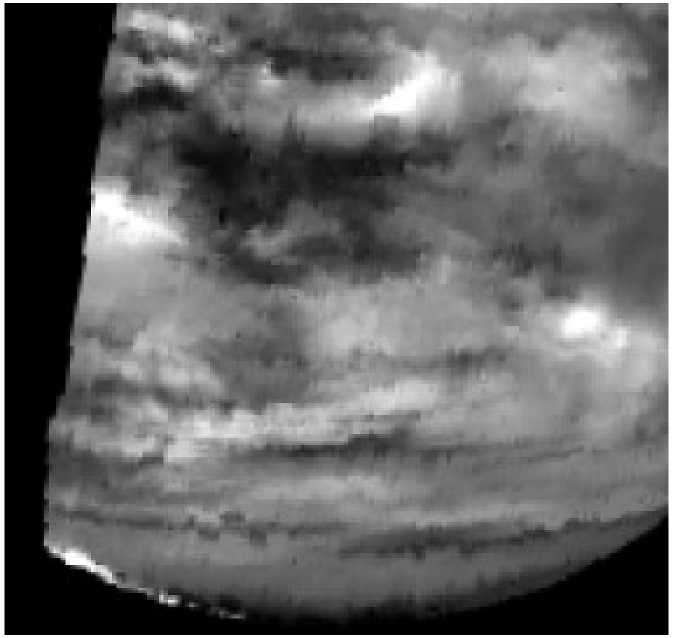


Jean-Pierre Maillard

0.9 – 5.2 μm, InSb, InGaAs detectors
Best spectral resolution ~ 0.01 cm^{-1} (R = 1,000,000 !)

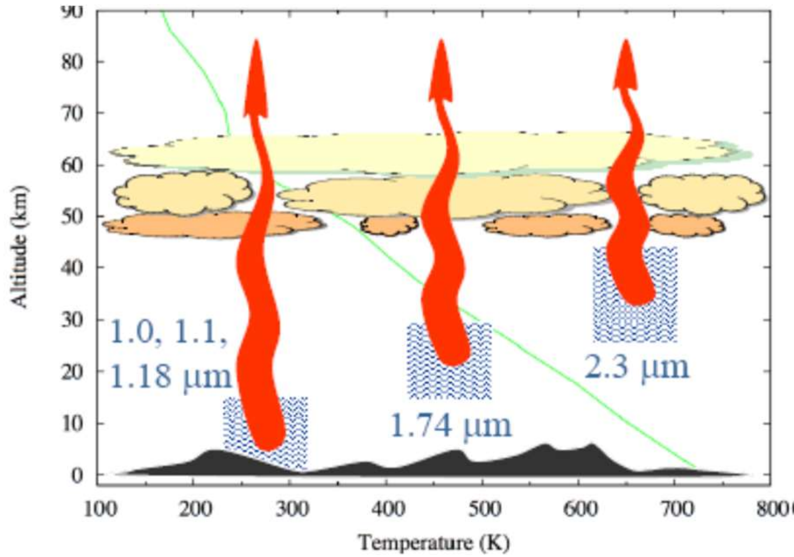
Strengths: broad instantaneous spectral coverage, easily adjustable spectral resolution independently of aperture
Weaknesses: single aperture (but then FTS/BEAR), relatively modest sensitivity (ok for planets)

Probing below Venus' clouds on the nightside in the near-IR

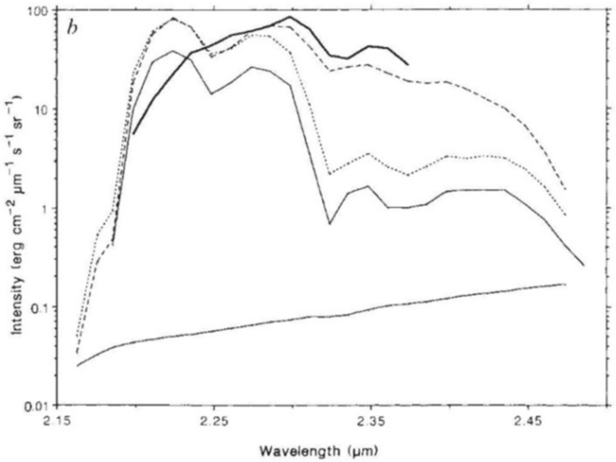


The uppermost clouds form a curtain and by day reflect sunlight back to dazzle us. By night, however, we become voyeurs able to peep into the backlit room behind

D. Allen, Icarus, 1987



Probing at ~0-10, ~15 and ~30-40 km

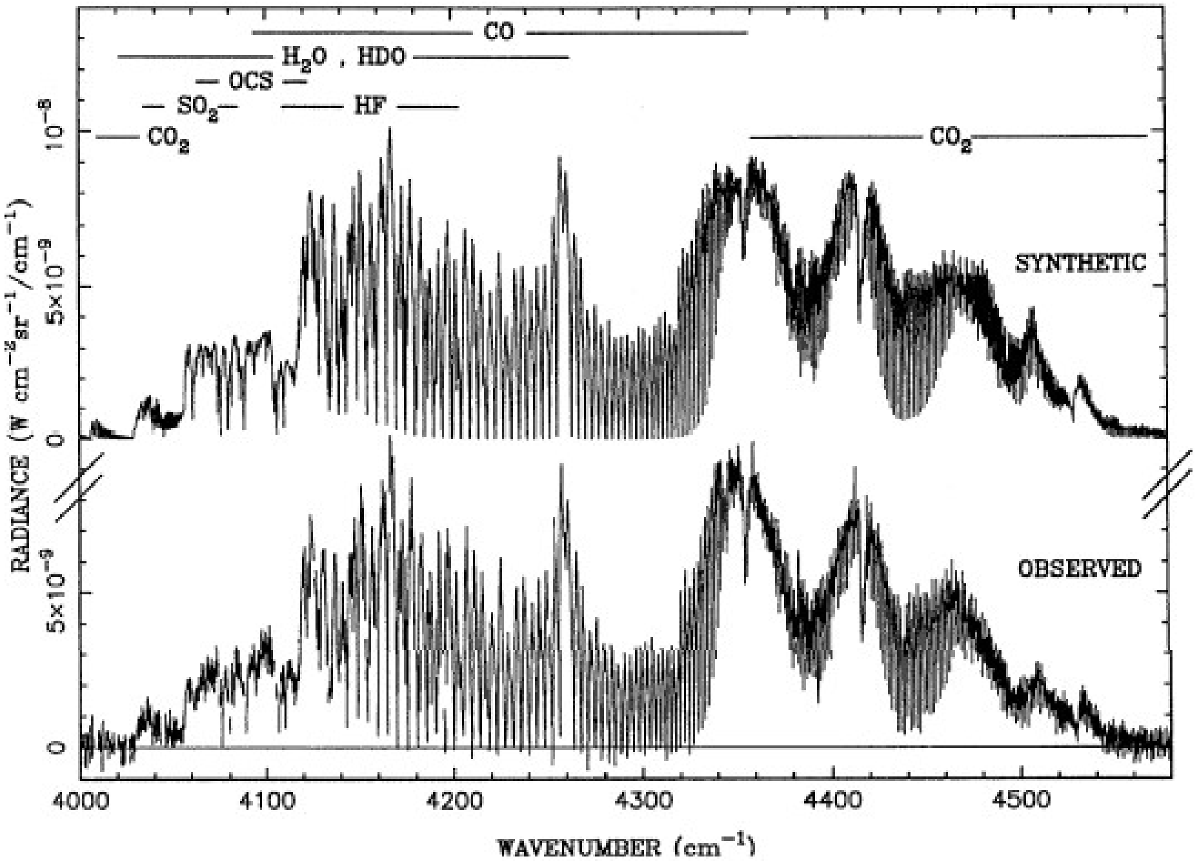


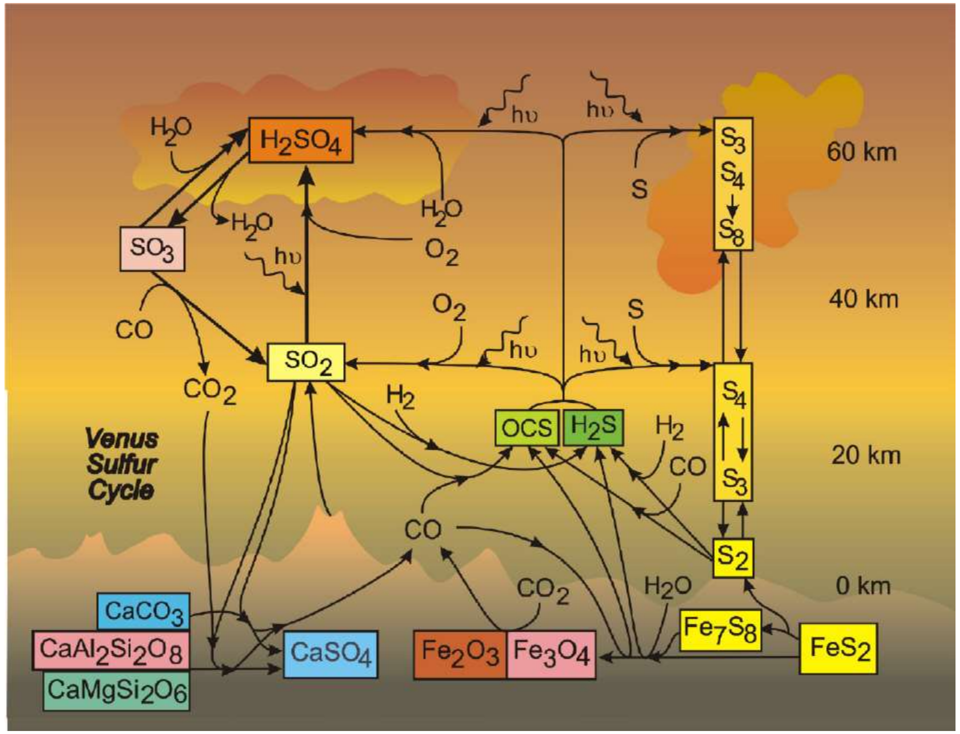
R ~100 (AAT)

Kamp et al. Nature 1988

Probing below Venus' clouds at high resolution in the near-IR

FTS/ CFHT, R ~20000 (Bézard et al. 1990, de Bergh et al. 1990)

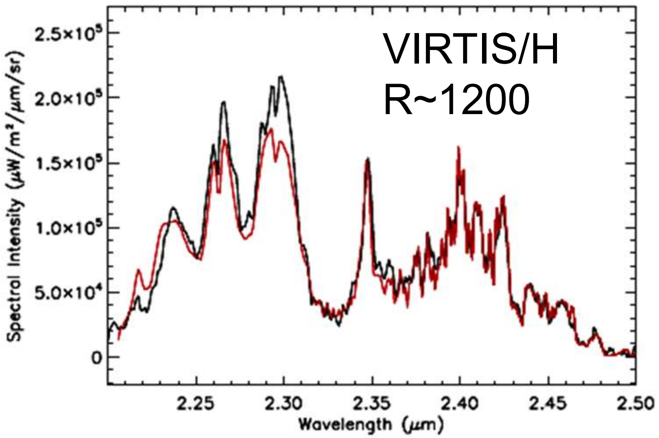


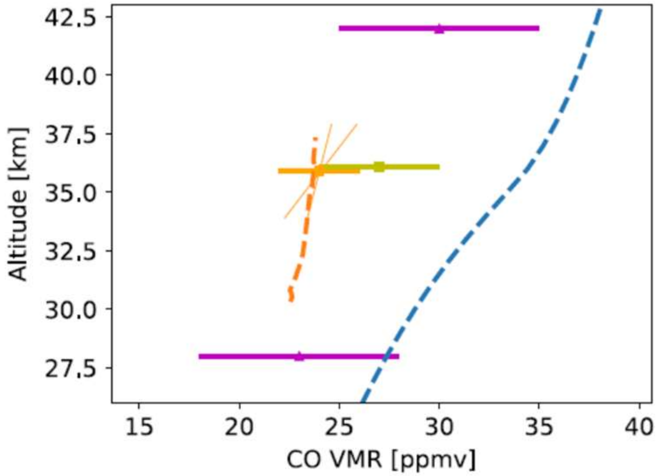


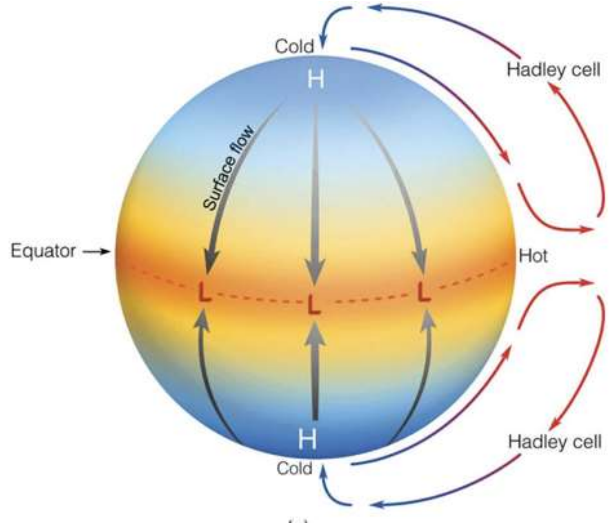
+ D/H: ~ 120 times terrestrial

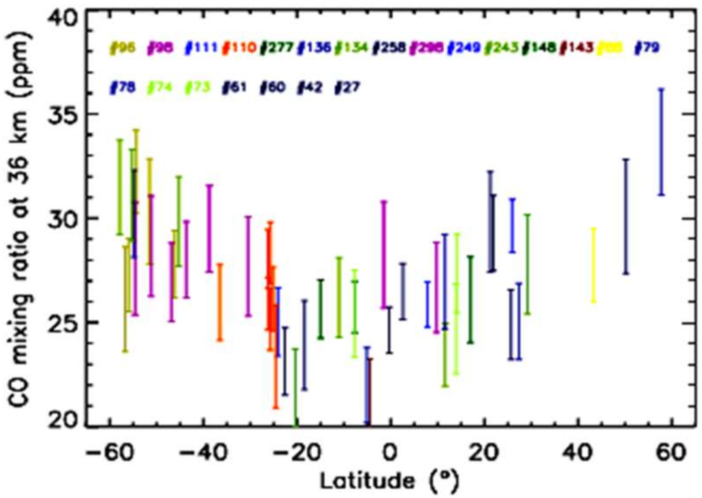
SO2 and CO abundances in lower atmosphere are partly controlled by surface atmosphere interactions

Venus Express results (2006-2014) : coupling between chemistry and dynamics









Marcq et al. 2017

CO produced in upper atmosphere from CO_2 photolysis → gradient with altitude

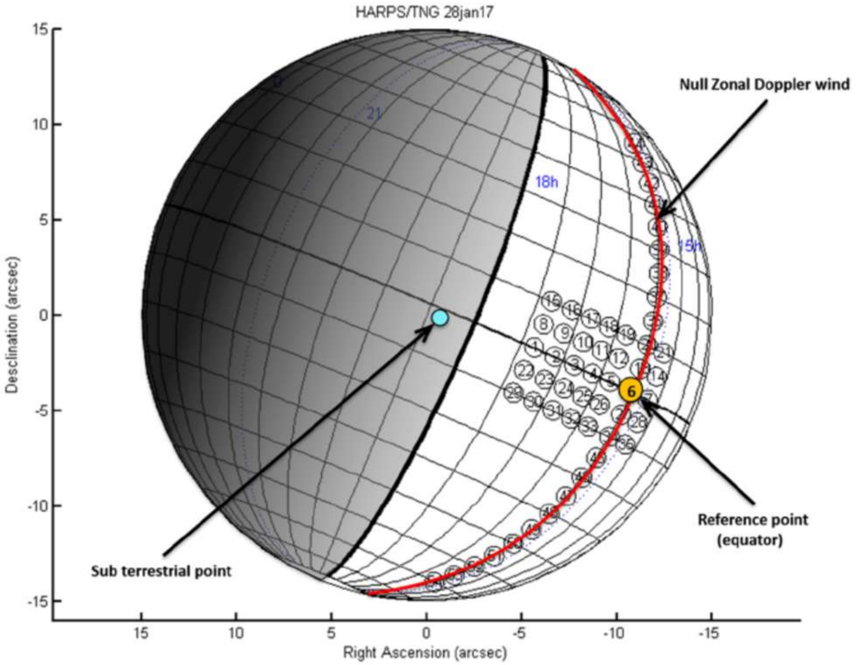
CO enhancement at high latitudes due to downward transport of CO-rich air in descending branches of Hadley cells

Similar couplings – and much more extensively studied (Cassini) – on Titan*

* Ask expert in your room

Venus wind Doppler velocimetry (HARPS)

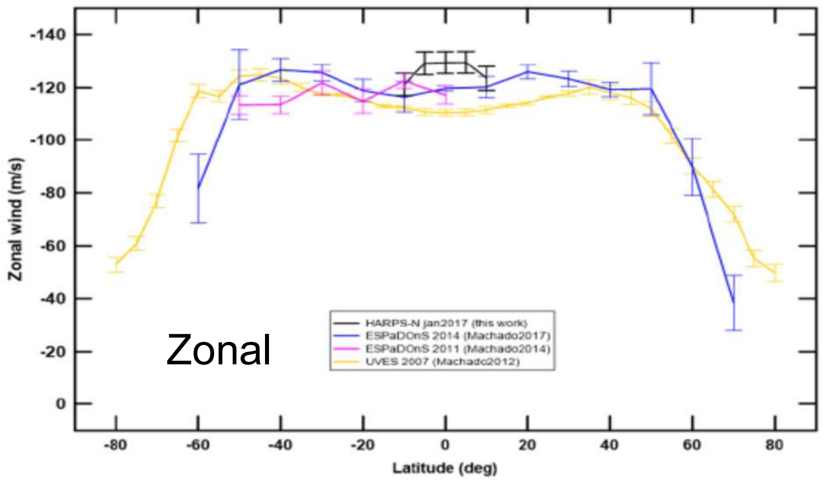
Gonçalves et al. 2020

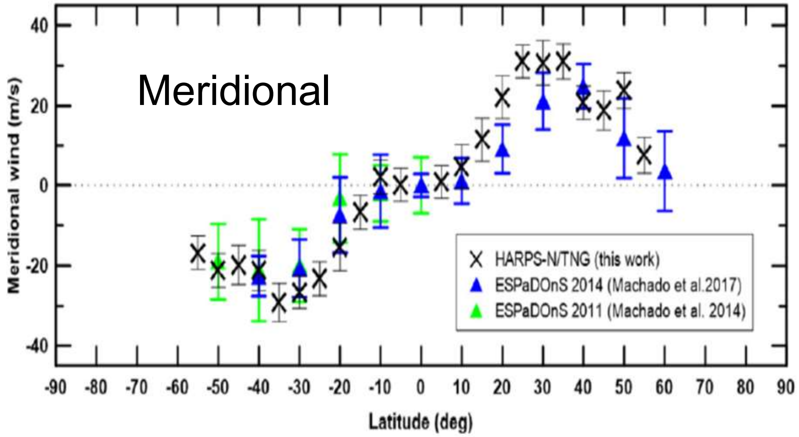


Uses solar lines → Doppler shift due to $V_{sun\text{-}atmosphere}$ $+V_{atmosphere\text{-}observer}$

Measure of zonal and meridional winds

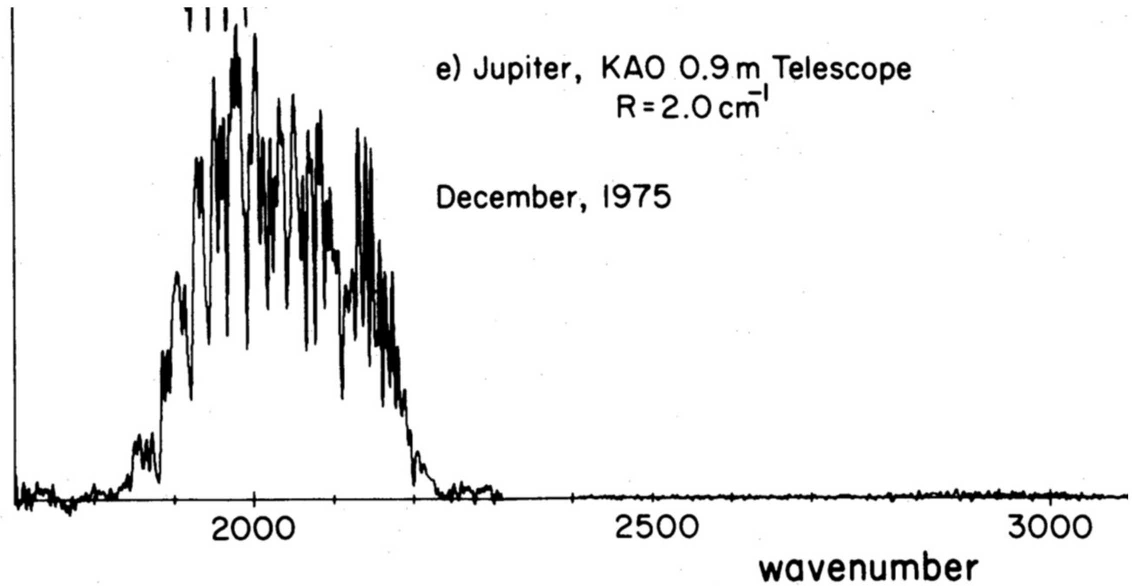
Feasible with SPIRou in near-IR (solar or CO2 lines)





Complements cloud-tracking techniques
Confirms the equator-to-pole Hadley cells

Sounding the tropospheres of the Giant Planets in the 5-µm window

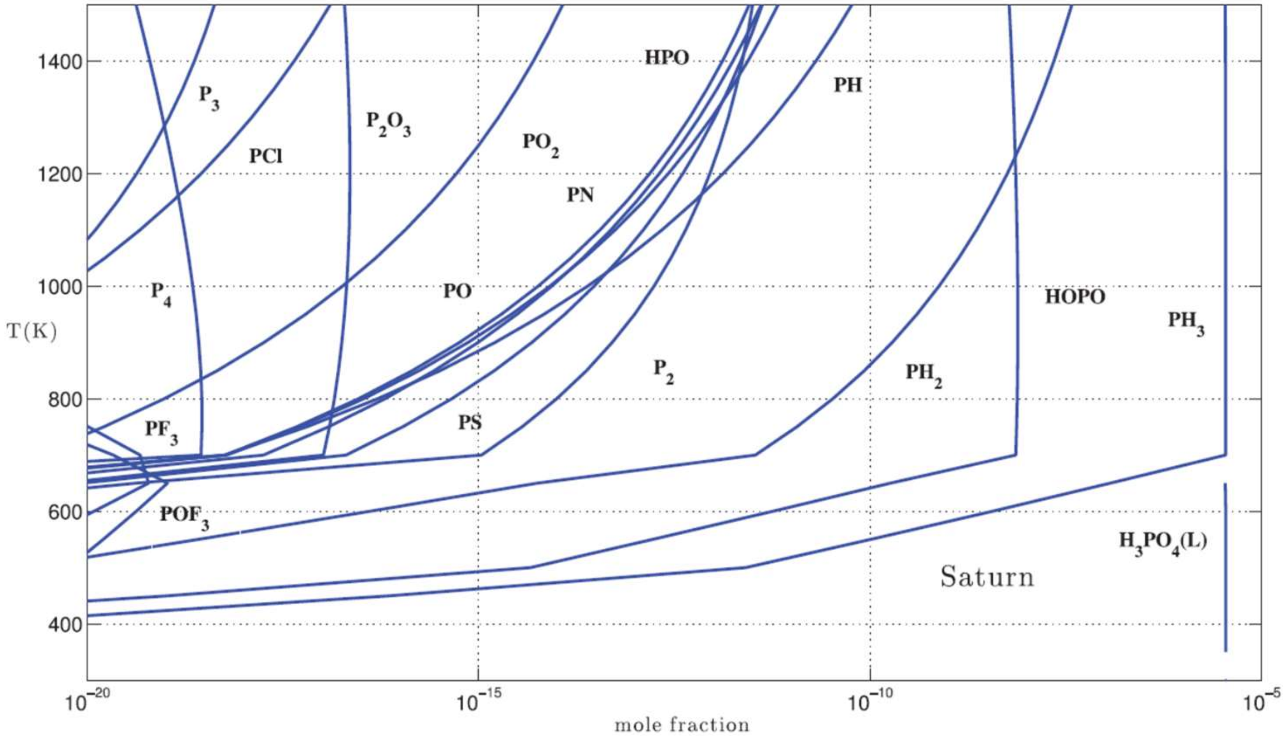


Hot radiation originating from ~ 3-5 bar levels (due to low H_2 and CH_4 opacity)

Phosphine (PH3)* detected in Jupiter & Saturn as early as 1975, and recognized quickly as a « disequilibrium species »

*** This phosphine detection is serious, unlike the Venus one**

PH3: a disequilibrium species in Giant Planets



Wang et al. 2016

At chemical equilibrium PH_3 is the dominant carrier of P only at T> 700 K

Observations probe only layers with T <~ 200 K → should see zero PH3 if atmosphere at equilibrium.

However, chemistry is not instantaneous… Competition between chemical destruction and vertical eddy transport

Quench level : where $t_{chem} \sim t_{dyn}$

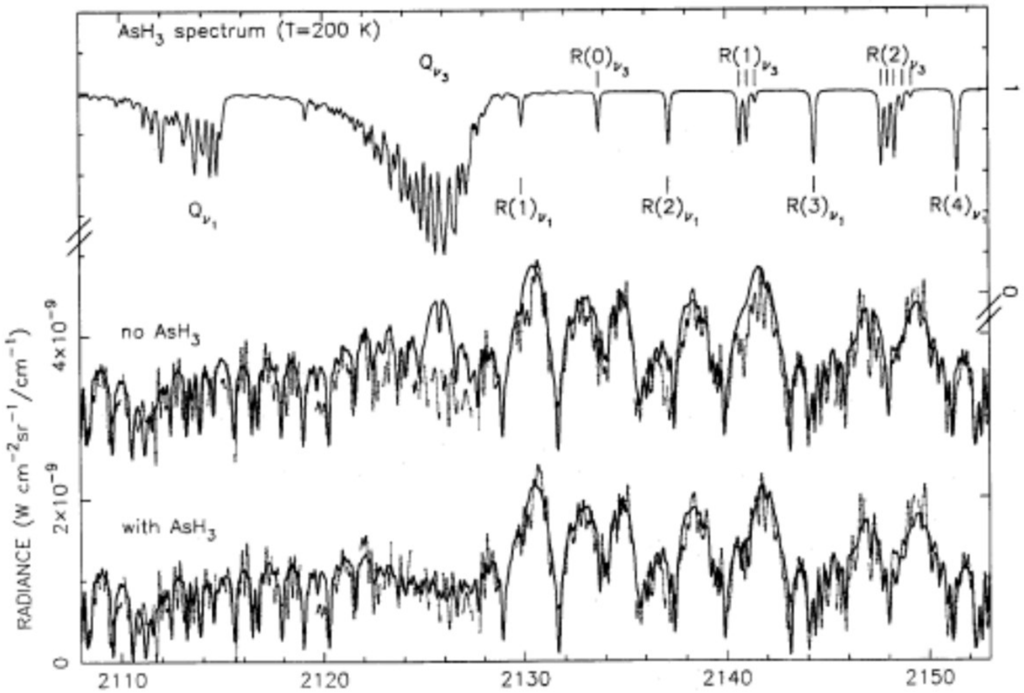
Observations « see » the quench level
Occurs at T ~900 K for phosphine, where PH_3 is stable

→ Measured PH_3 abundance still gives P/H ratio !

Exploiting the 5-µm region at high-resolution: Probing Giant Planet disequilibrium chemistry

Disequilibrium species in Jupiter and Saturn

CO, PH_3 ,GeH_4, $\mathbf{AsH_3}$



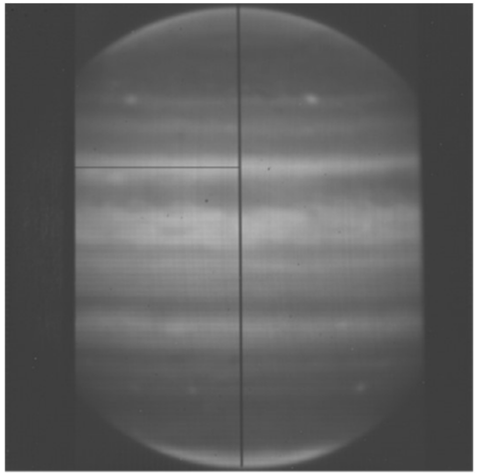
Detection of arsine (AsH_3) in Saturn

FTS/CFHT, R=22000

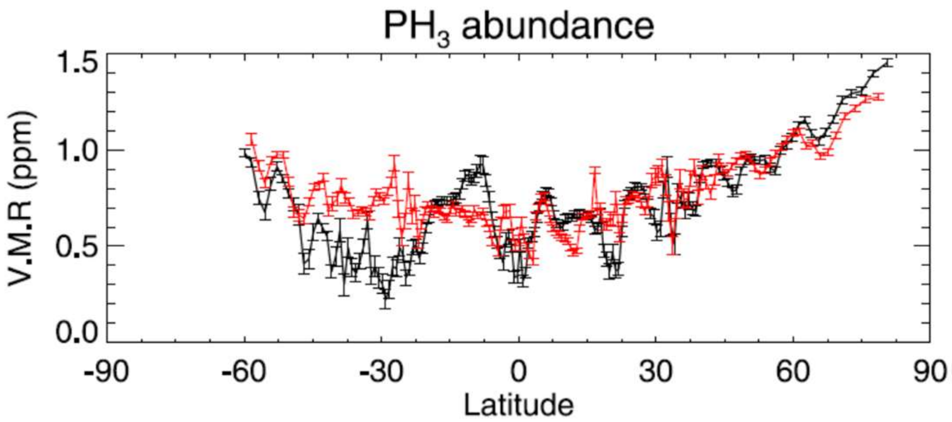
Bézard et al. 1990 → **As / H ~ 5-10 times solar**

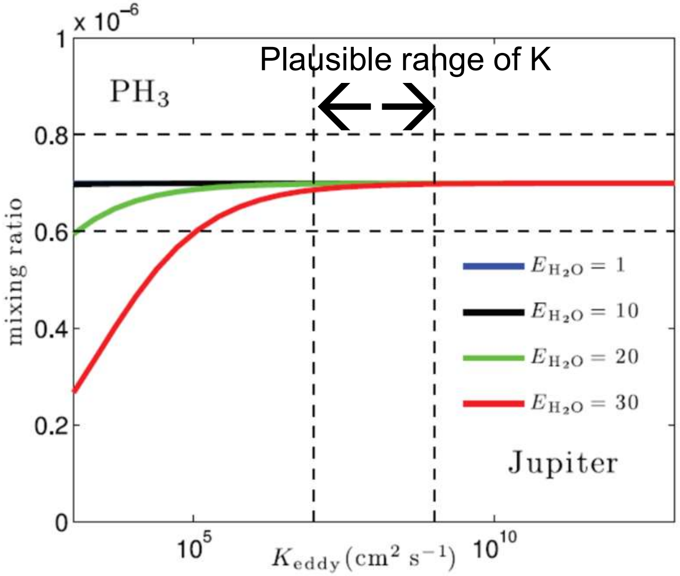
Jupiter and Saturn are enriched in heavy elements (C, N, P, As; + O and noble gases for Jupiter); Saturn more enriched than Jupiter

Latitudinal variations of disequilibrium species



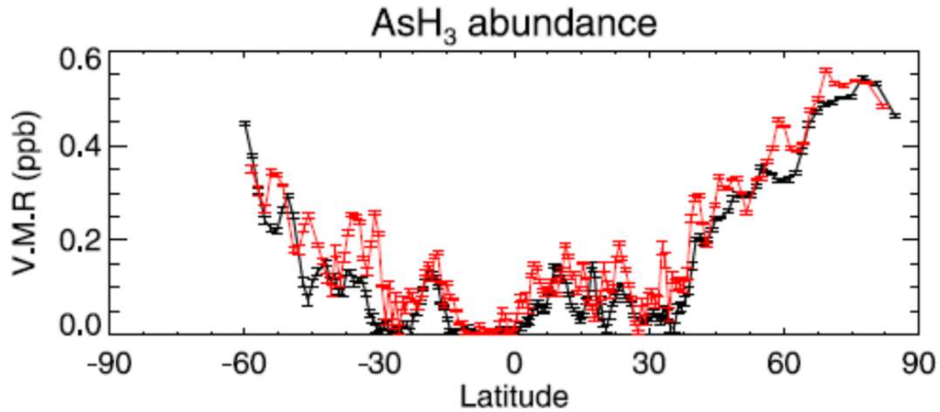
Giles et al. 2017
CRIRES/VLT
Long-slit spectro.
R = 96000





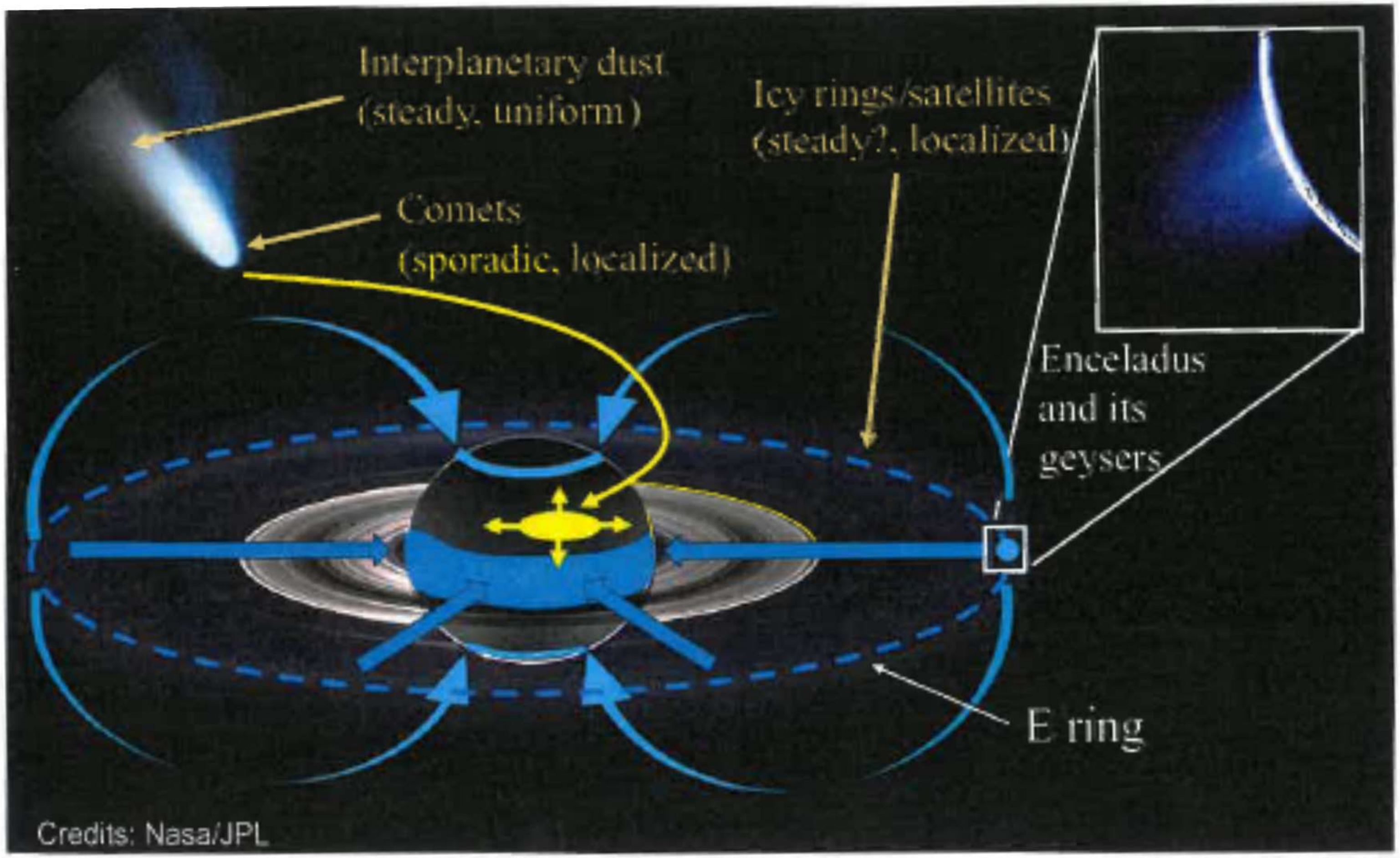
Expected PH3 abundance vs K

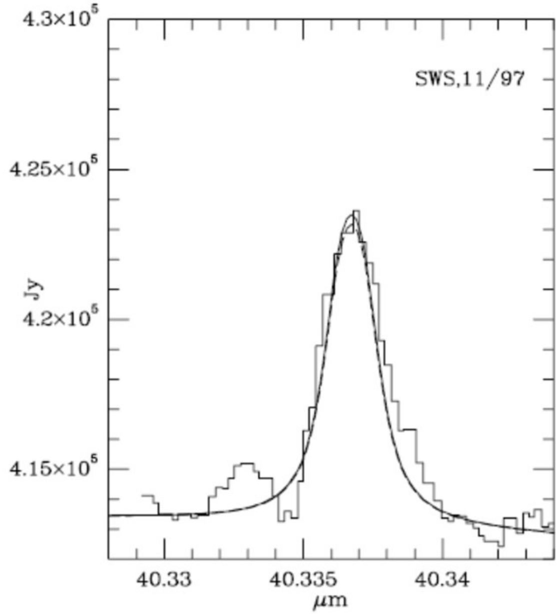
Wang et al. 2016



→ Increased vertical mixing at high latitudes?

Complication: external sources of material: oxygen in Giant Planets



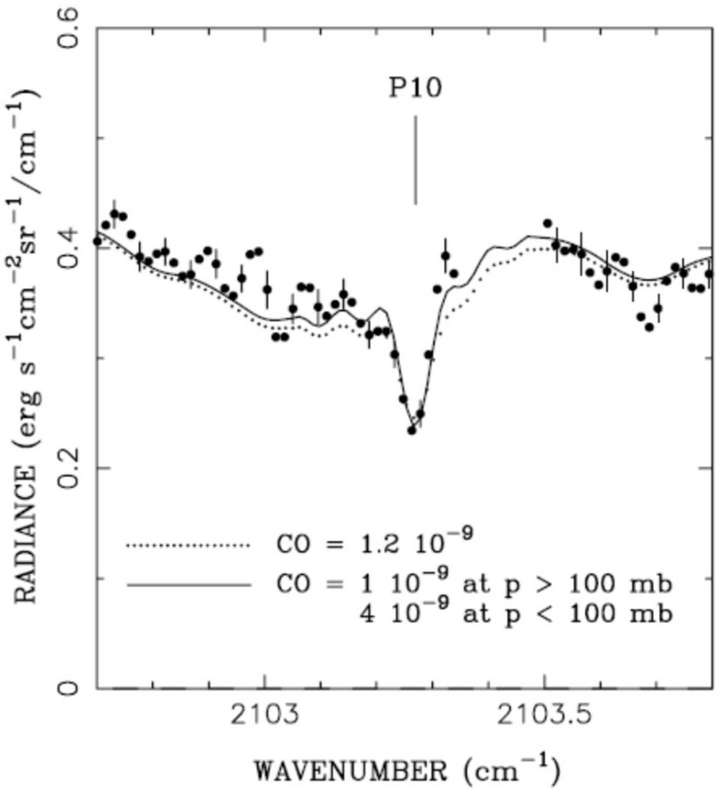


Detection of stratospheric H2O in Jupiter

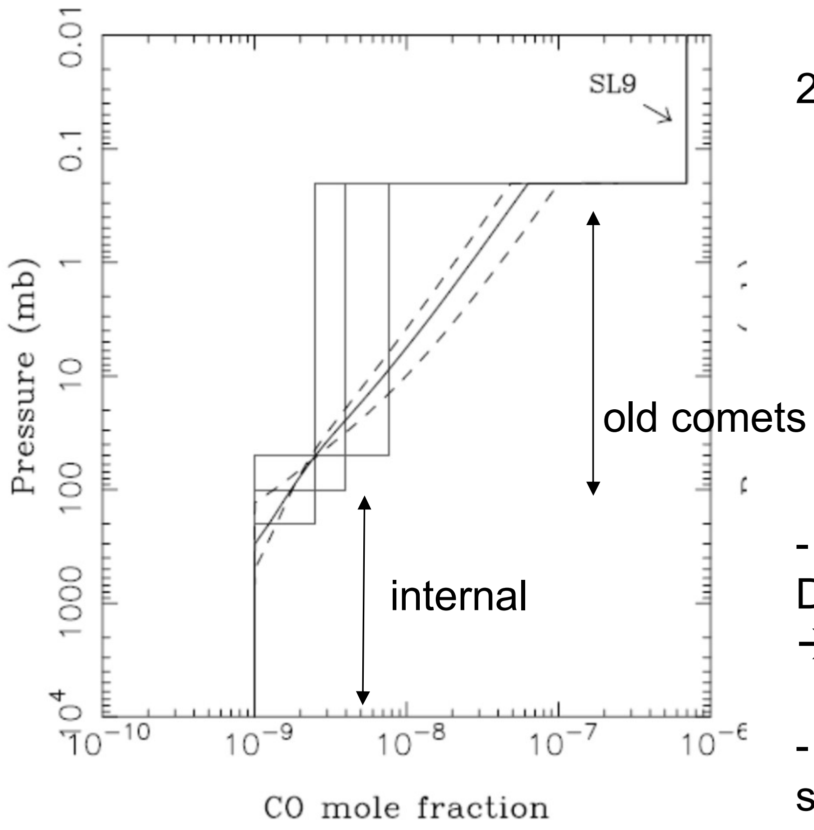
ISO/SWS Fabry Perot
R = 31000
Lellouch et al. 2002

CO in Jupiter: internal (disequilibrium) or external ?

Disentangling between internal and external sources: CO in Jupiter



Bezard et al. 2002
CFHT/FTS, R ~50000

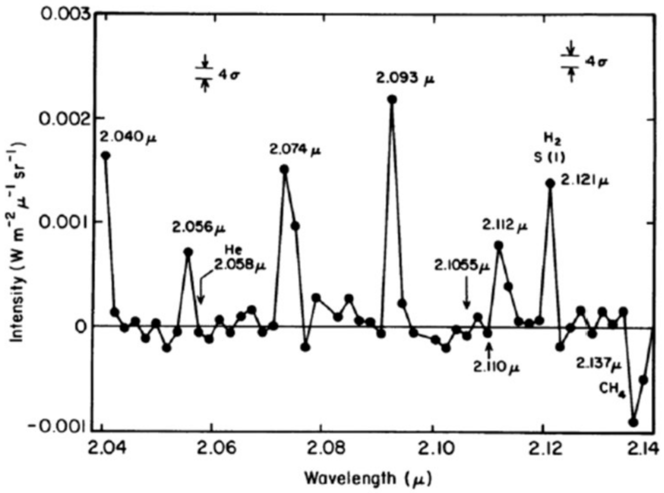


2 CO components (+SL9)

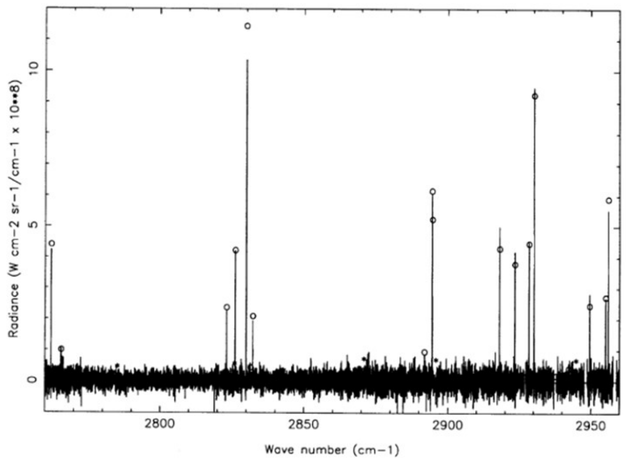
- Internal (1ppb in troposphere)
Disequilibrium chemistry
→ O/H (in principle)

- External (enhanced stratospheric abundance) →
infall of « old » comets;
constraints on cometary flux

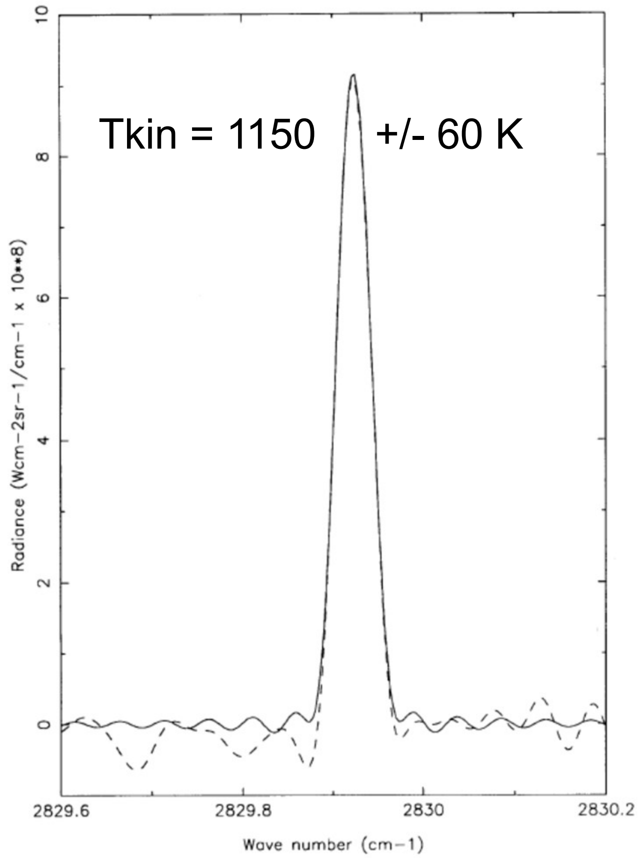
Probing upper atmospheres: H3+ in Jupiter auroral regions



Unidentified lines in 2 micron spectrum of Jupiter's auroral zones
Trafton et al. 1989
(Mac Donald grating spectrometer R=1200)



Detection of H3+: first detection in space
Trot = 1250+/-70 K

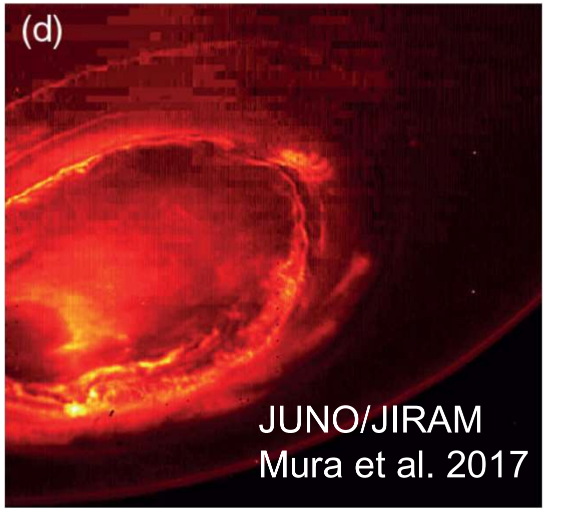


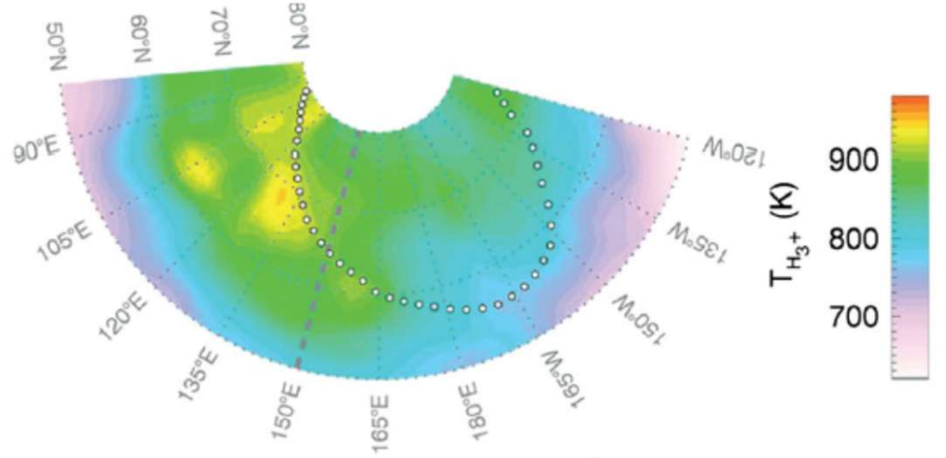
FTS / CFHT: R = 115,000; Drossart et al. 1989, 1993

- Quasi LTE emission (Tvib ~T rot ~T kin) from sub-microbar region (10-10 – 10-6 bar)
- Jupiter's auroral upper atmosphere is hot!

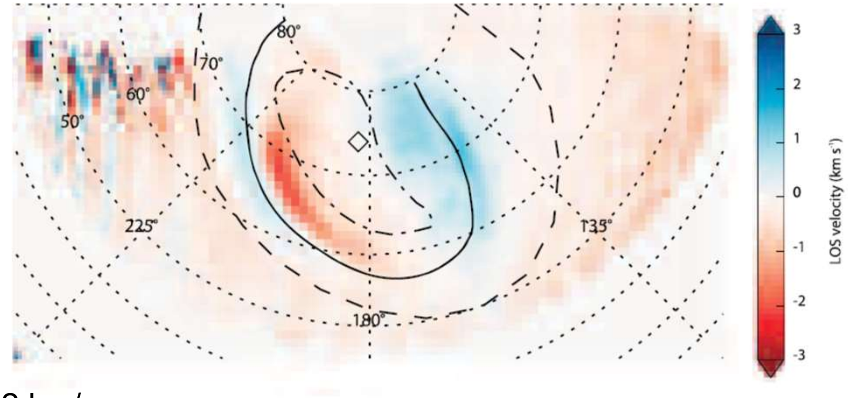
H_3+: a new sounder of Jupiter's auroral atmosphere

- H_3^+ produced from particle impact and solar EUV ionization of H_2 in sub-microbar atmosphere
- The H_3^+ emission and its morphology constrain: temperature, H_3^+ column densities, winds, and their spatial variations → energy budget, external vs internal forcings (waves…) , dynamics, etc.





H3+ temperature map
Keck/NIRSPEC, R= 25000
Moore et al. 2017



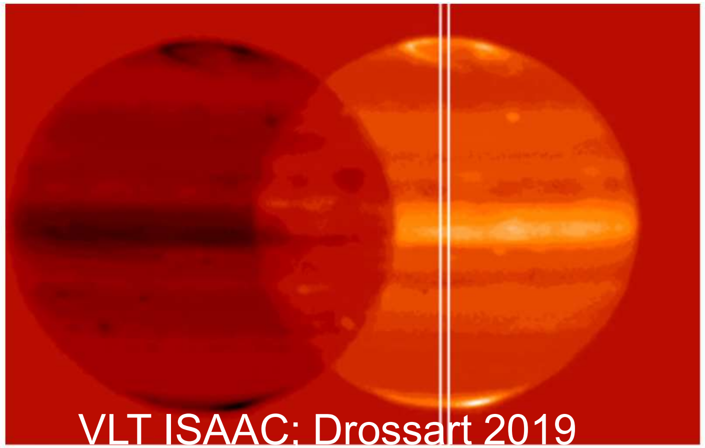
H3+ winds ~ 2 km/s
VLT/CRIRES, R=100000
Johnson et al. 2017

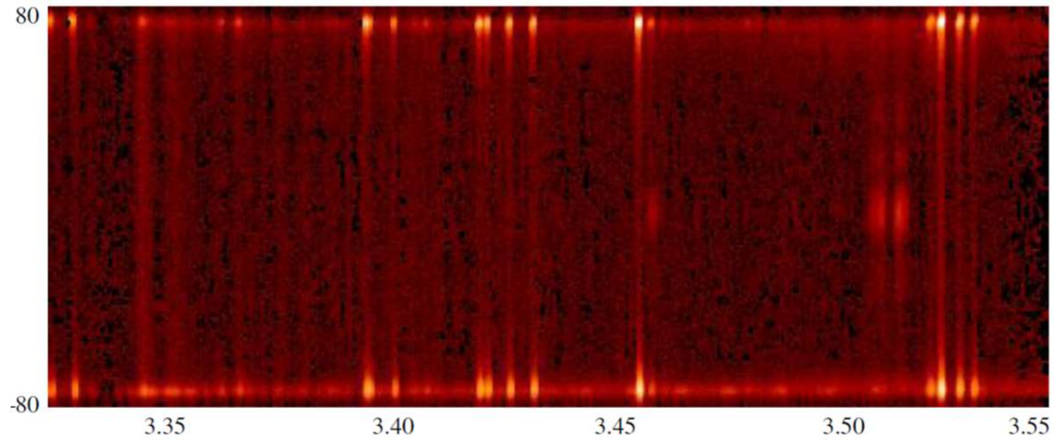
… and beyond

- Detected also on **Jupiter low latitudes**, Saturn, Uranus, and beyond the solar System (ISM, extragalactic…)
- Not detected yet on exoplanets

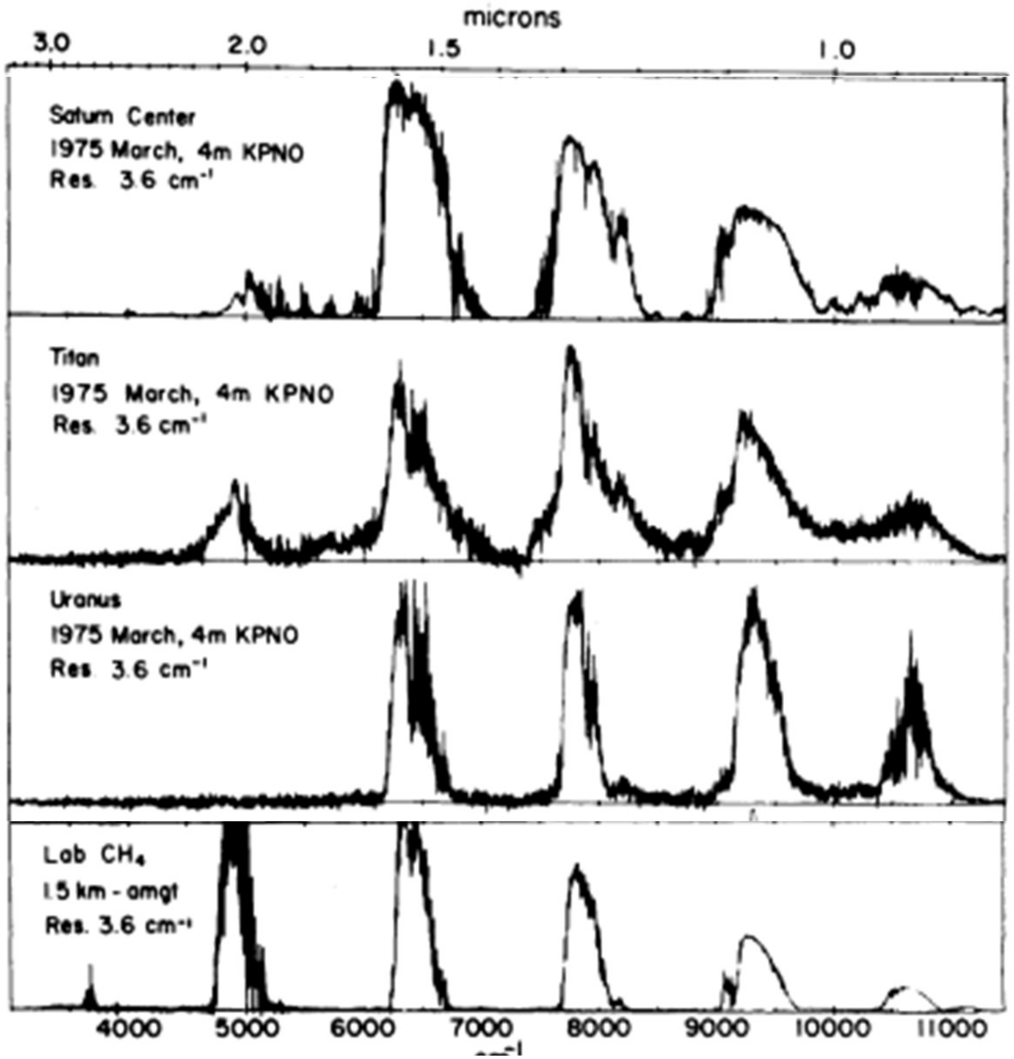
- A key-species, energy-wise
  - Atmospheric coolant (« H3+ thermostat »)
  - Cooling by H_3+ may also participate in stabilization of exoplanets against escape (not on too irradiated exoplanets due to H2 dissociation)

- See extensive review by Miller (2020): « Thirty Years of H_3+ astronomy »





Outer planets in the 0.8- 2.5 μm: Lord Methane



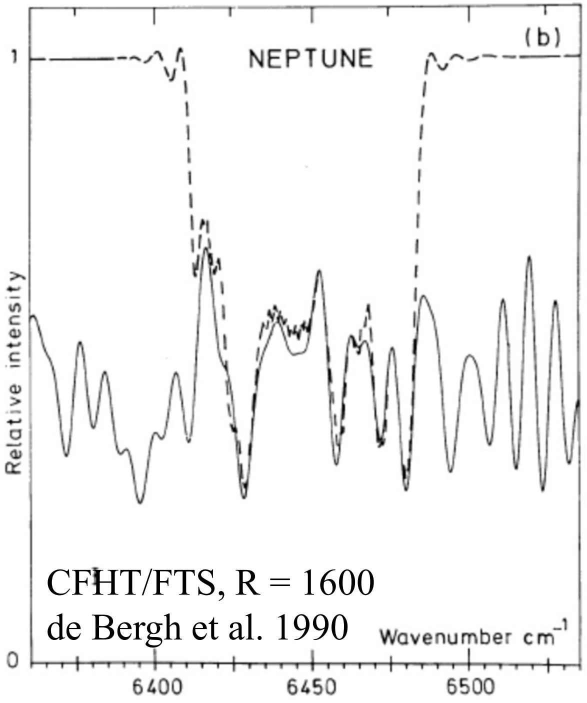
- Absorption by methane gas
- Scattering by haze

Not fully exploited due to lack of spectroscopic parameters for methane –long paths, low temperature

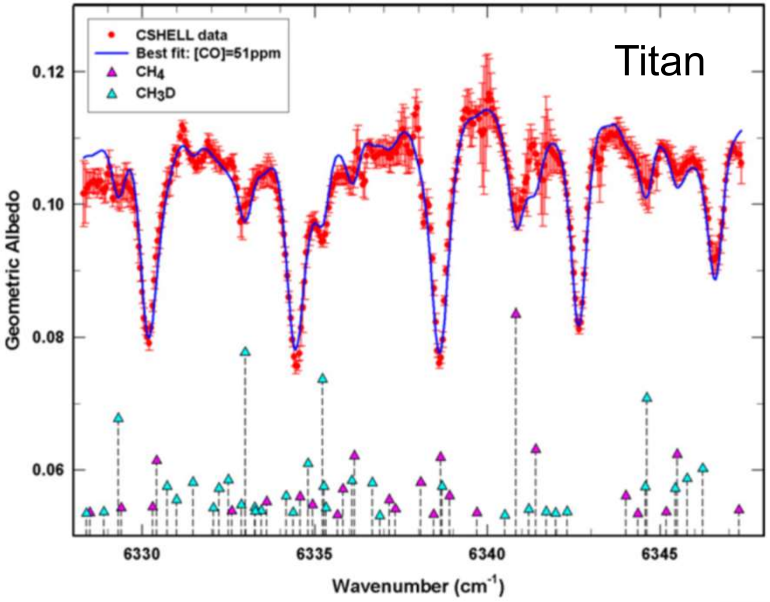
Initially, focus on some specific regions

Fink and Larson, 1979
R = 3.6 cm-1; KPNO/FTS

Deuterium in the outer Solar System (CH3D)



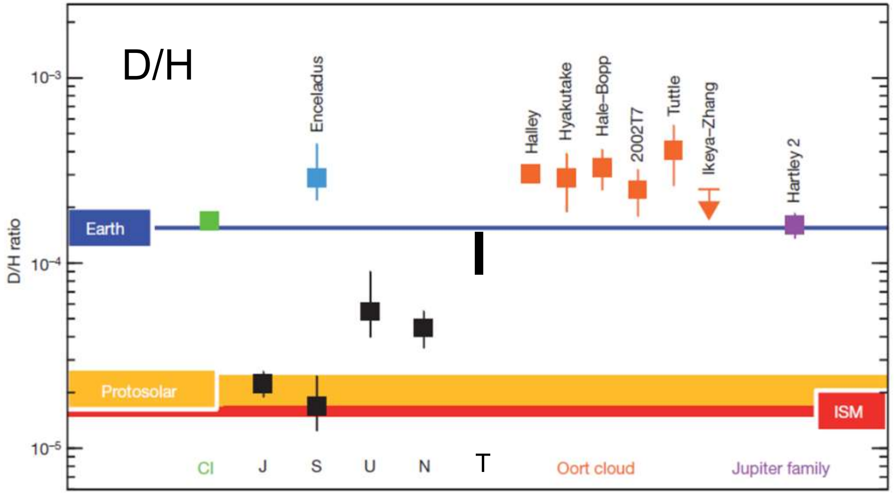
CFHT/FTS, R = 1600
de Bergh et al. 1990



IRTF/CSHELL R=18000
De Bergh et al. 2012

Distinction between D/H in
- J, S (solar nebula gas)
- U, N (D enrichment due to mixing of atmosphere with D-rich icy cores, or accretion of ices in the envelopes)

Owen et al. Nature, 1986. **Deuterium in the outer solar system – Evidence for two distinct reservoirs**



Hartogh et al. 2011

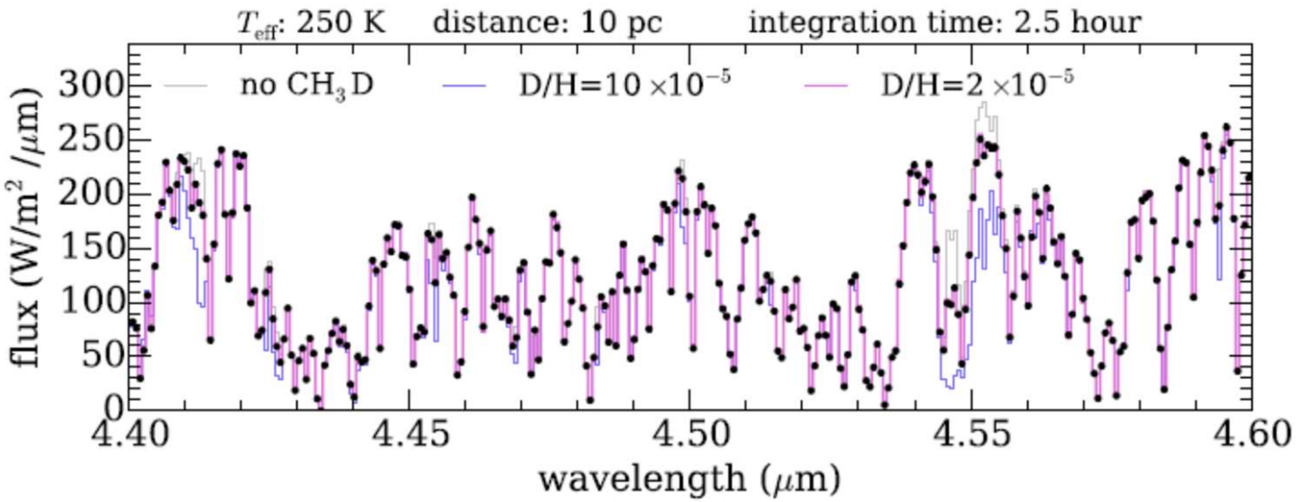
Deuterium in exoplanets (CH3D, HDO): when?

THE ASTROPHYSICAL JOURNAL LETTERS, 882:L29 (8pp), 2019 September 10
https://doi.org/10.3847/2041-8213/ab3c65

CrossMark

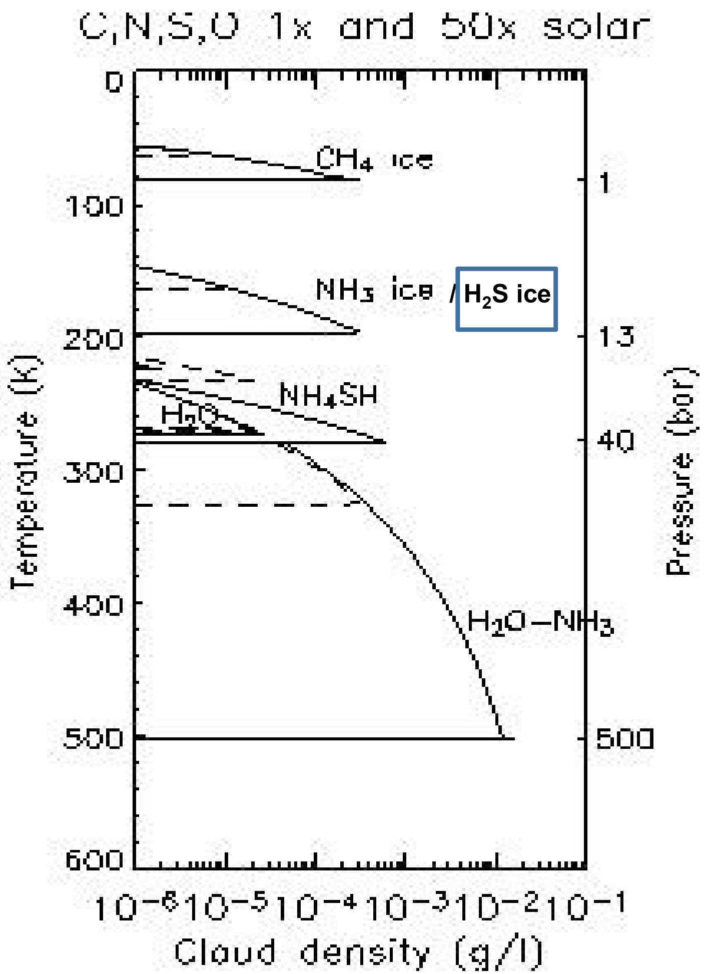
Measuring the D/H Ratios of Exoplanets and Brown Dwarfs

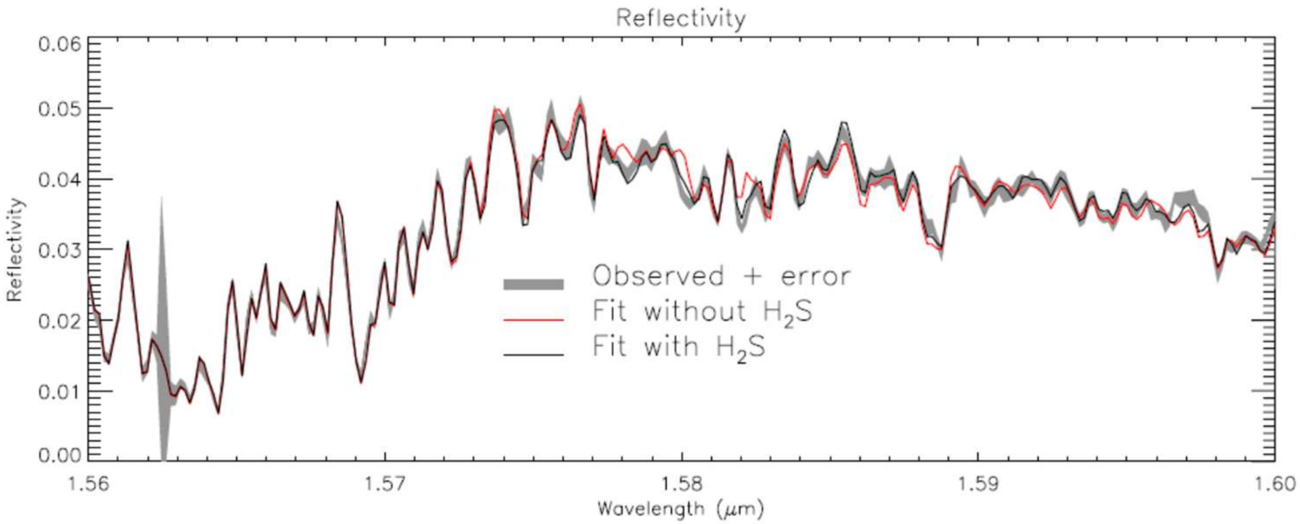
Caroline V. Morley[1], Andrew J. Skemer[2], Brittany E. Miles[2], Michael R. Line[3], Eric D. Lopez[4], Matteo Brogi[5,6,7], Richard S. Freedman[8,9], and Mark S. Marley[9]



Detection of H2S on Uranus (finally !)

Equilibrium cloud condensation model

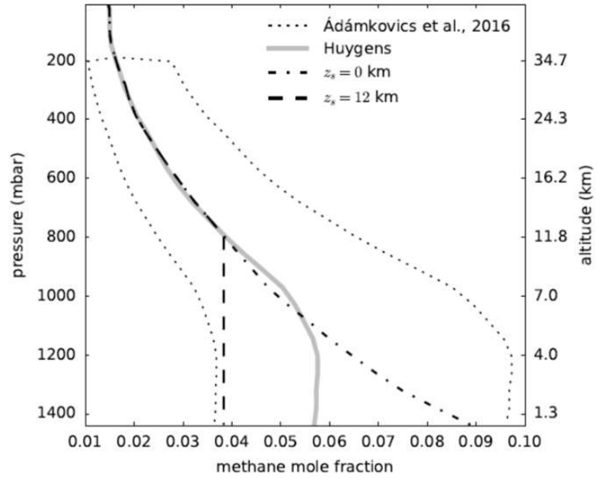


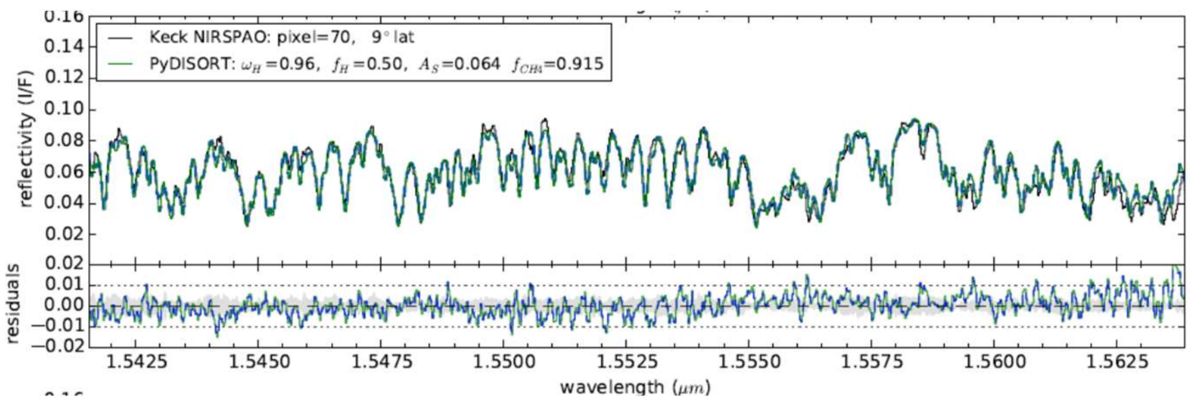


Gemini/NIFS, R = 5300
Irwin et al. 2018

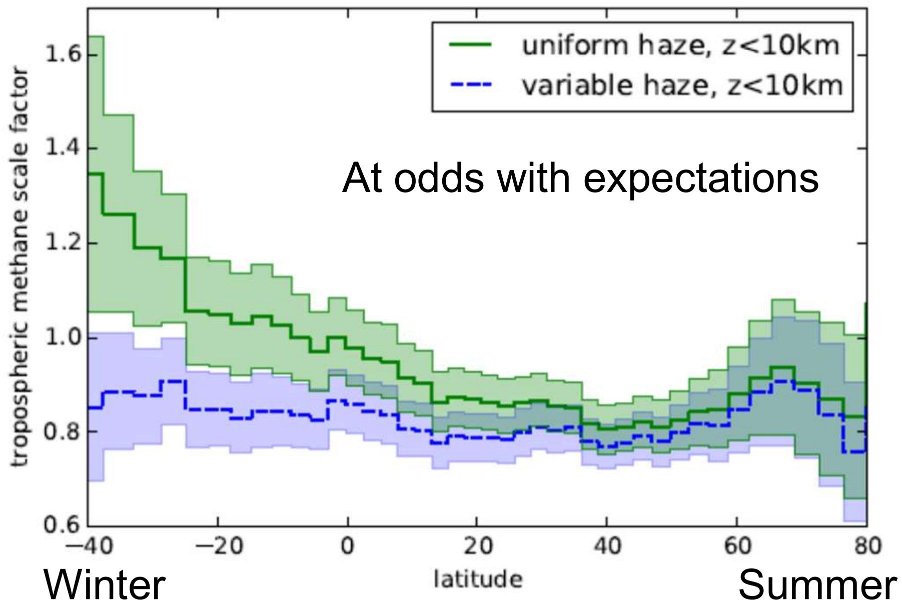
Trying to characterize Titan methane cycle in the near-IR

- Titan's methane exhibits « hydrological » cycle, including clouds, rain, lakes, mare, sources at the surface (evaporation) and likely sub-surface reservoirs
- Huygens measured very precisely the methane profile at the entry site
- How does the methane abundance / profile in the troposphere vary with latitude location and time ?

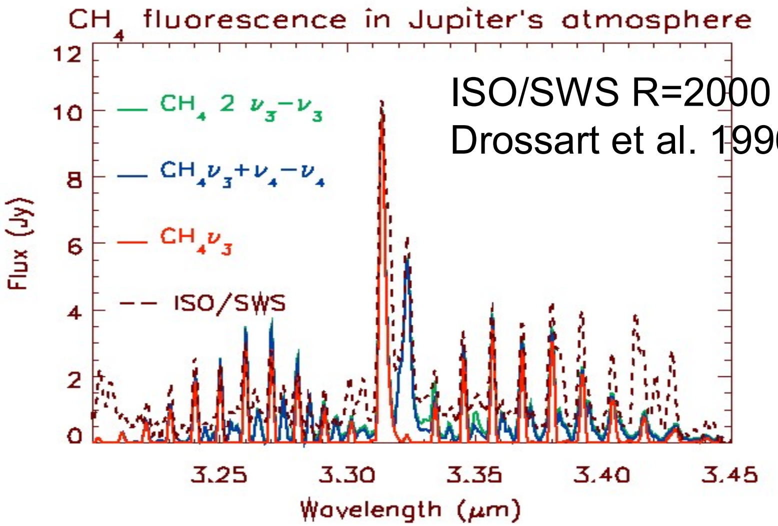




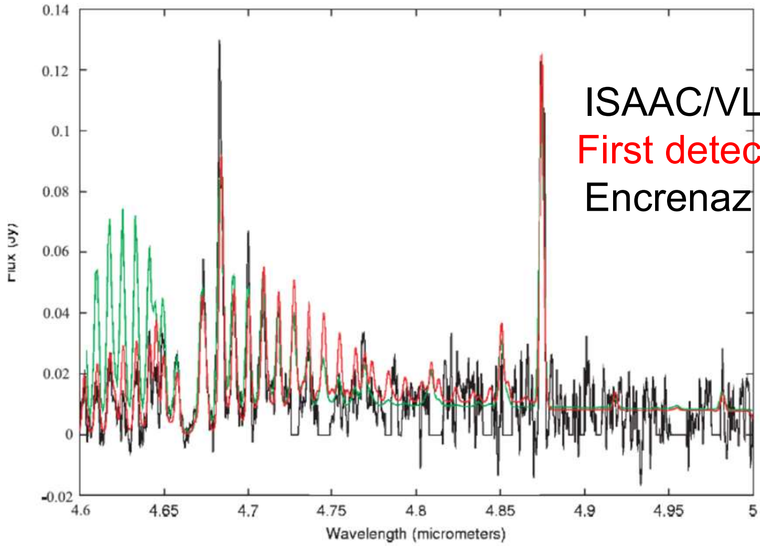
Adamkovics et al. 2016
Keck/NIRSPEC, R ~25000



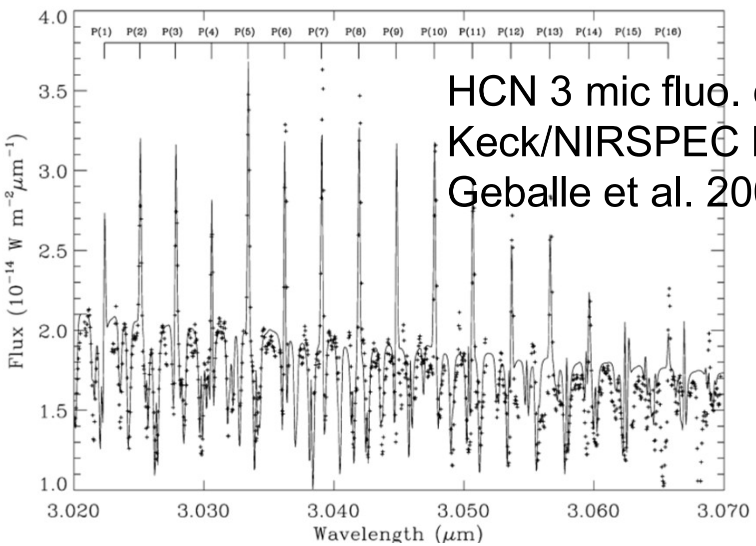
Fluorescent (non-LTE) emissions from upper atmospheres



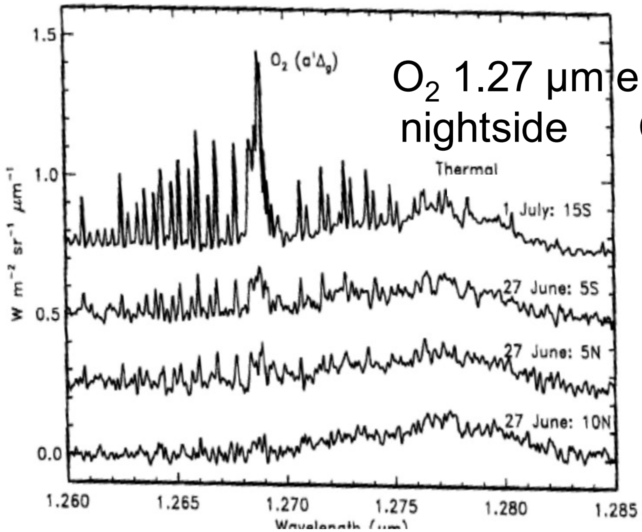
ISO/SWS R=2000
Drossart et al. 1996



ISAAC/VLT R = 1500
First detection of CO on Uranus
Encrenaz et al. 2004



HCN 3 mic fluo. on Titan
Keck/NIRSPEC R=25000
Geballe et al. 2003



O_2 1.27 μm emission on Venus nightside
CFHT/FTS R~25000
Crisp et al. 1996

Fluorescence: not trivial to model…

- Many non-thermal processes (energy transfer between bands, photochemistry, chemical recombination…)

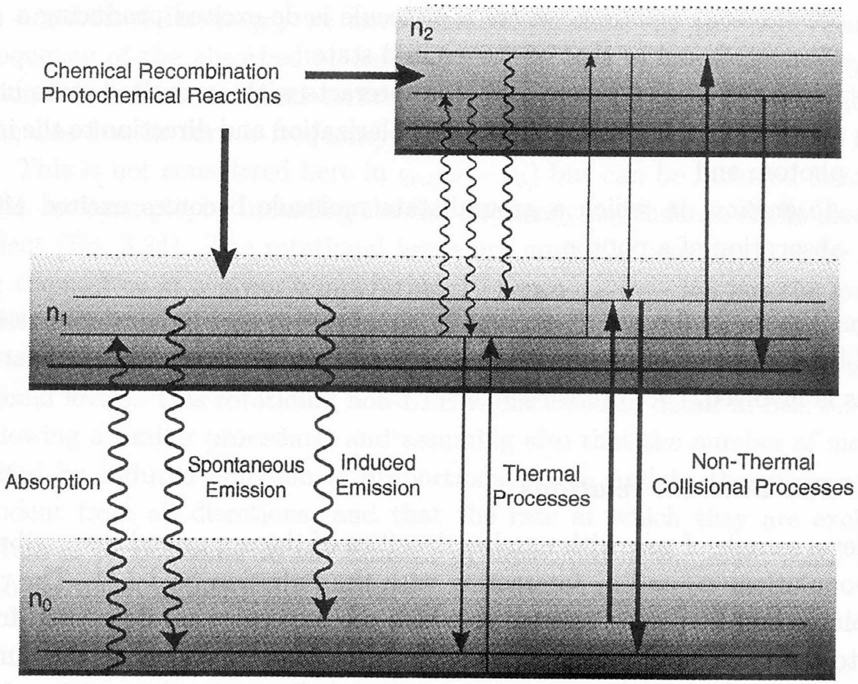
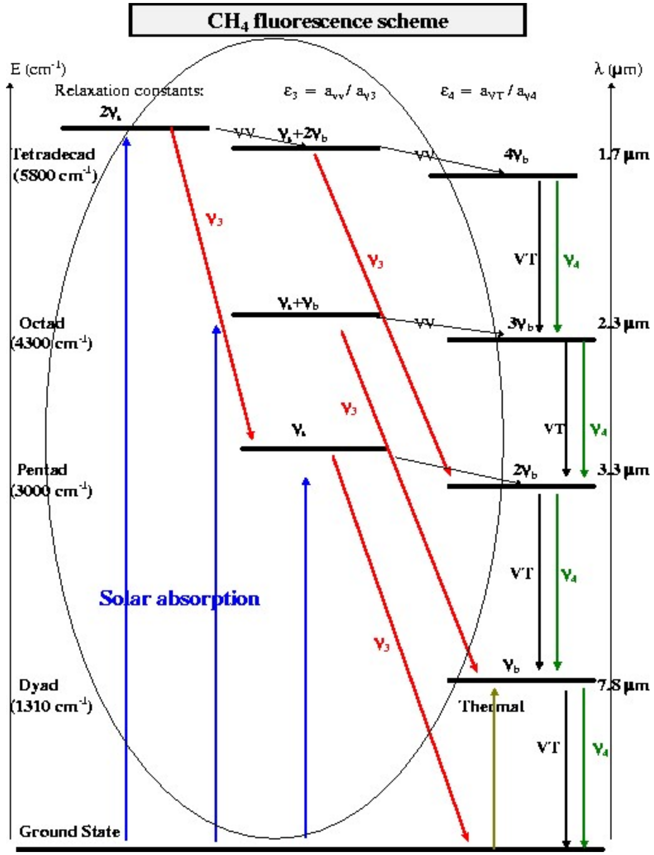


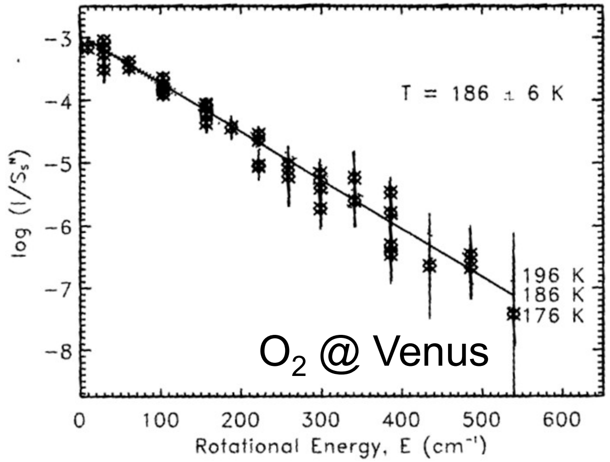
Fig. 3.3 Processes affecting the populations of vibrational levels.

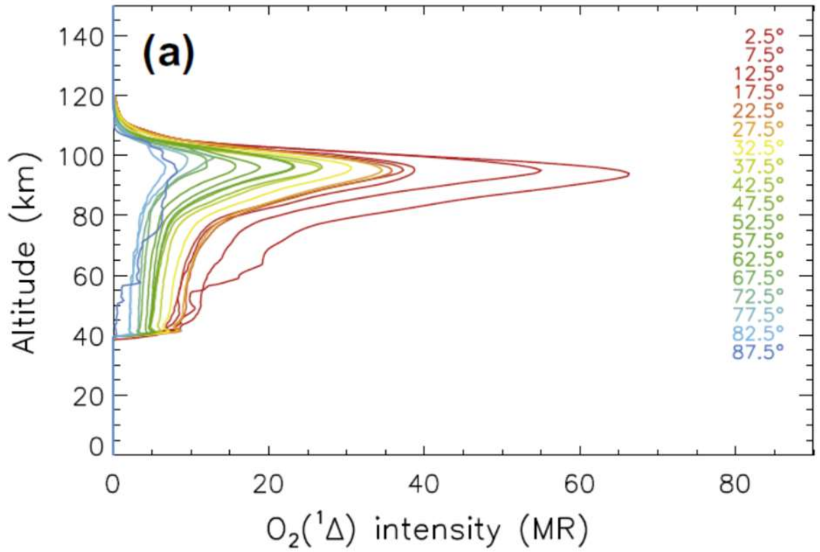


Often difficult to use them for quantitative composition measurements…

Fluorescent (non-LTE) emissions from upper atmospheres what do they teach us ?

- Temperature of emitting layer from rotational diagram
- Altitude of emisson determined
  - From model ?
  - From vertical profiles of emission (limb sounding from spacecraft)
- Mapping → Morphology of emission → atmospheric dynamics

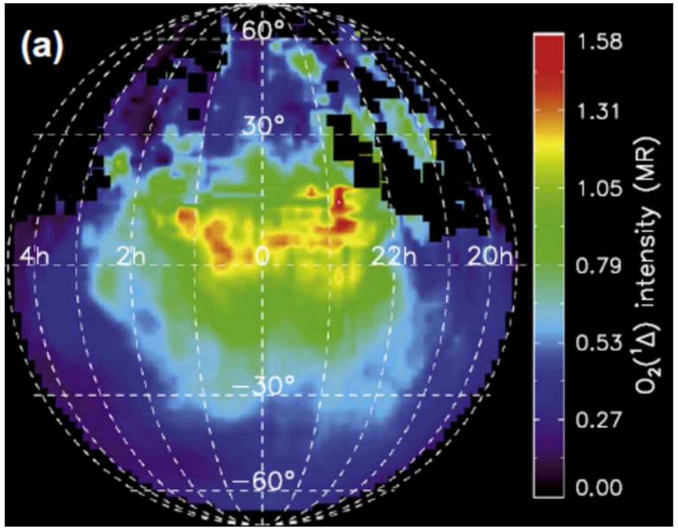




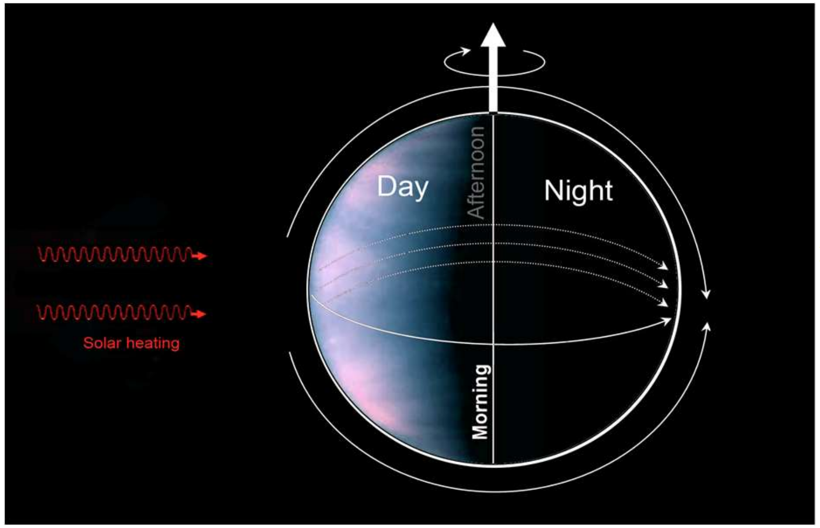
Soret et al. 2012 – O2 fluorescence @ Venus

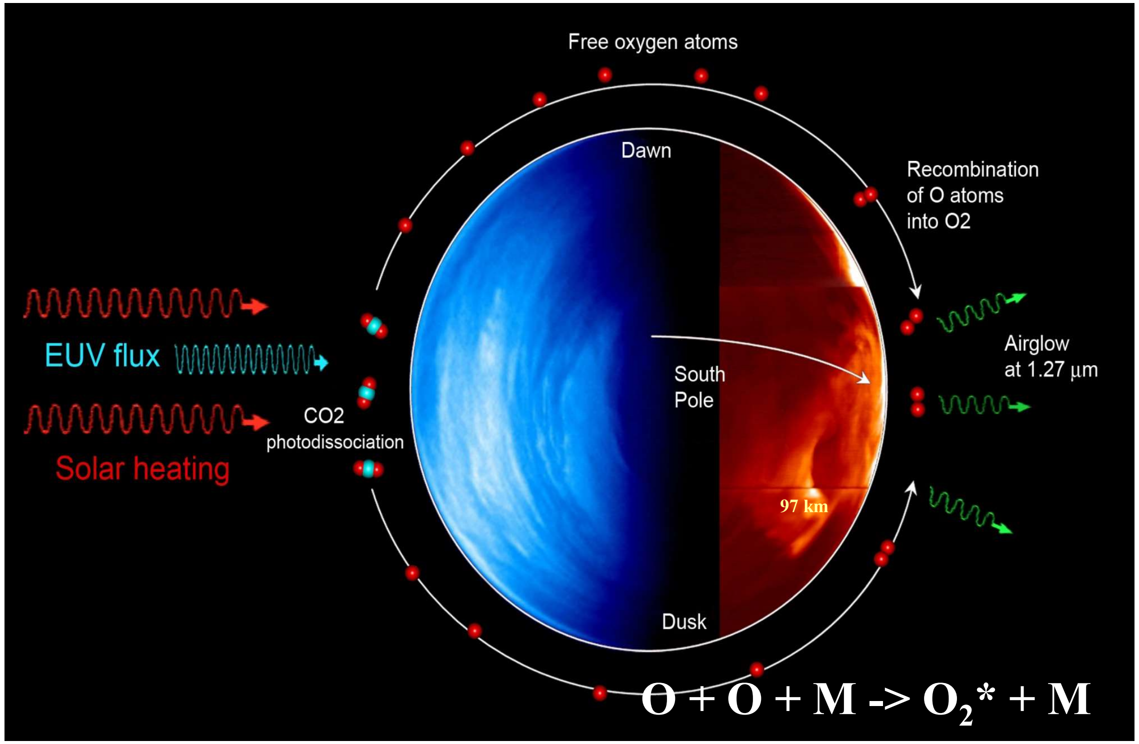
Venus Express

O2 emission peaks near midnight



O_2 (Δ) production and nightglow on Venus





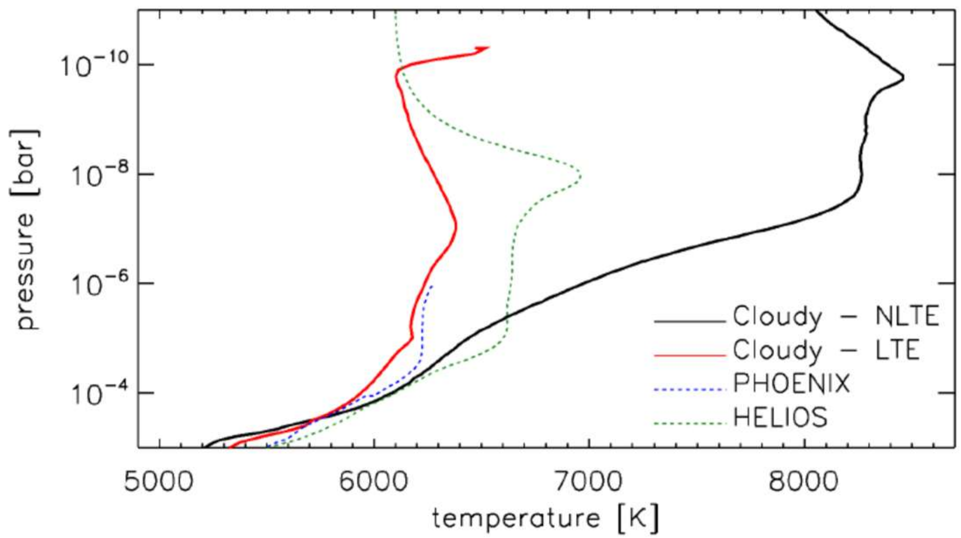
→ a tracer of winds in the atmosphere of Venus near 95 km (subsolar-to-antisolar & zonal flows)

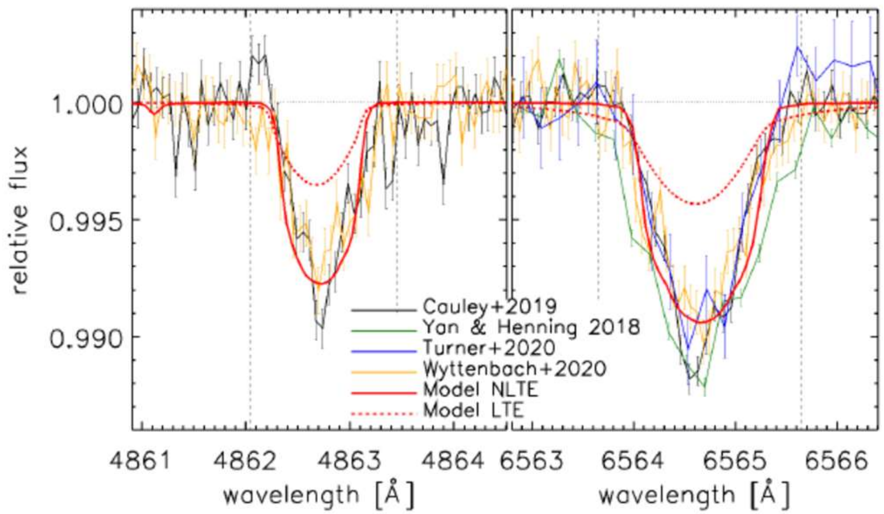
But so far no direct wind measurements in O2 1.27 micron emission → SPIRou ?

Probably important for exoplanets, too…

Non-local thermodynamic equilibrium effects determine the upper atmospheric temperature structure of the ultra-hot Jupiter KELT-9b

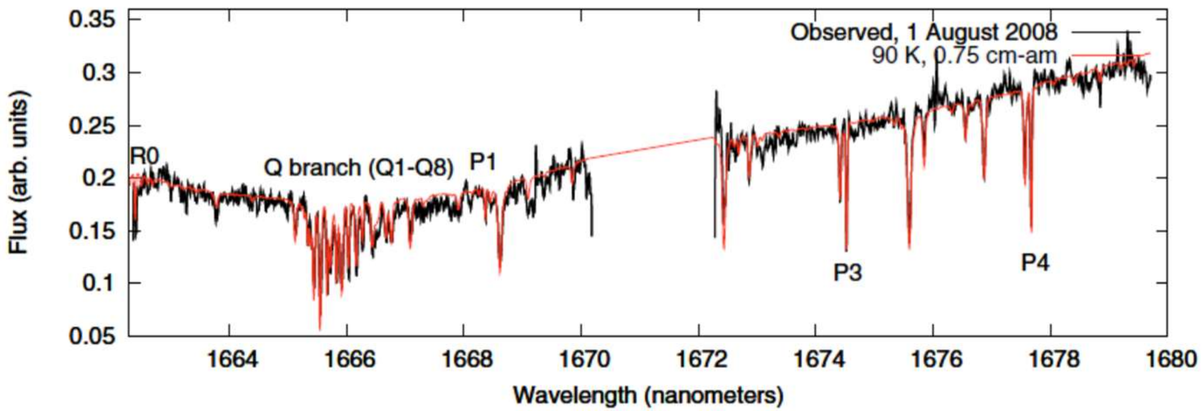
L. Fossati[1], M. E. Young[2,1], D. Shulyak[3], T. Koskinen[4], C. Huang[4], P. E. Cubillos[1], K. France[5,6], and A. G. Sreejith[1]



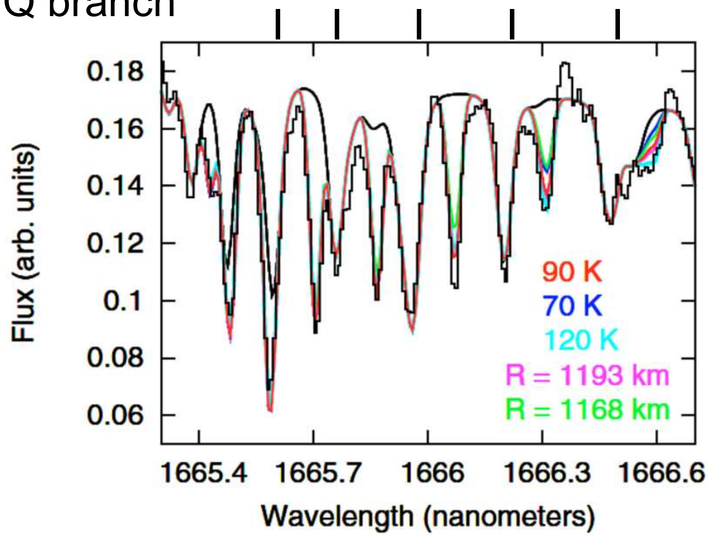


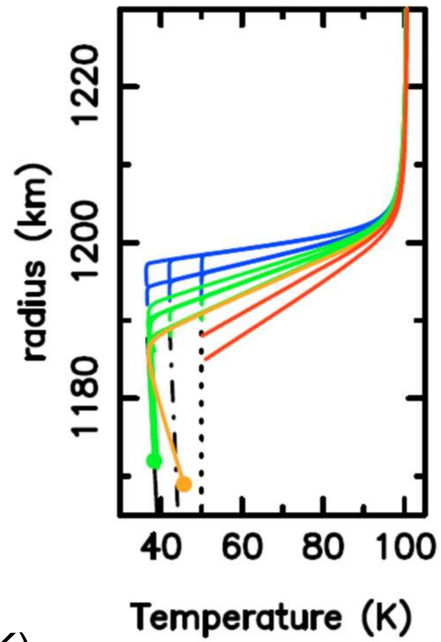
Probing tenuous atmospheres at high resolution

Pluto's atmosphere (~10 μbar) from combined VLT/CRIRES spectroscopy (R=60.000) and stellar occultation



Q branch





Pluto's Doppler shift ~20 km/s

Has constrained

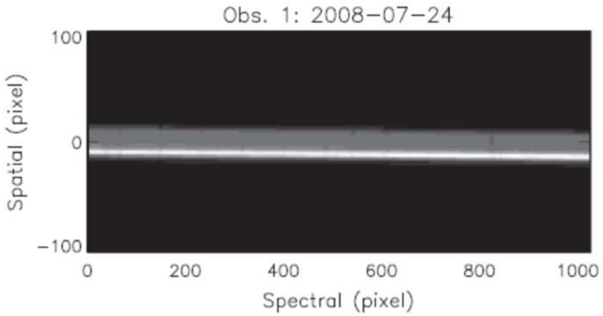
- Mean atmosphere temperature (90 K)
- Methane abundance
- Lower atmosphere structure and Pluto radius

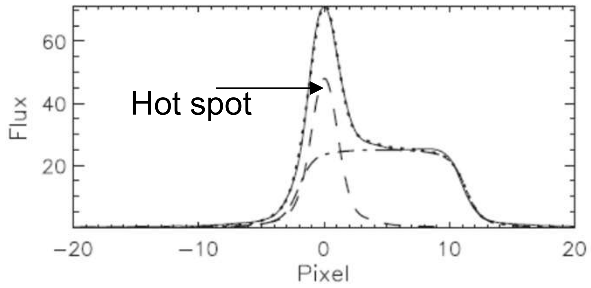
Results later validated by New Horizons space probe

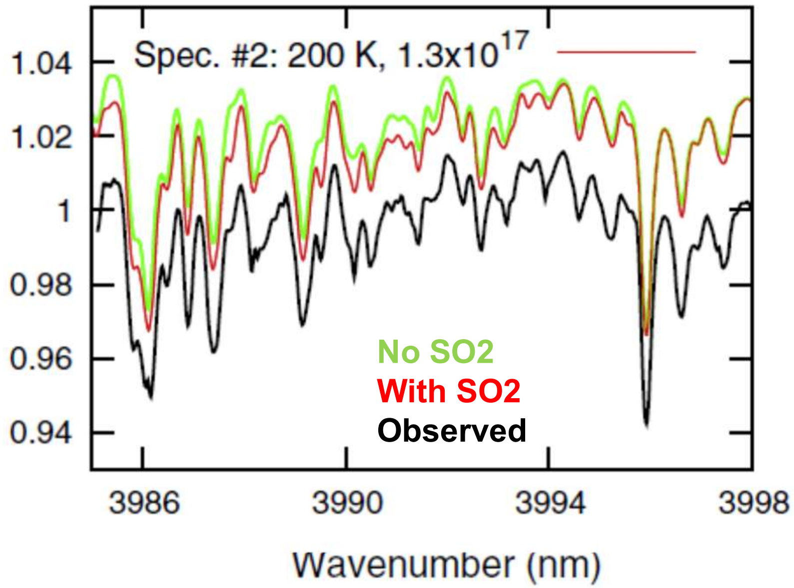
Lellouch et al. 2009

Even more tenuous atmosphere: Io (SO_2, ~1 nbar)

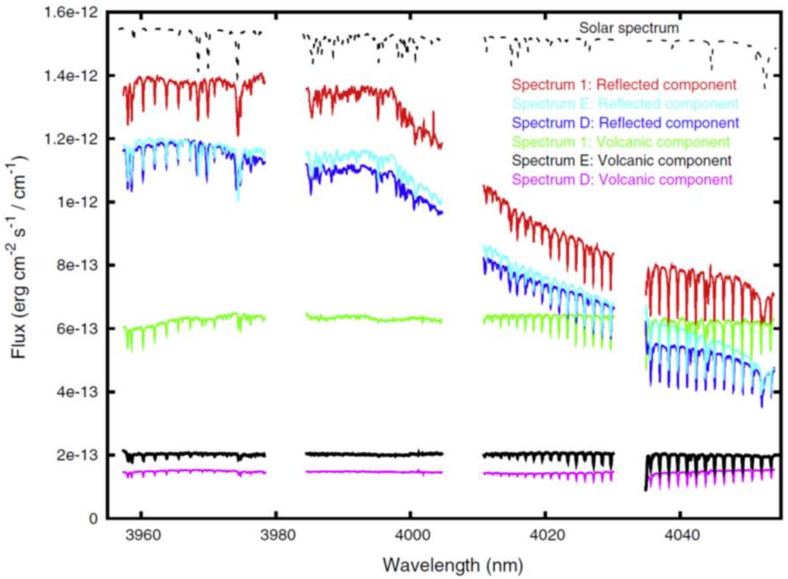
Extracting SO2 from the jungle of solar lines







CRIRES/VLT R = 40,000



Measuring SO_2 in both solar reflected light and thermal (volcanic) emission → constraints on both the sublimation and volcanic components of Io's atmosphere

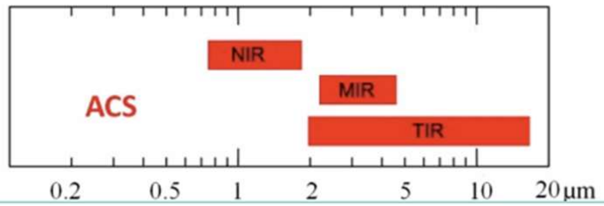
Lellouch et al. 2015

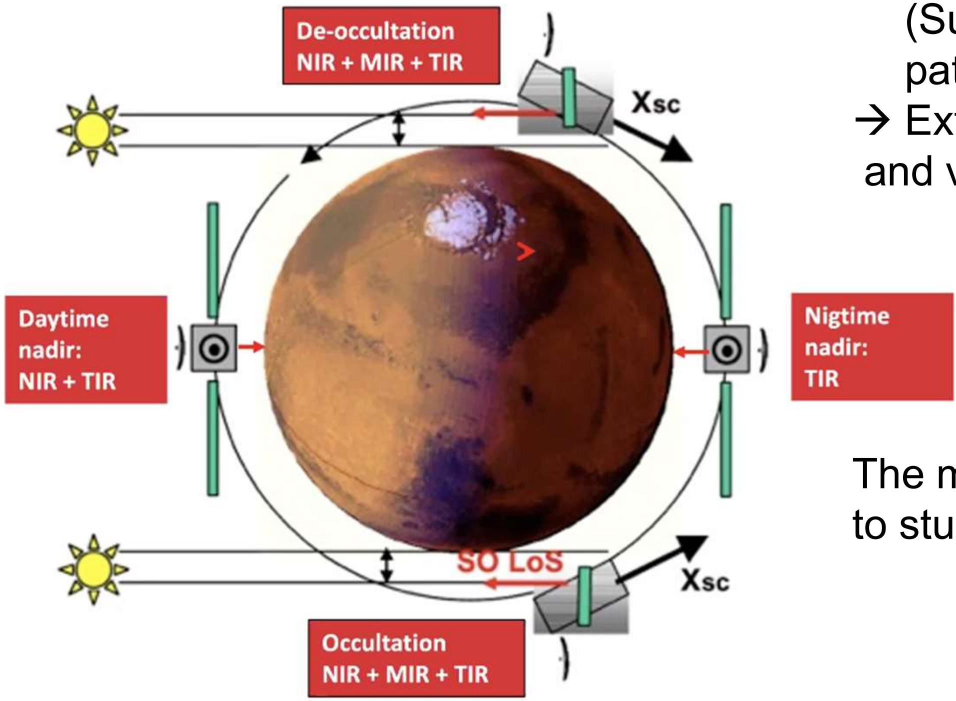
The ultimate weapon to study atmospheres in the IR: High resolution coupled with limb sounding from spacecraft

ACS on Trace Gas Orbiter (Mars)

Mass:	33.5 kg
Dimensions:	600×470×520 mm^3
Power consumption:	55 W (average)
Data rate:	1 to 3 Gbit/day

ACS Channel	Spectral range (µm)	Inst. Range (µm)	Spectral resolution
Mid-IR (MIR)	2.3-4.2	0.1-0.25	>30 000
Near-IR (NIR)	0.75-1.7	~0.17	>24 000
Thermal-IR (TIR)	1.7-17	full range	Occ.: 0.25cm^{-1} Nad.:1.6 cm^{-1}



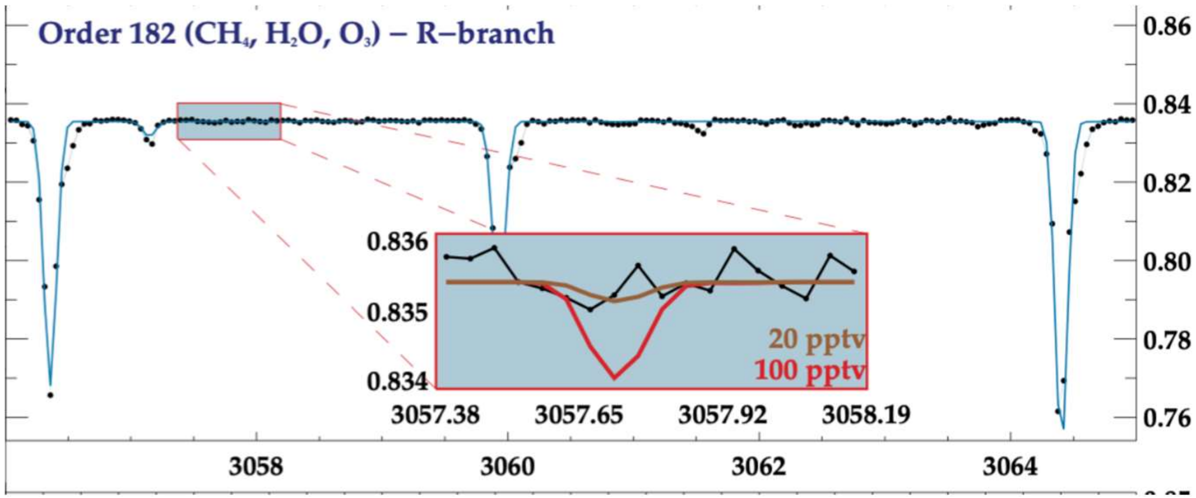


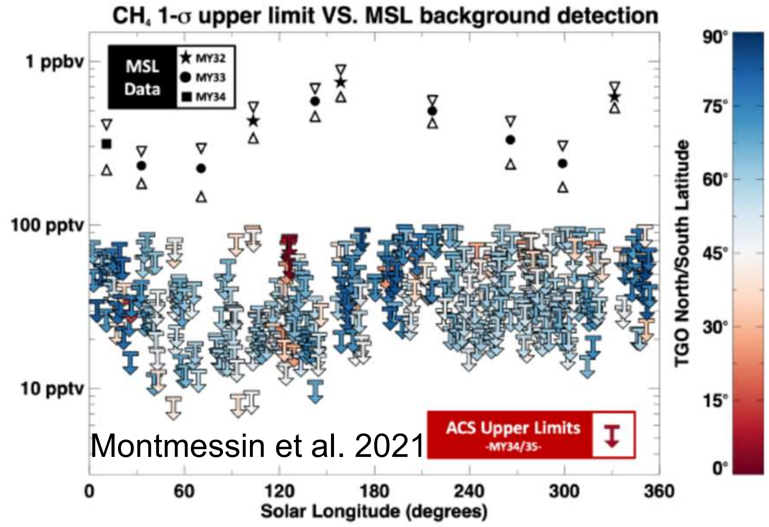
- R ~ 30.000
- Solar occultation
- Strong continuum source (Sun) and long absorption path along limb

→ Extremely strong sensitivity and vertical resolution

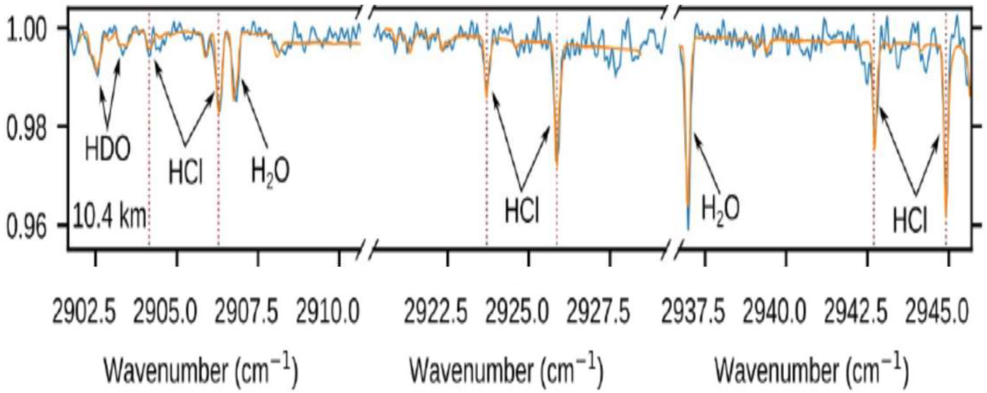
The most powerful instrument to study Mars's atmosphere ?

After a full martian year of operation
No methane, but HCl on Mars

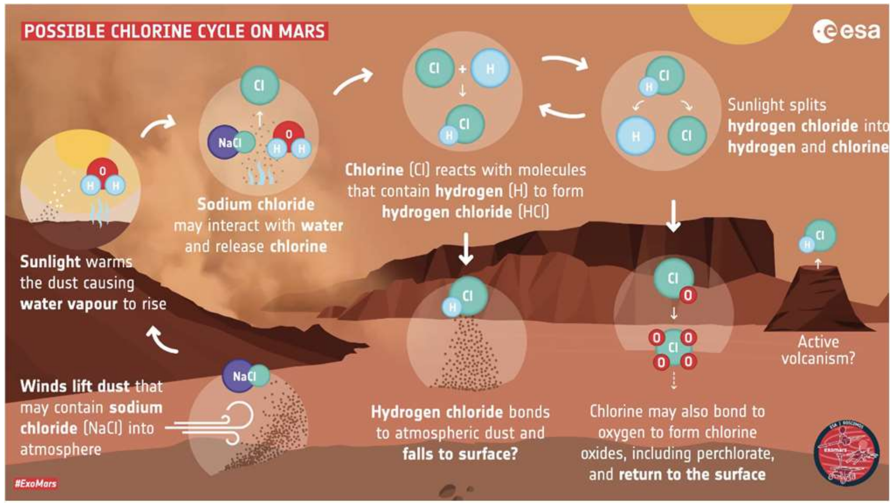




Montmessin et al. 2021



Korablev et al. 2020



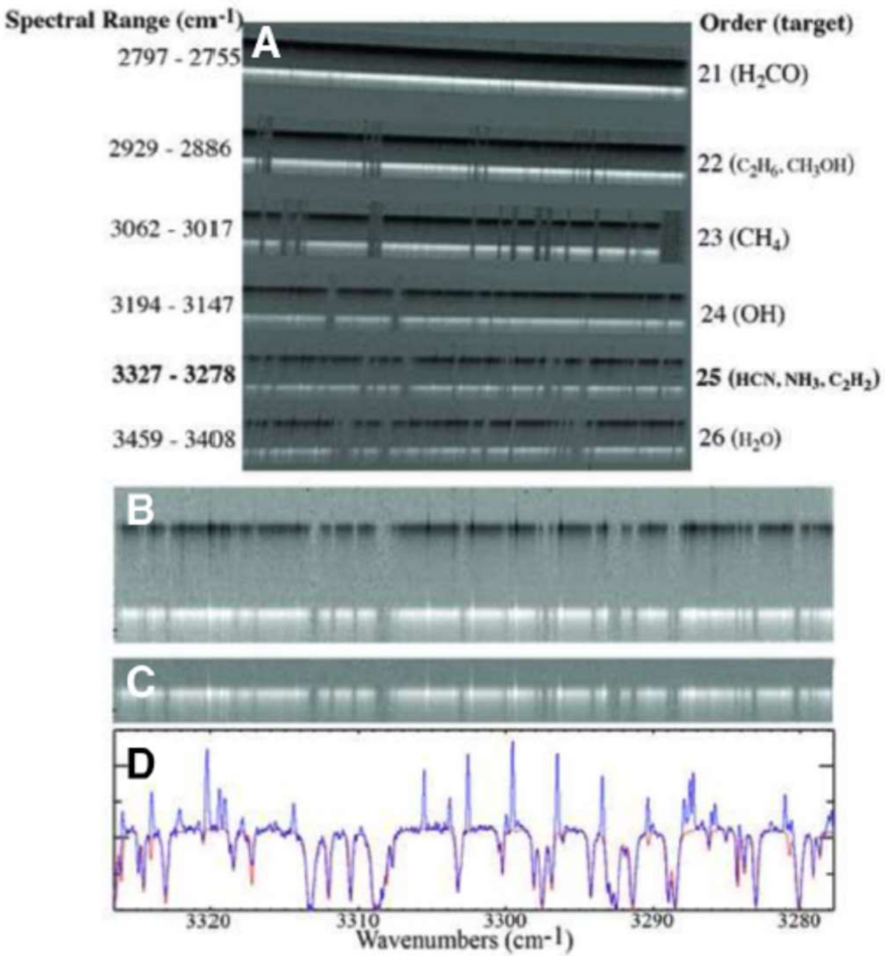
Probing comets in the near-IR (and visible) at high resolution

- Measure abundance ratios of parent molecules (H2O, CH3OH, CH4, C2H2, C2H6, NH3, CO, HCN, H2CO) in many comets and search for trends between comet families

- Measure isotope ratios (D/H, 15N/14N) and other possible diagnostics of comet formation (e.g. ortho-para ratio in H2O)

- Study coma dynamics / chemistry from line profiles (so far in done in visible range only)

Parent molecule inventory and cometary diversity from IR (~ 30 comets observed)



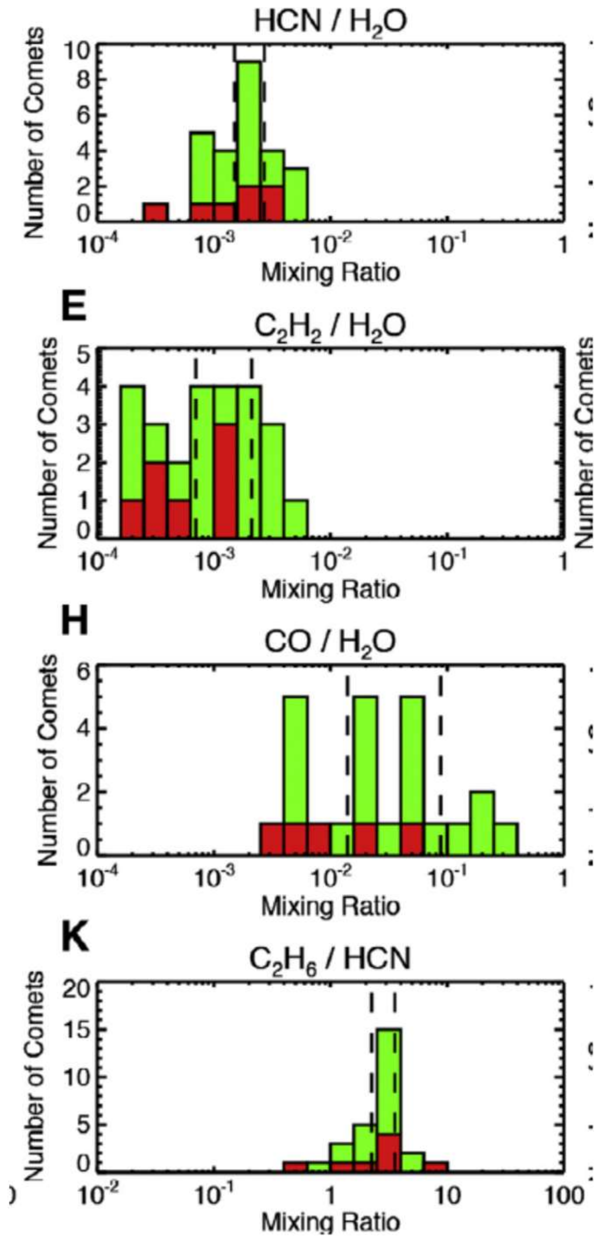
Keck/NIRSPEC long slit echelle spectro. R~25000

Dello-Russo et al. 2016

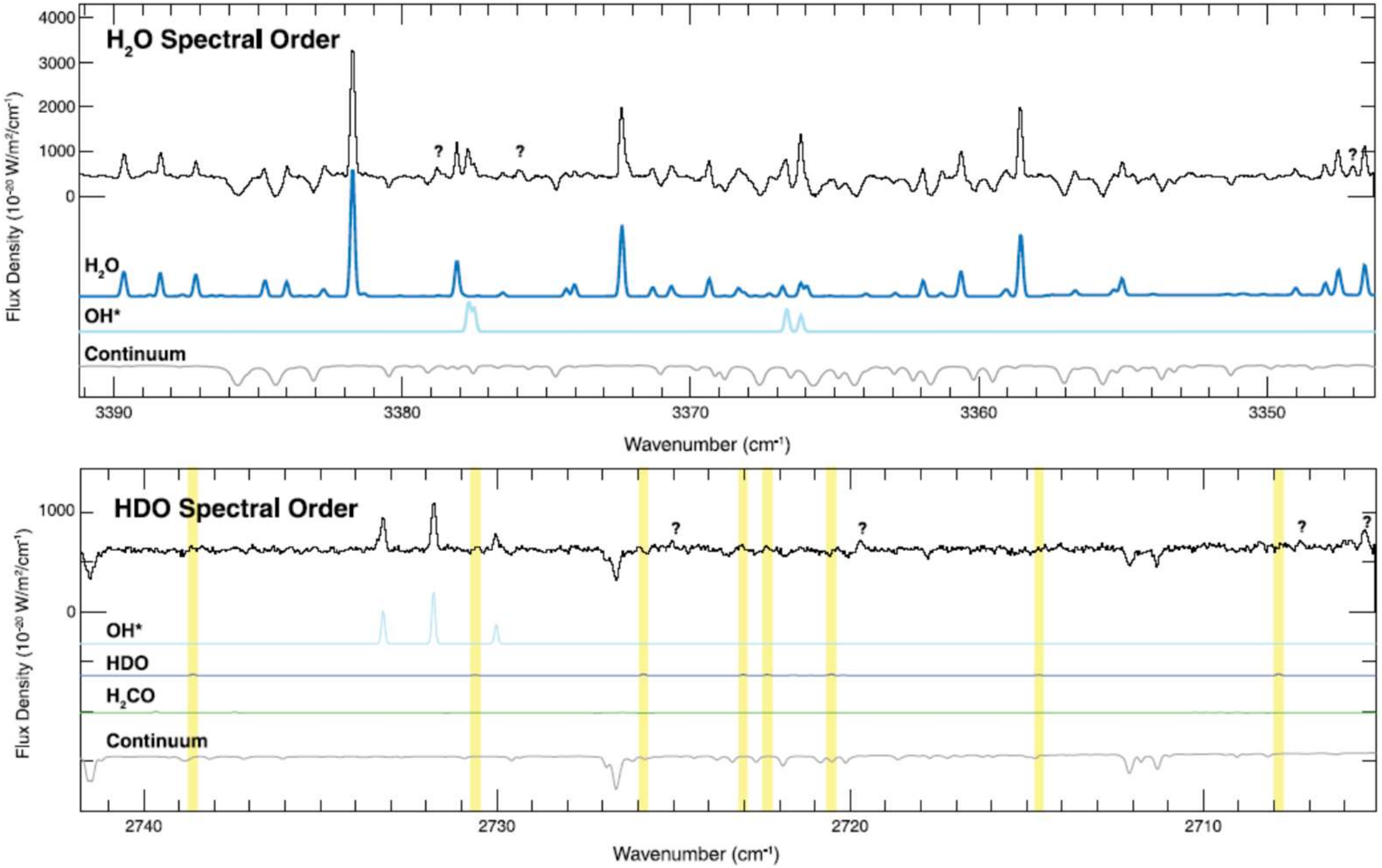
Large diversity in molecular abundances, but in general uncorrelated with dynamical family (Jupiter Family Comets vs Oort-Cloud)

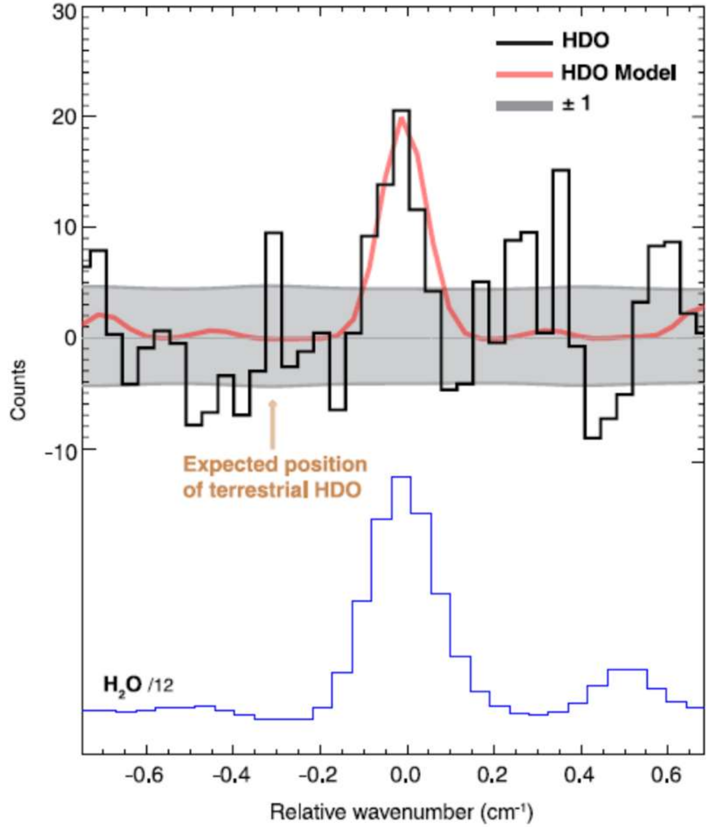
Exception: CO, depleted in JFC by factor ~ 4

- *Cause for diversity (e.g. within families) :*
- *evolutionary ?*
- *original ?*
- *observational bias ?*



Isotopes: HDO in comets in the IR



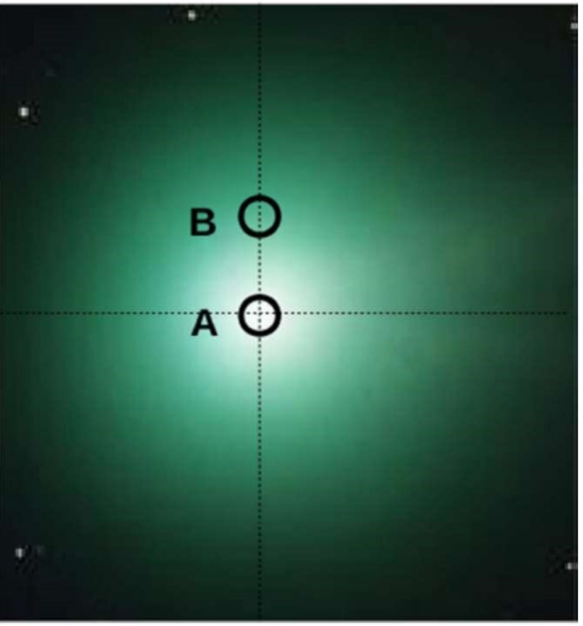


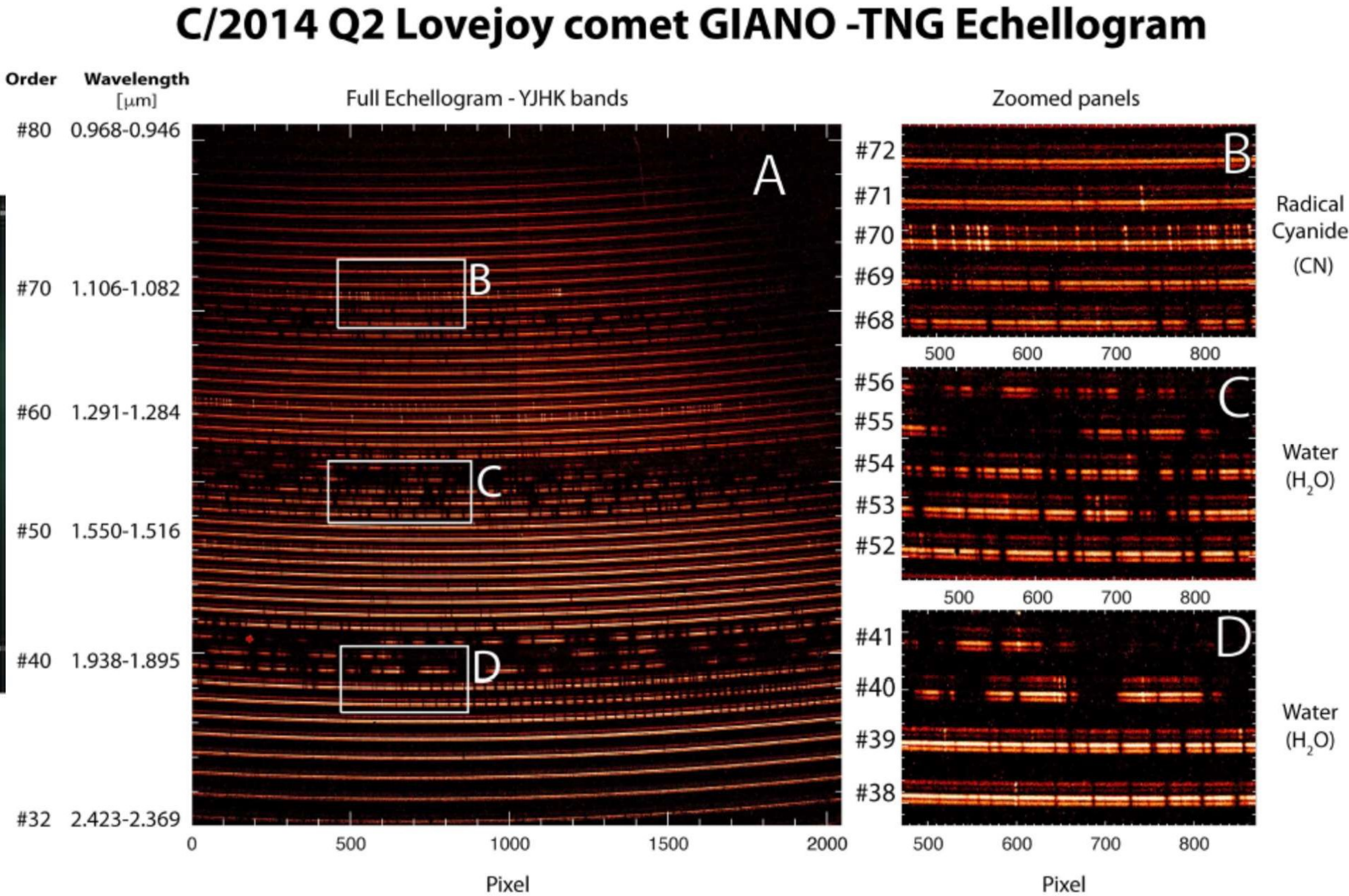
Comet C/2014 Q2 Lovejoy Keck/NIRSPEC

Paganini et al. 2017

D / H = (3.0+/-0.9) x 10
~2 x terrestrial

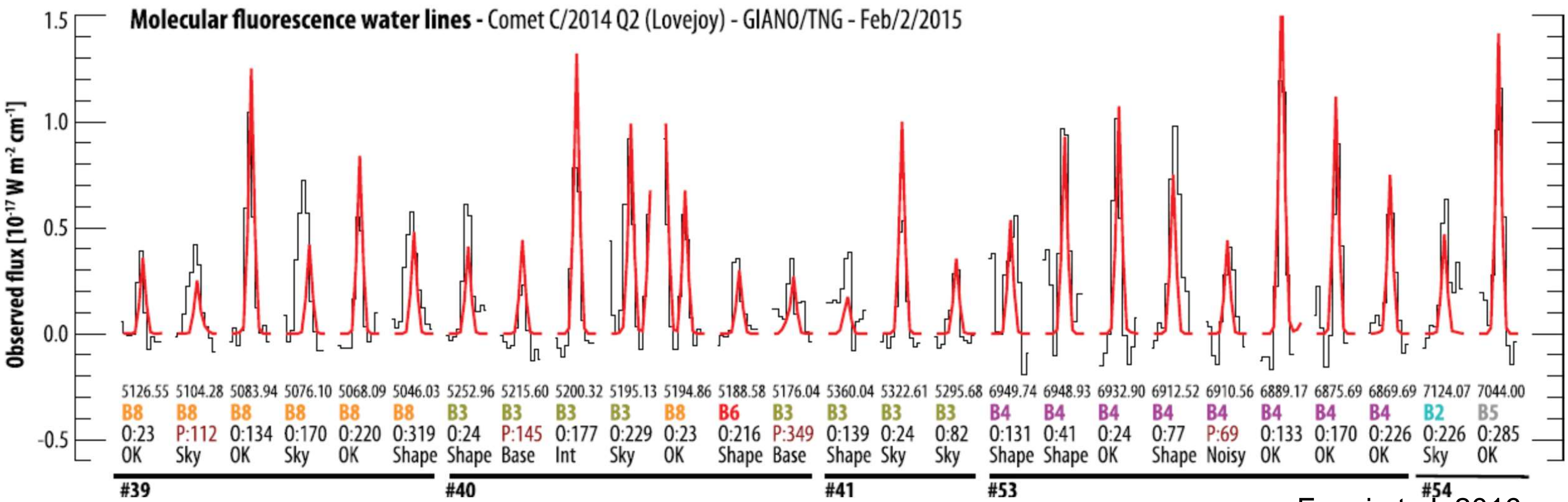
The entire 0.95-2.45 μm spectrum of a comet at R=50000





Faggi et al. 2016

Water lines (ortho and para) in the near-IR spectrum of a comet



Faggi et al. 2016

Measurement of

- Rotational temperature (here 90 K): constrains excitation and physical conditions in coma
- Ortho-to-para ratio (here ~2.70) . Encodes some information on formation temperature

(e.g. o/p → 0 at 0 K, and → 3:1 at T> 50 K).

*La bêtise consiste à vouloir conclure**

Gustave Flaubert

* (approx.) It is a silly thing to conclude

Polarimetry of solar system atmospheres

• Planetary emission lines can also be partially polarized, as recently demonstrated in the particular case of the Earth (eg Lilensten et al 2008, GRL 35, L08804)

• It has never been detected unambiguously in the upper atmospheres of other planets yet.

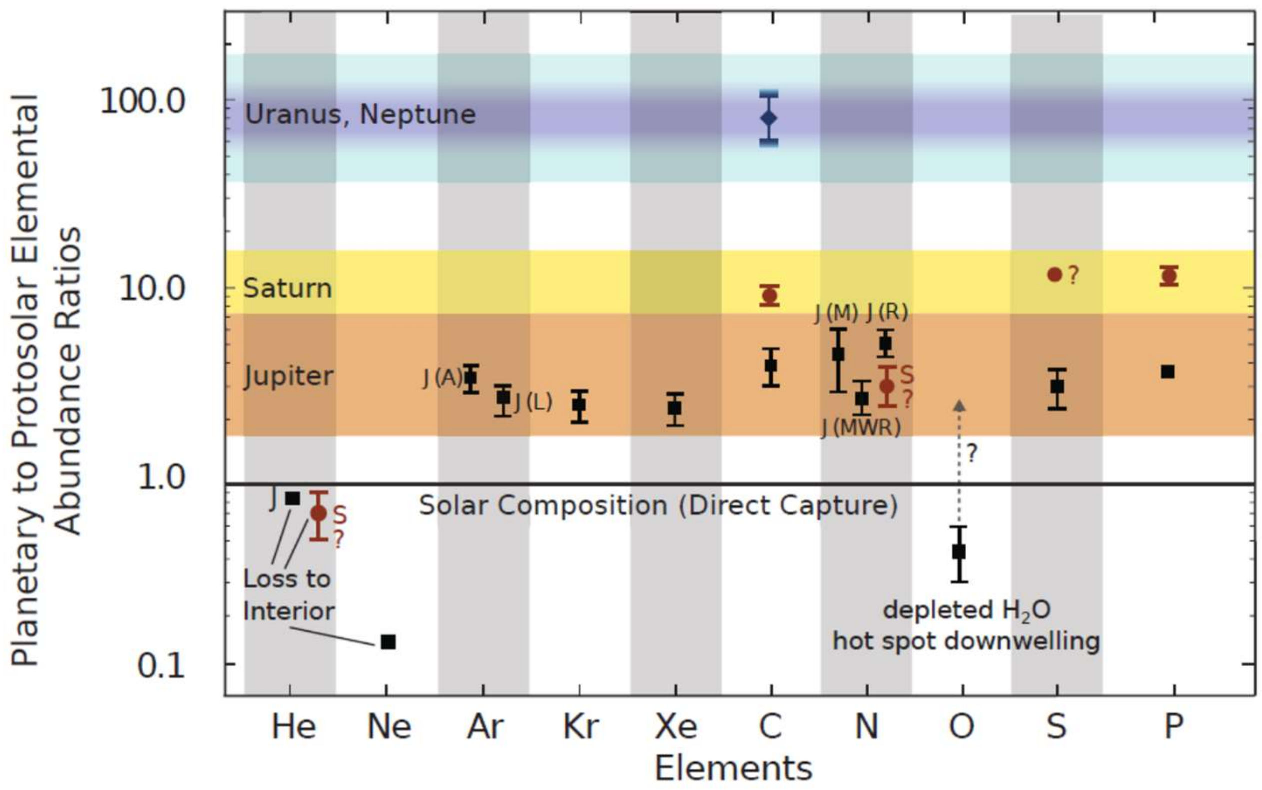
• Even though the exact polarizing mechanism depends on the specific line, polarization is very often a proxy of possible anisotropies within the emission region, and in particular those related to the presence & local configuration of magnetic fields.

- Barthélémy et al. 2011. Possible polarization of H3+ lines in Jupiter

Exploiting the 5-μm region at high-resolution: Probing Giant Planet disequilibrium chemistry

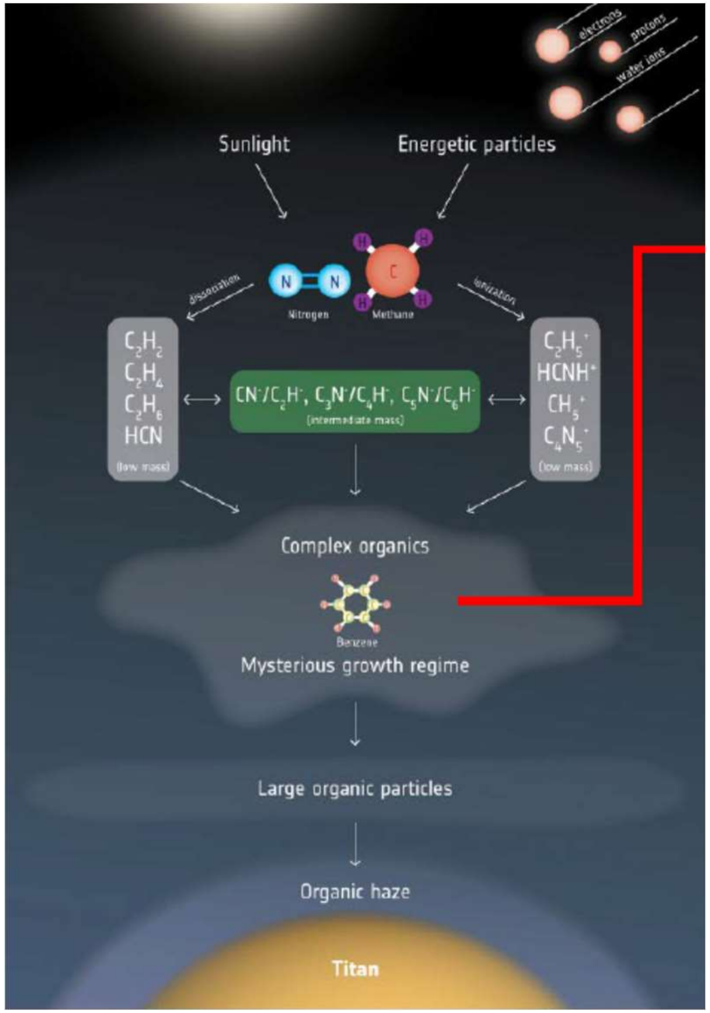
Disequilibrium species in Jupiter and Saturn

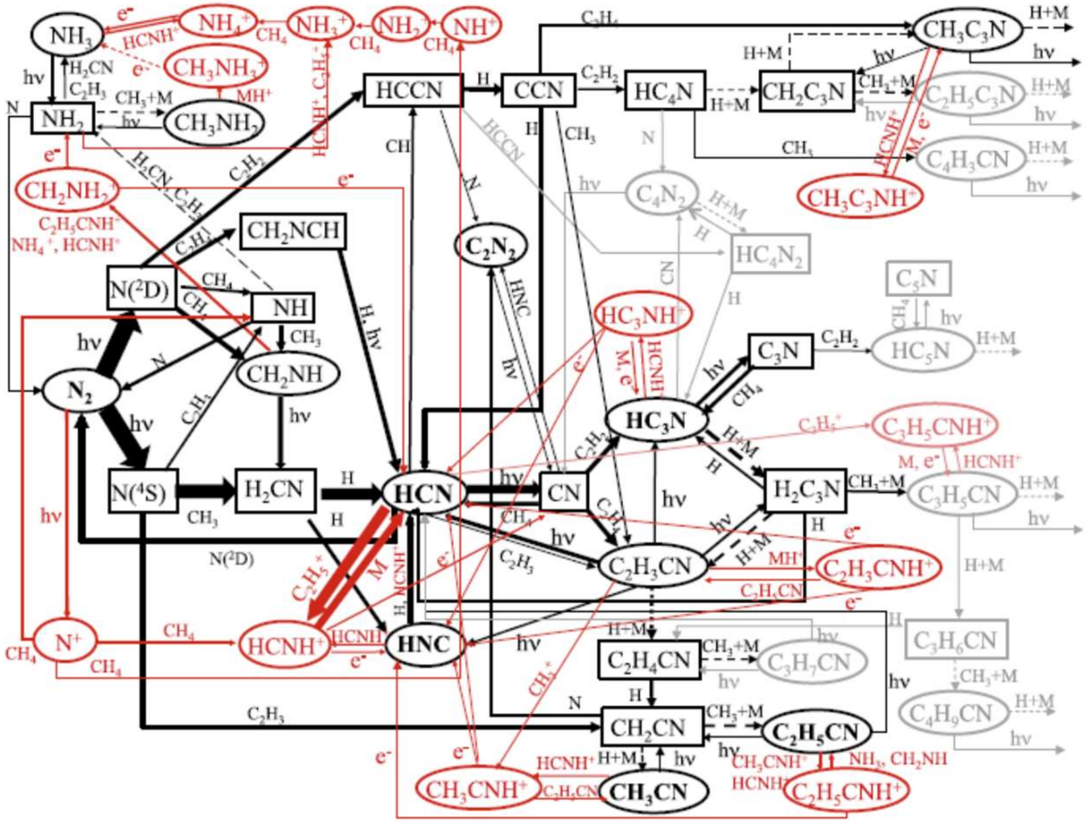
CO, PH_3 , GeH_4, AsH_3



Jupiter and Saturn are enriched in heavy elements (C, N, P, As); Saturn more than Jupiter

Probing Titan's stratospheric chemistry

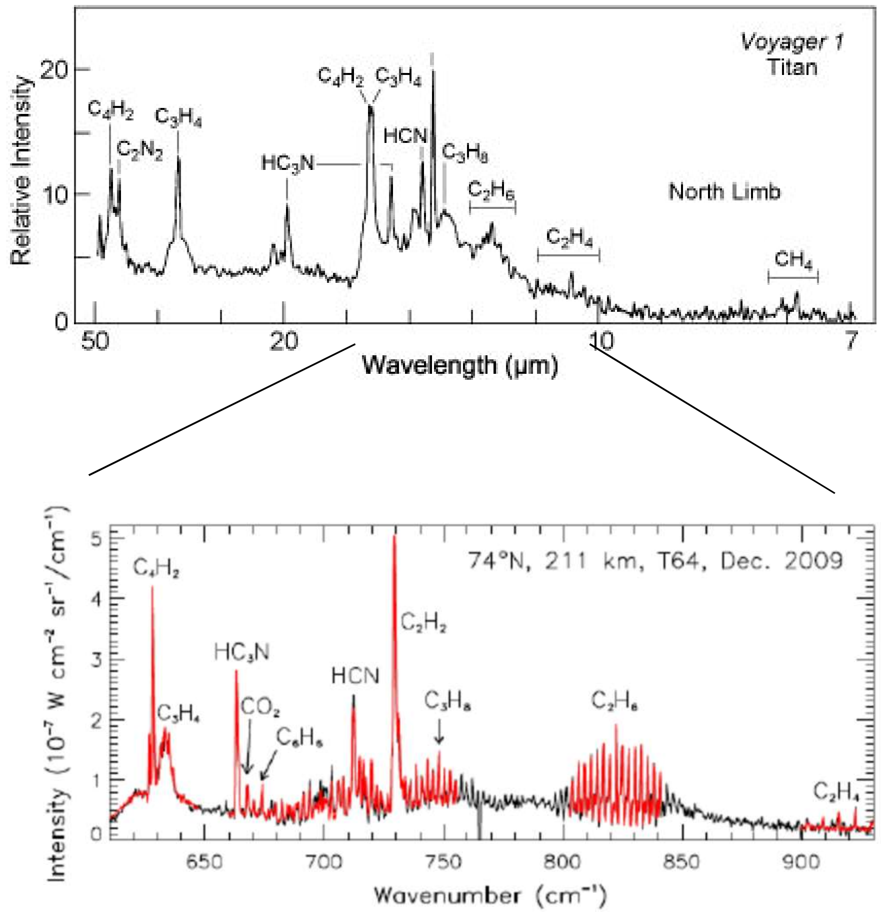


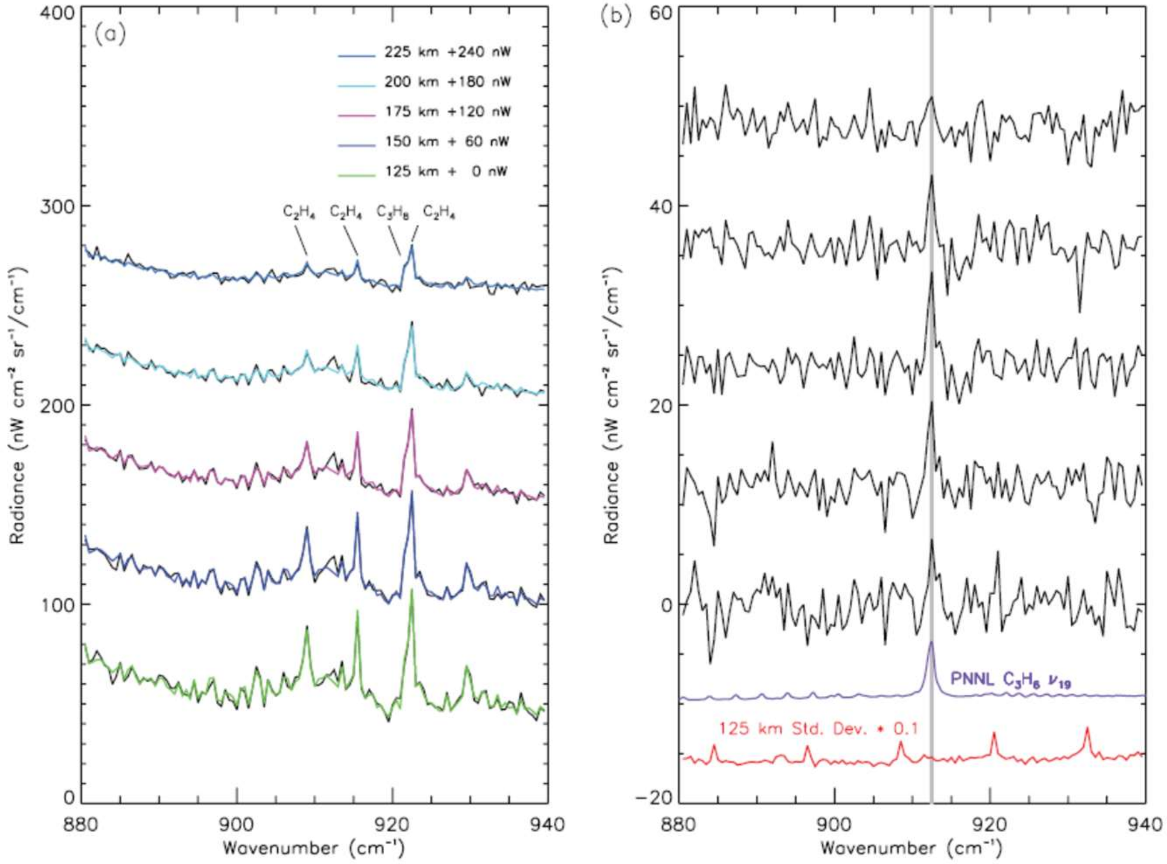


Probing Titan stratospheric chemistry

From Voyager (R~250) to Cassini

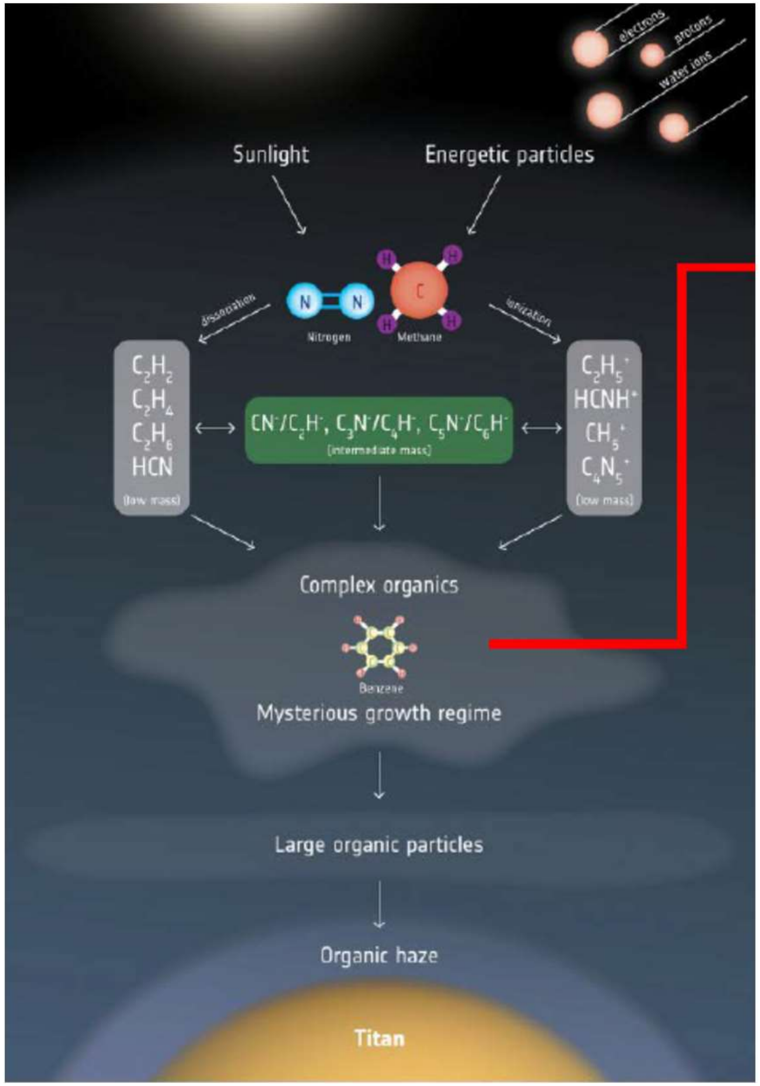
Detection of propene (C3H6) from Cassini/CIRS (R =2000)

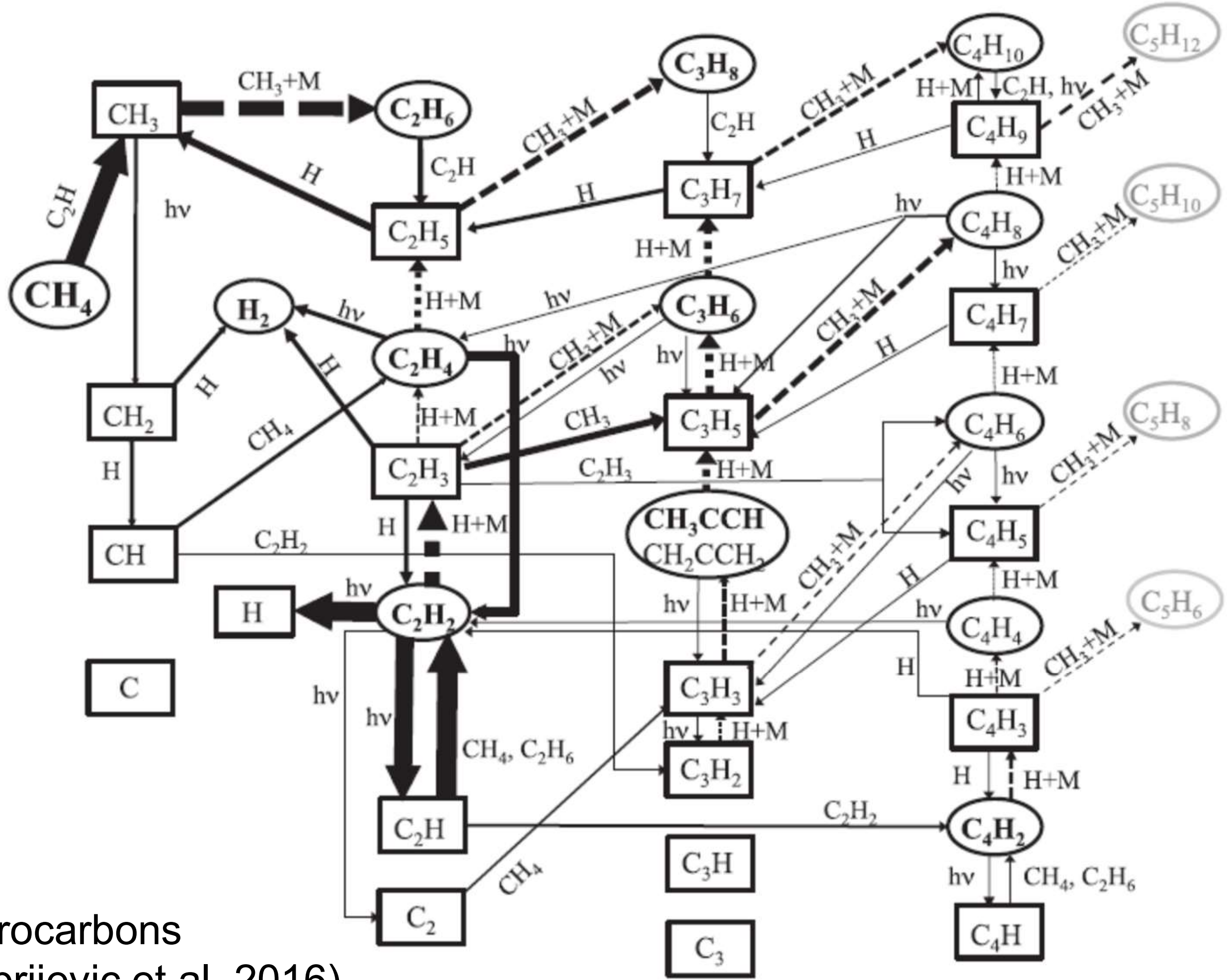




Nixon et al. 2013

Titan’s atmospheric chemistry

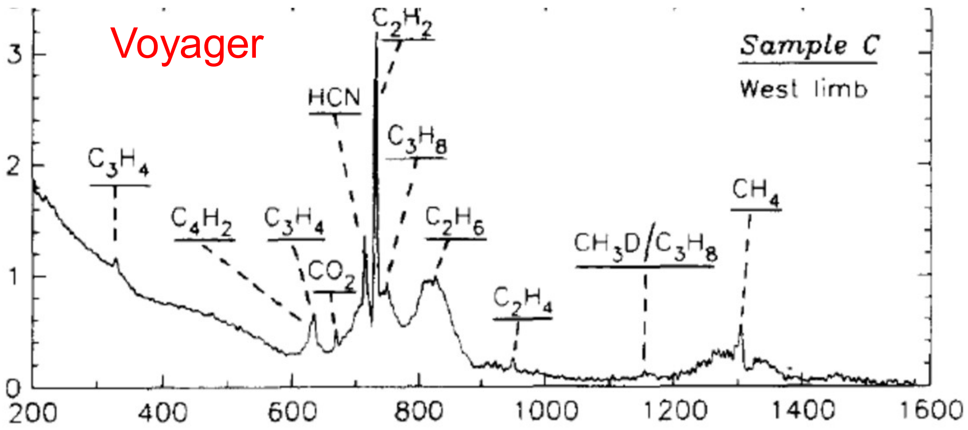


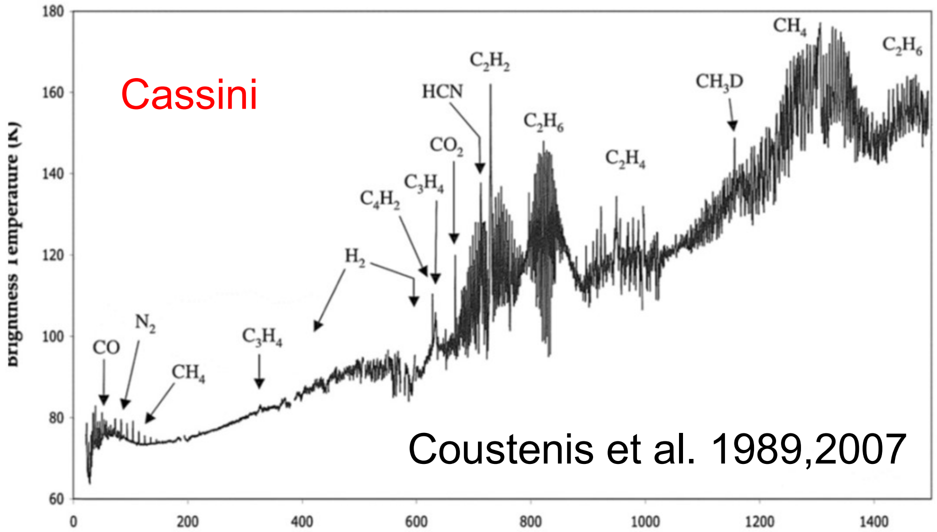


Hydrocarbons
(Dobrijevic et al. 2016)

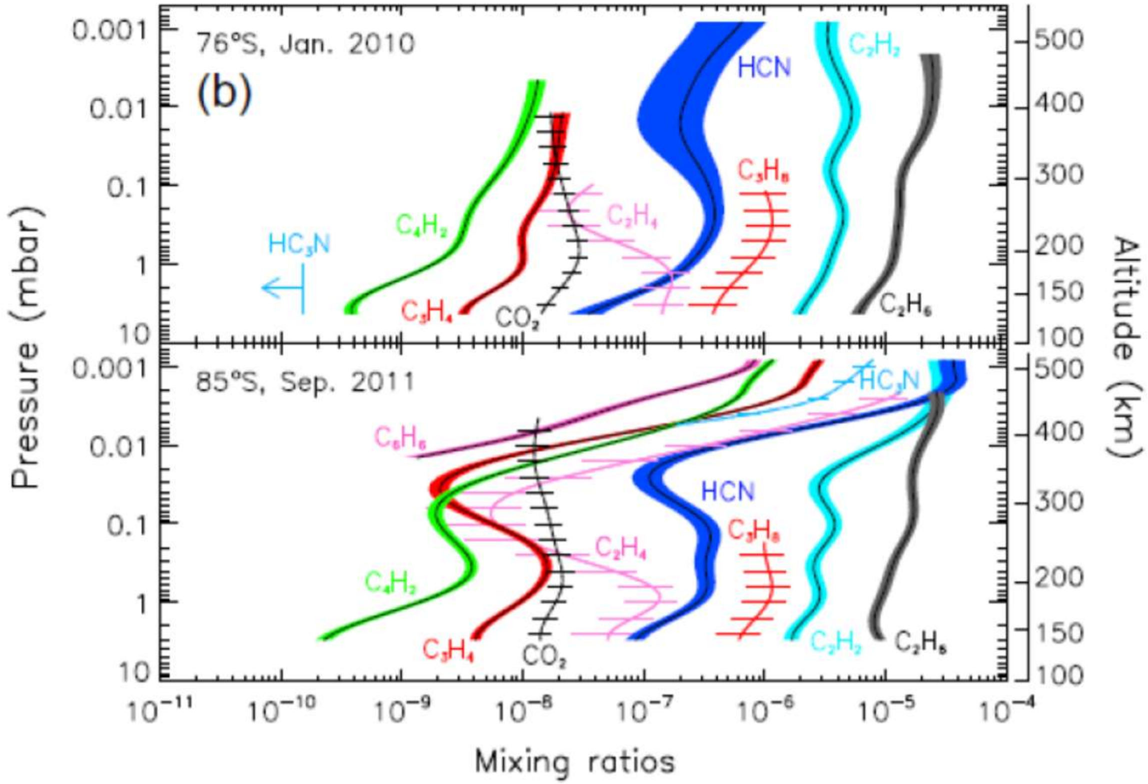
Probing Titan stratospheric chemistry

From Voyager (1981, R~250) to Cassini (2004-2019, R ~2000 + limb)





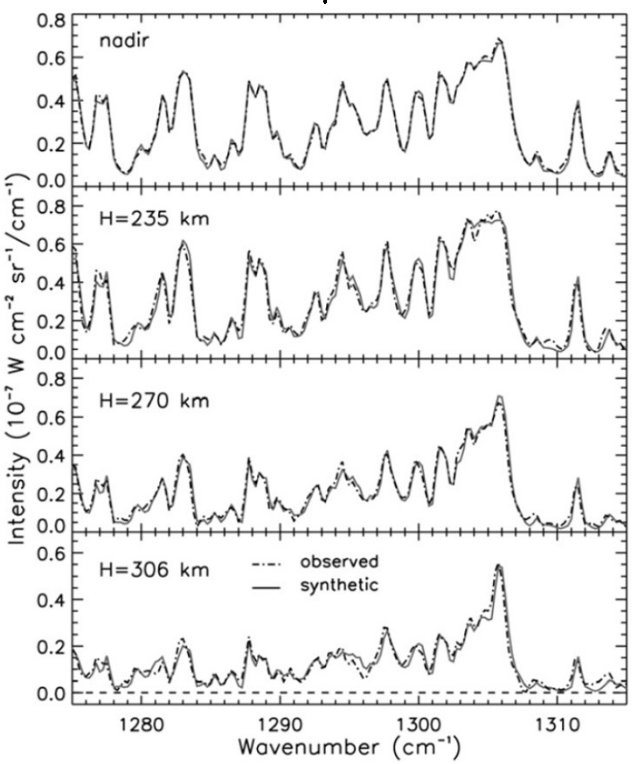
Coustenis et al. 1989,2007

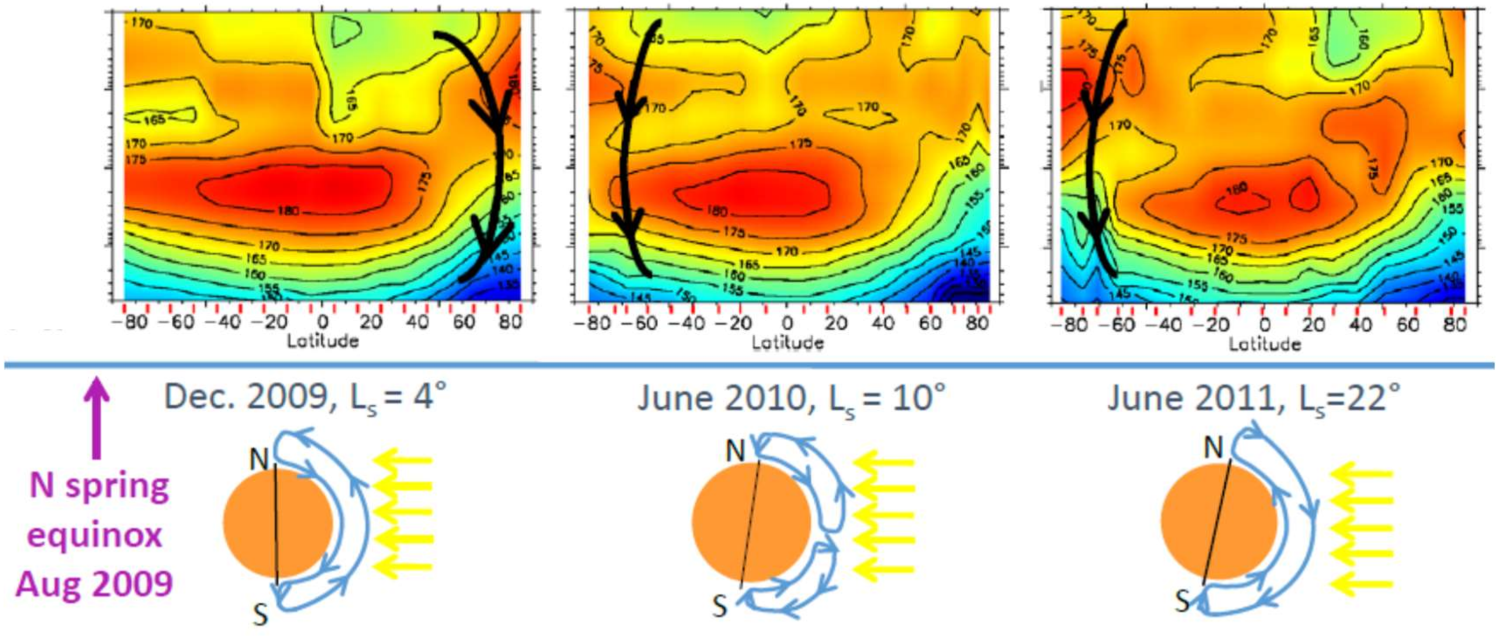


Vinatier et al. 2012

Probing Titan stratospheric dynamics from Cassini

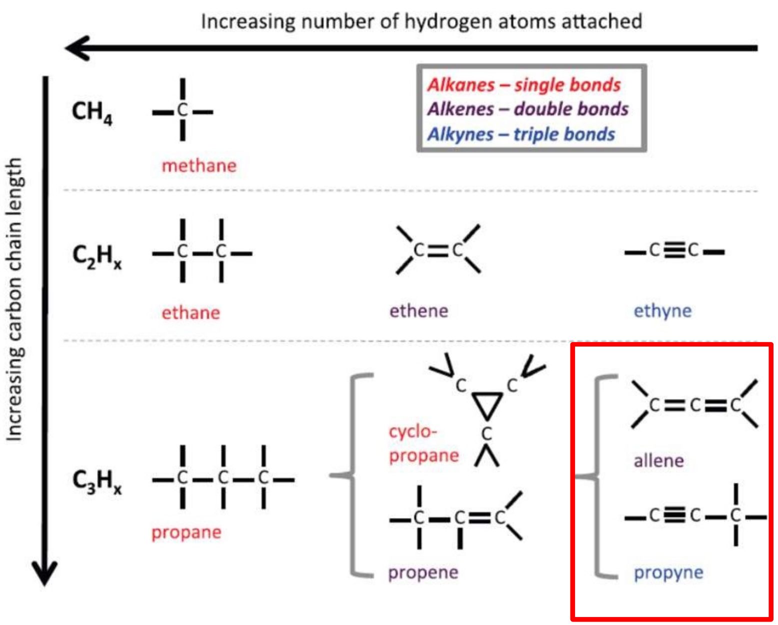
CH4 7.7 μm emission

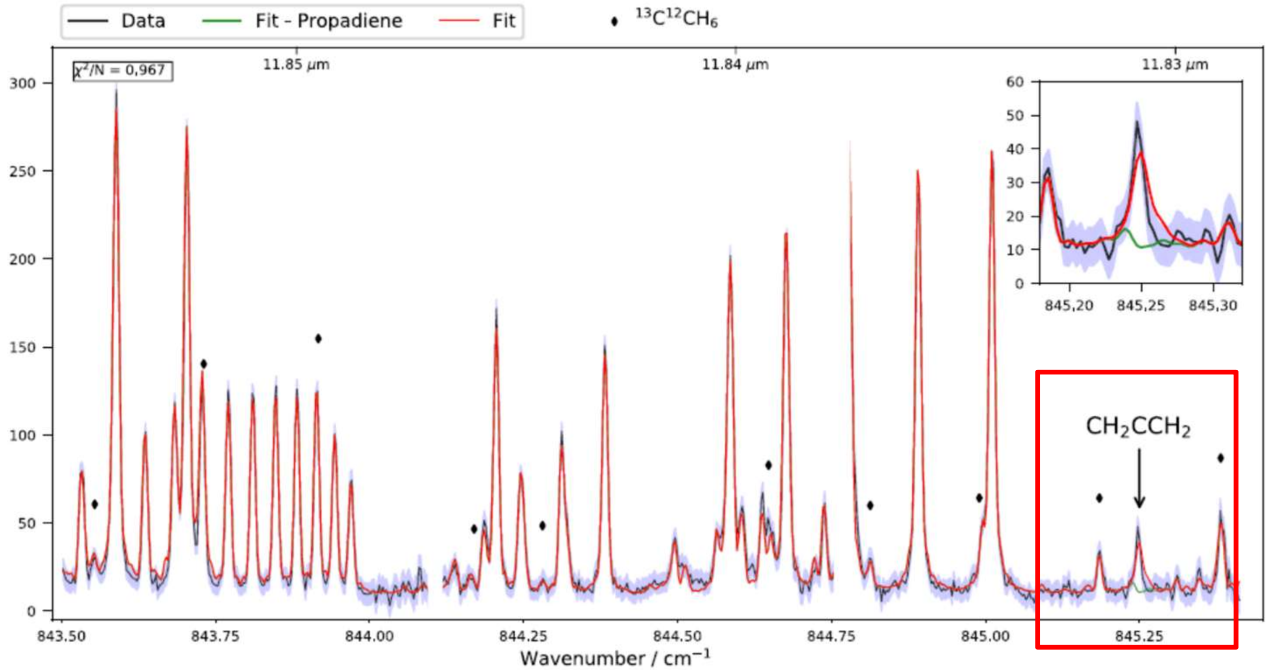




Vinatier et al. 2007, 2020

Detection of allene (H2CCCH2) on Titan (TEXES/IRTF, R = 80,000)

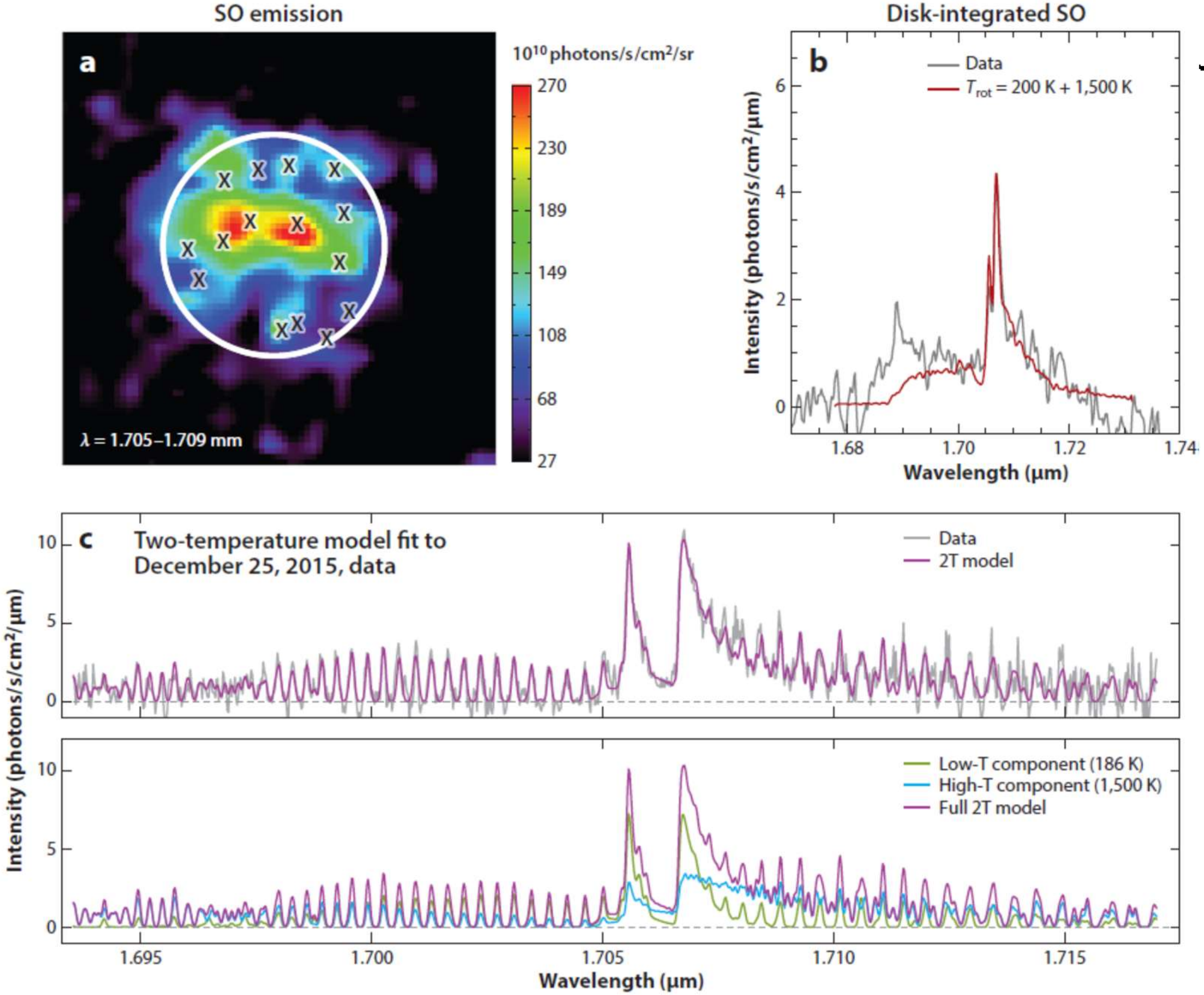




Nixon et al. 2019

Even more complex molecules (N-bearing) have been detected with ALMA, and from mass spectrometry onboard Cassini.

IR still unique for non-polar species (not observable in mm), and isomeric variants (not separable from mass spec.)



Io:
The baffling SO IR emission

$$a^1\Delta \to X^3\Sigma^-$$

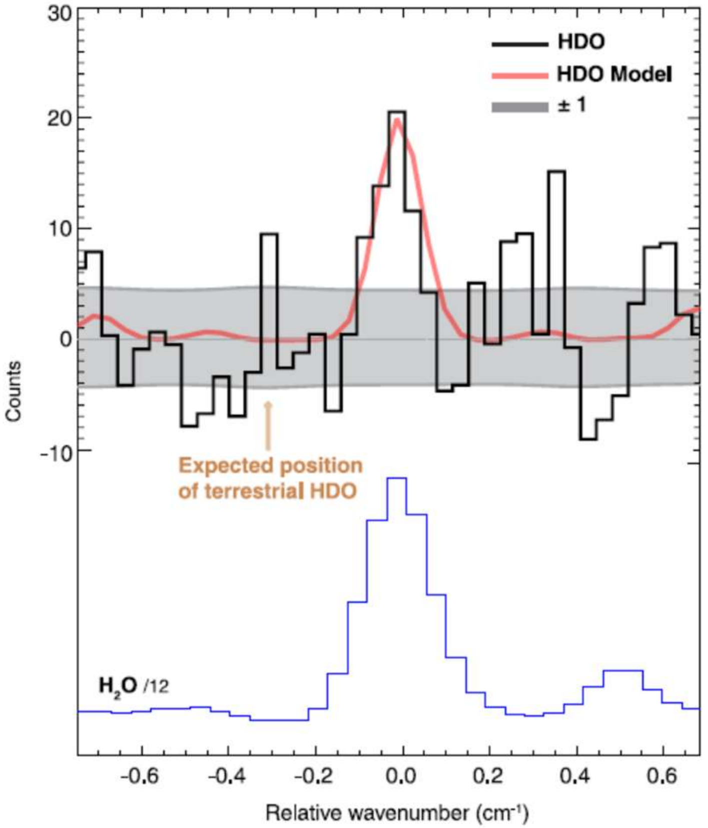
- Observed in eclipse
- Rotational distribution indicates high-temp. (~1500 K) and low-temp (~200 K) gas

→ Evidence for gas directly injected From volcanic vents?

- But spatial emission not well correlated with volcanic hot spots…

Search for winds (volcanic plumes) with SPIRou?

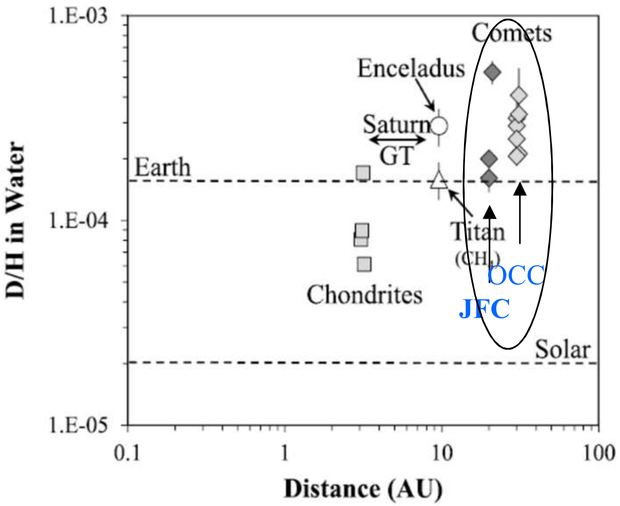
D/H ratio in comets

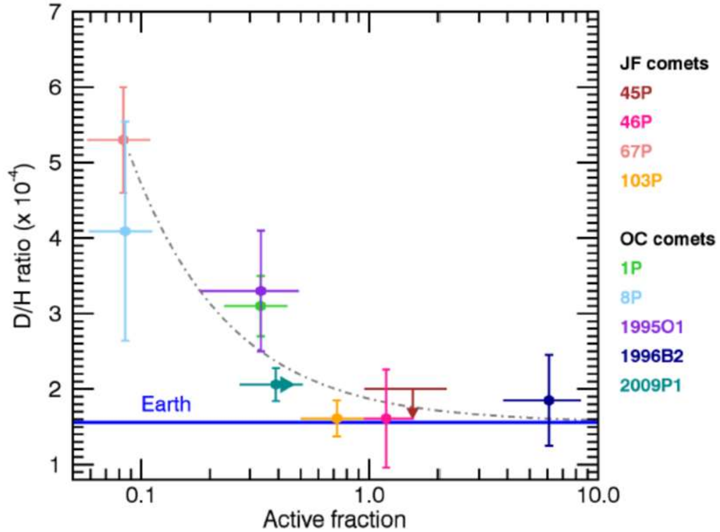


Paganini et al. 2017

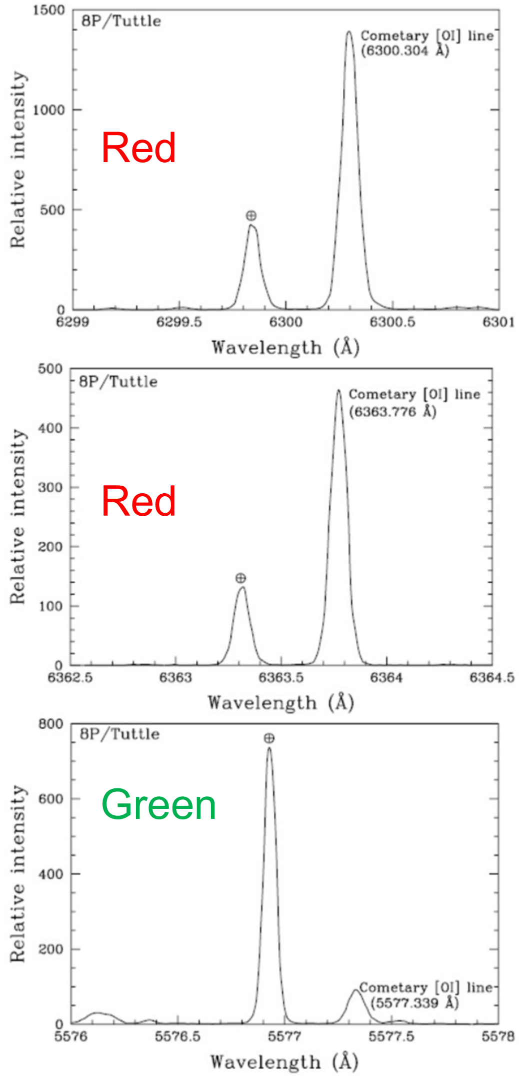
- D/H is variable between comets (1 to 3.5 x terrestrial), but again not correlated with dynamical class

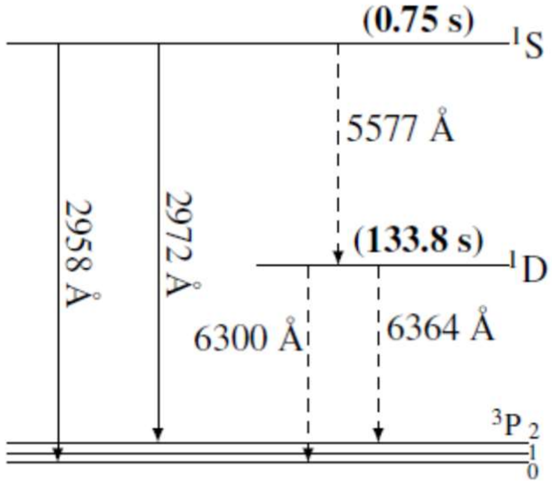
- An apparent anticorrelation with comet active fraction?



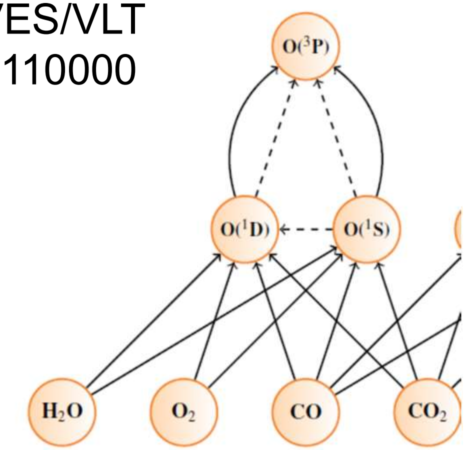


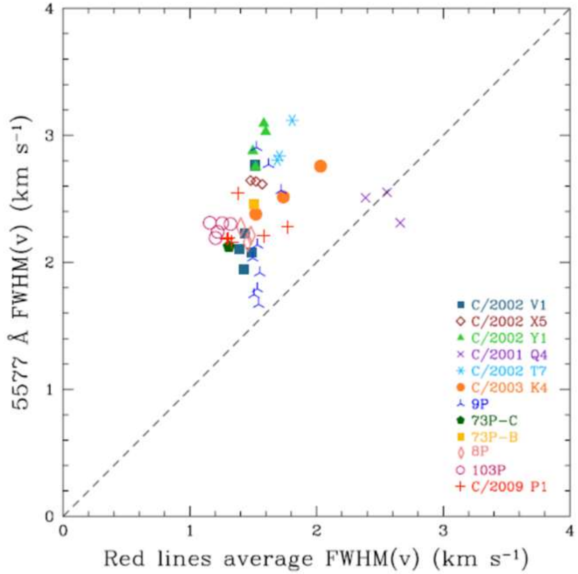
Resolving atomic OI lines in comets (visible)





UVES/VLT
R=110000





→ Information on relative chemical pathways at the origin of these emissions

Decock et al. 2013, Raghuram et al. 2020