Abundances in the solar system: what we achieved and how much was it dependent on space probes?

Sandrine VINATIER
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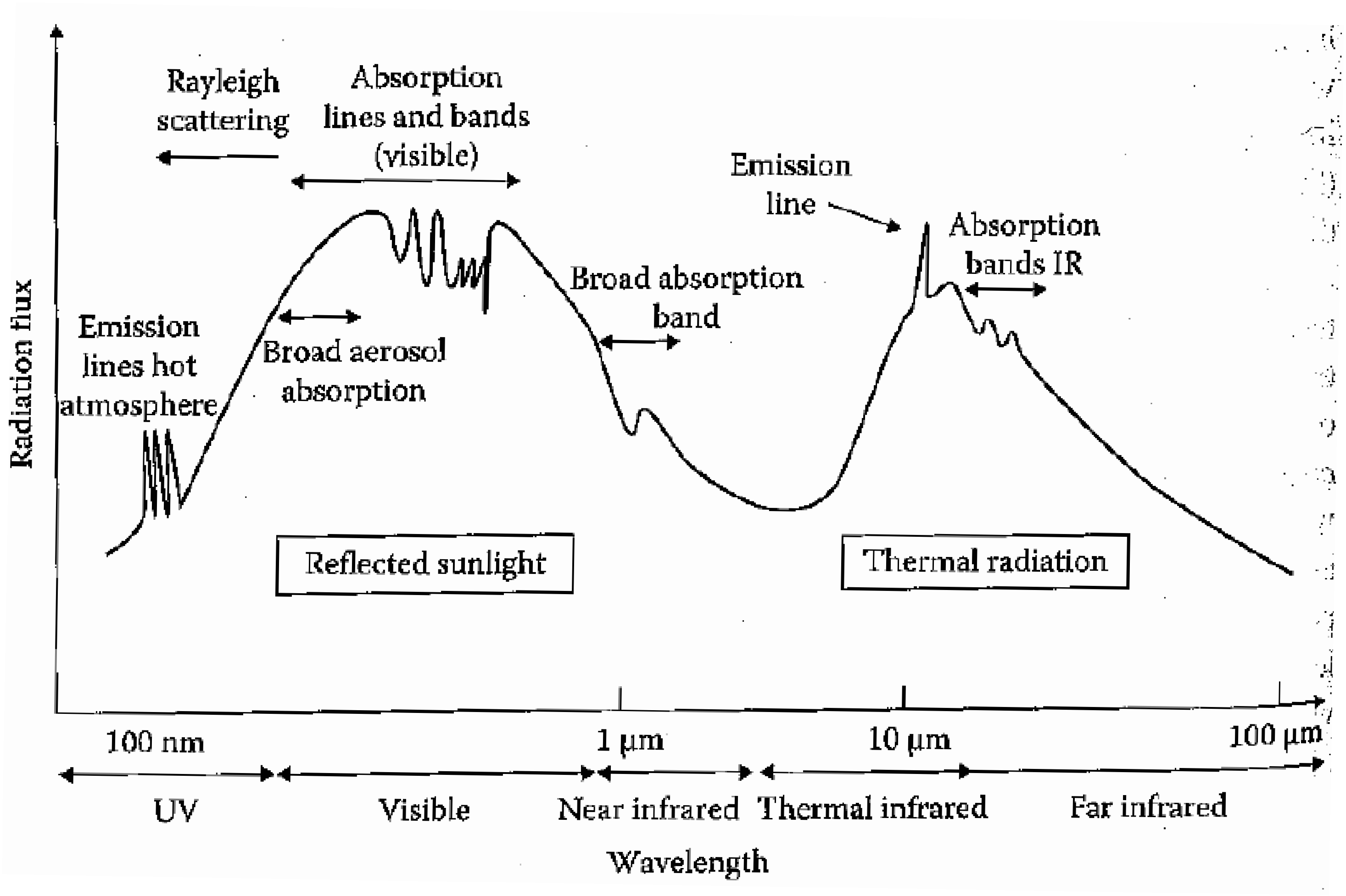
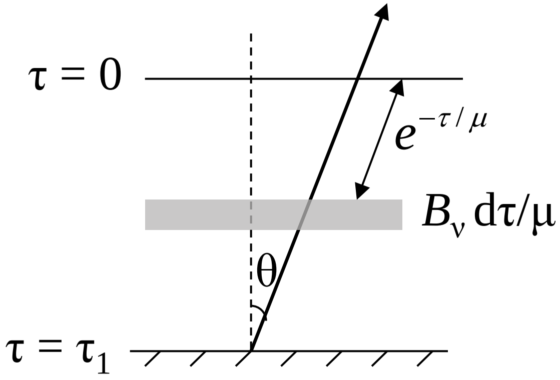
Introduction: a typical planet radiation



Introduction: thermal IR emission

- **Outgoing thermal emission of a planet**

$$I_\nu(\mu,0) = \underbrace{B_\nu(T_1)e^{-\tau_1/\mu}}_{\text{Surface/clouds}} + \underbrace{\frac{1}{\mu}\int_0^{\tau_1} \boxed{B_\nu(T)}\, e^{\boxed{-\tau}/\mu}\, d\tau}_{\text{atmosphere}}$$



Planck function,
depends on T

opacity: depends on composition
(molecular abundances)

Pb: How to decouple temperature and composition contributions?

- Temperature:
  - fit of the observed I_ν
  - a gas uniformely mixed with known abundance

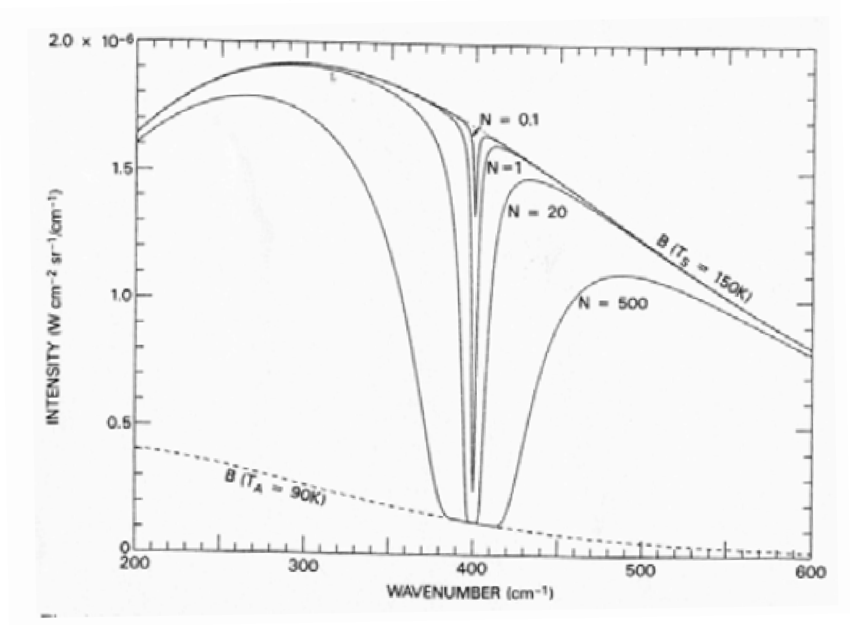
  $\Rightarrow$ T

- Abundance:
  - fit of the observed I_ν
  - T is known

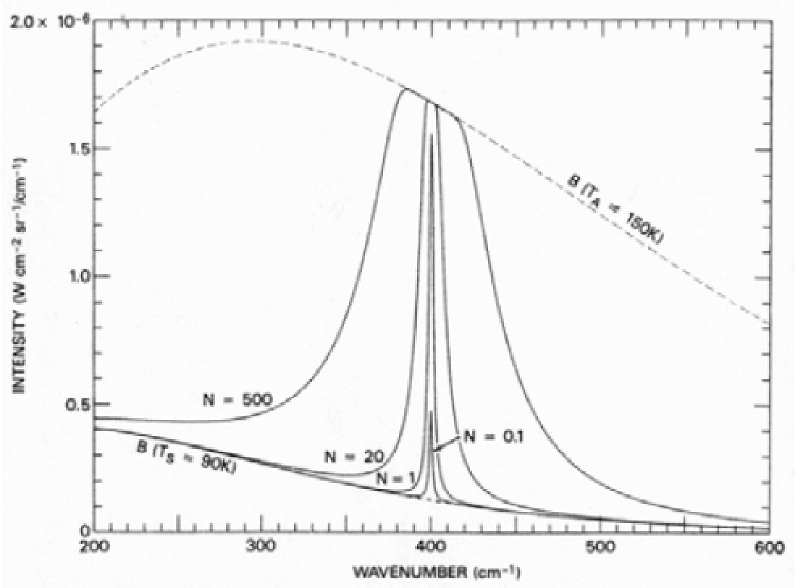
  $\Rightarrow \tau \Rightarrow q$

Introduction: radiative transfer

Absorption line



Emission line



Width of the line depends on the gas density: the higher is the abundance, the larger is the line ⬄ pressure broadening

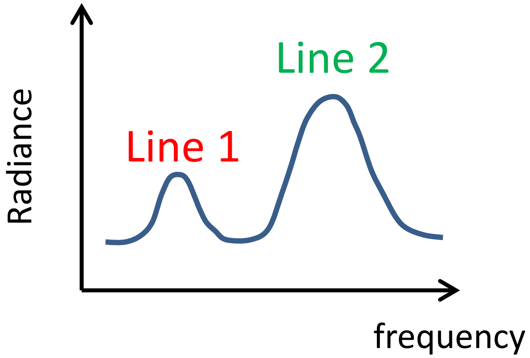
Absorption/emission depends on the temperature gradient in the region of the radiation emission (where $\tau = 1$).

Introduction: line opacity and level probed

- **How to probe several levels?**

For a given molecule, lines of different intensities originate from different levels

Molecular spectrum



Line 1 has a small absorption coefficient => probe deeper in the atmosphere.

Line 2 has a high absorption coefficient => probe higher in the atmosphere.

Introduction: line opacity and level probed

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$$I_\nu(\mu,0) = B_\nu(T_1)e^{-\tau_1/\mu} + \frac{1}{\mu}\int_0^\infty B_\nu(p)\boxed{WF(p)}\,d\ln p$$

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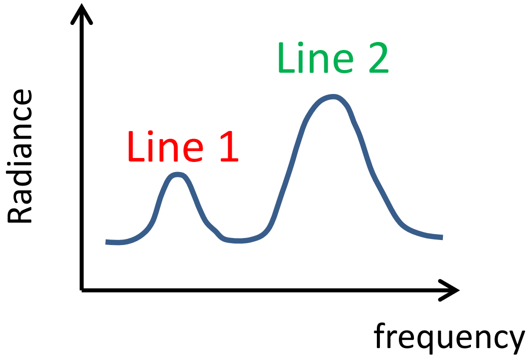

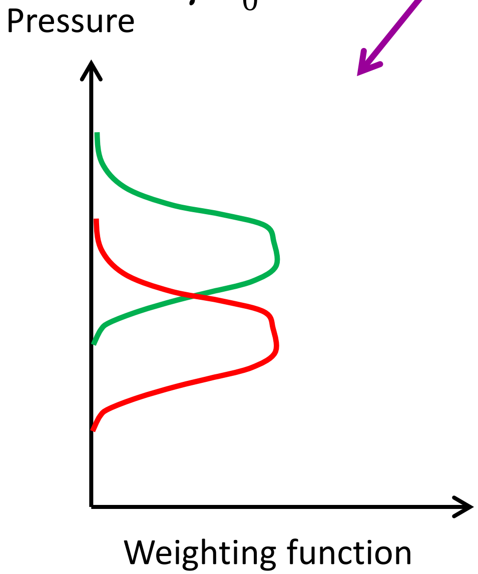

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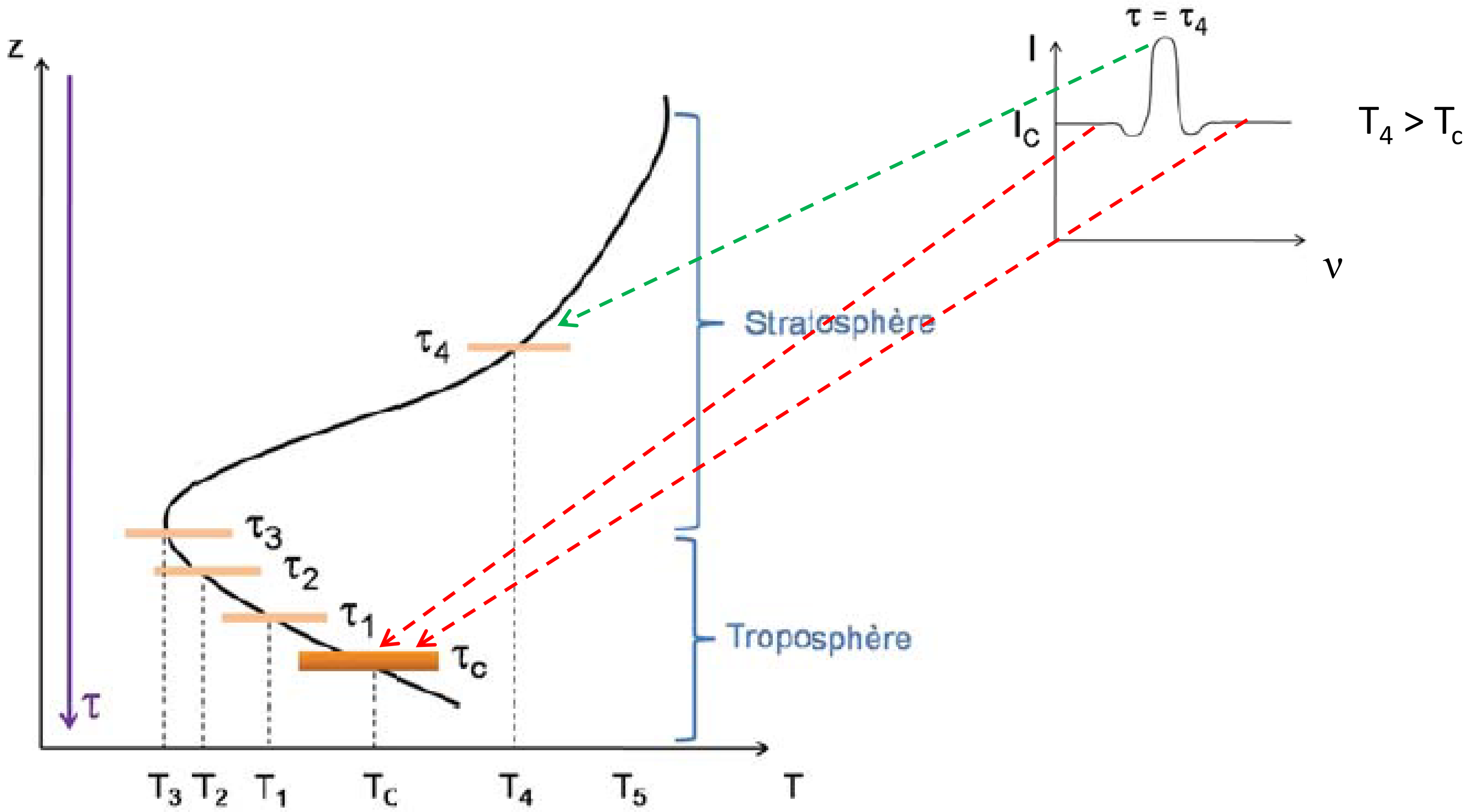
Introduction: line profile vs thermal profile



Region of positive thermal gradient => emission line

Region of negative thermal gradient => absorption line

If isothermal profile => no line

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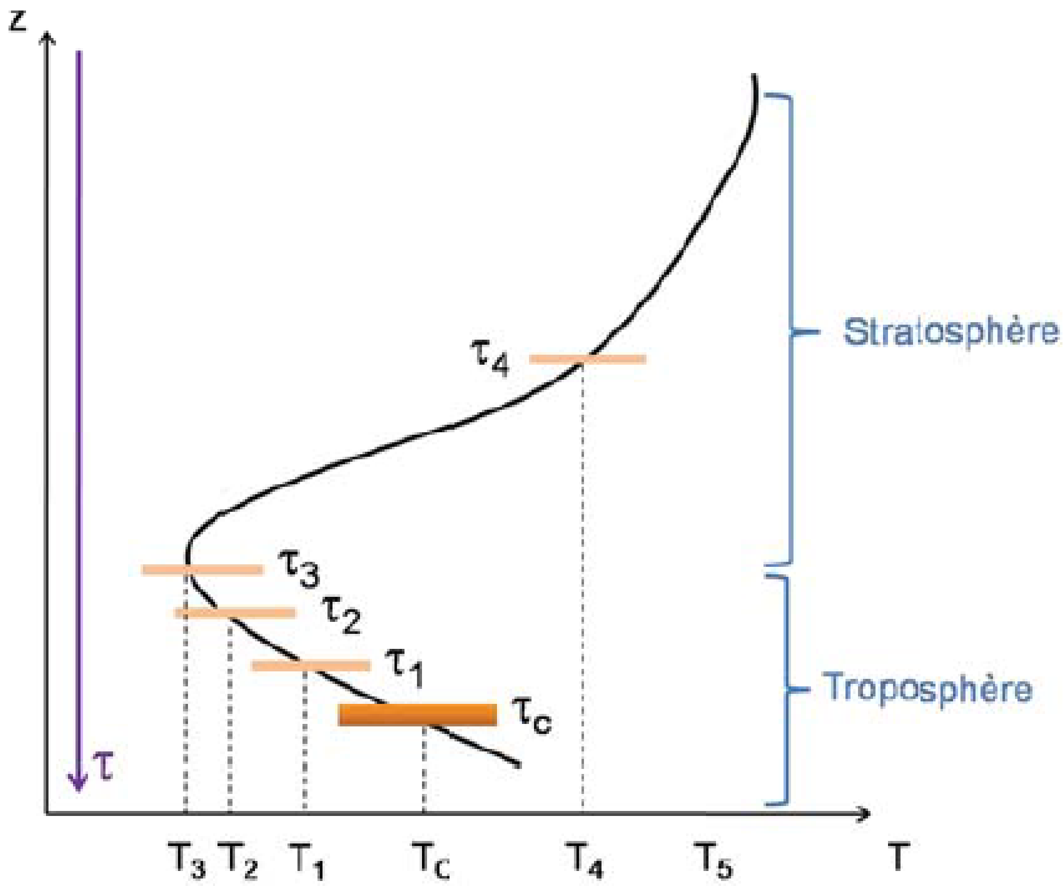

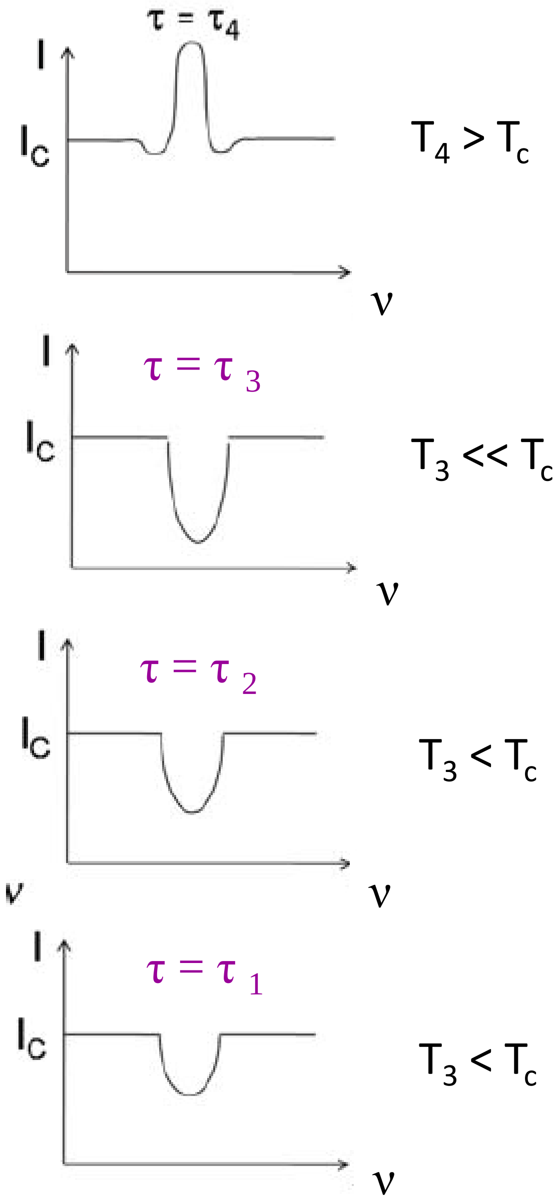

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Titan

Titan’s composition: an historical overview

- 1925: Jeans studied the atmospheric escape process => Titan should have kept an atmosphere.

→ gas of molecular weight ≥ 16 : possibly Ar, Ne, N_2, CH_4, NH_3 from thermodynamical theory

→ no H_2 and He because they are too light and should have escaped

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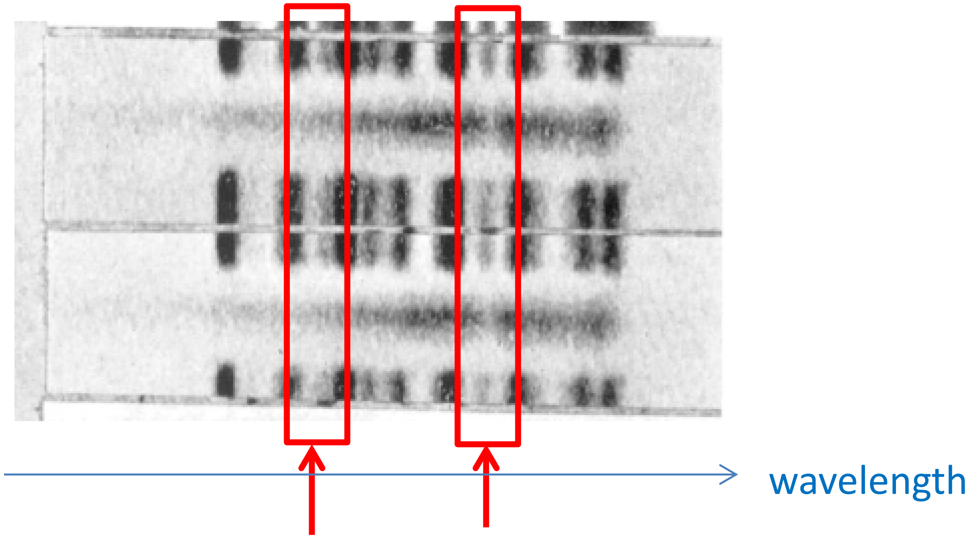
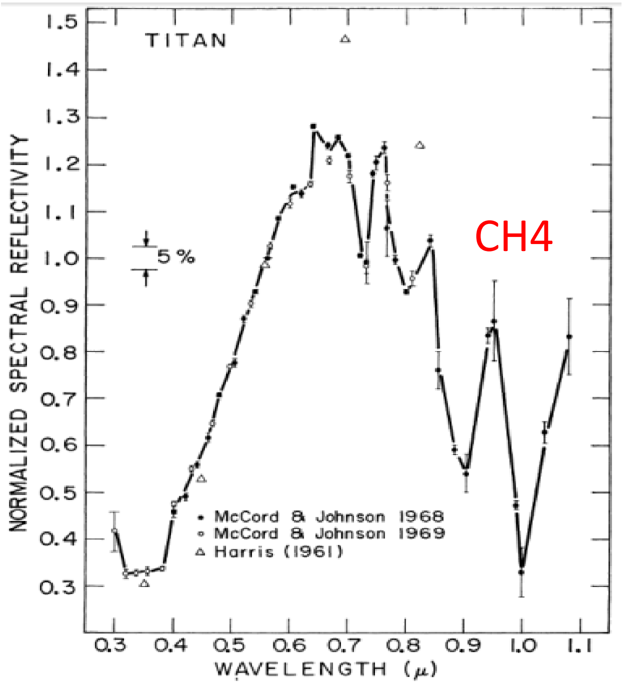
- 1944 : first detection of CH_4 (Kuiper, 1944)



Titan’s spectroscopy: reflected light

- 1961 – 1973 : UV ground-based observations (McCord et al. 1971) and space observations with the Orbiting Astronomical Observatory (Caldwell et al., 1973)



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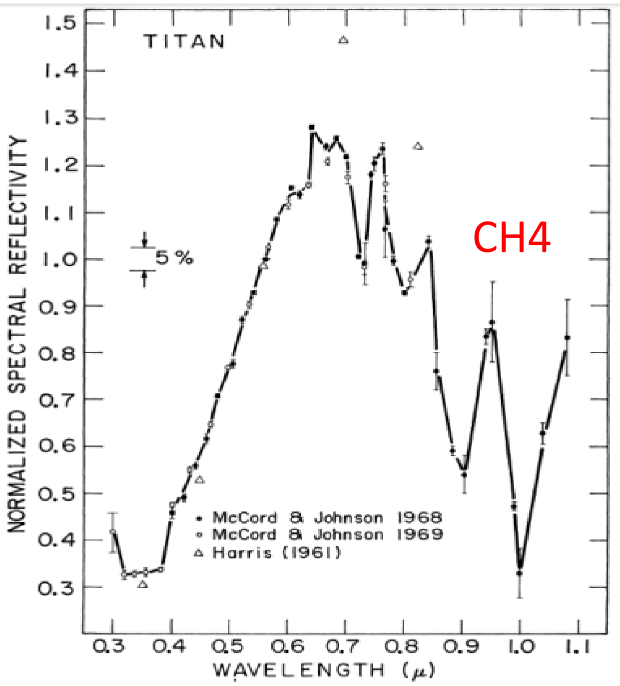
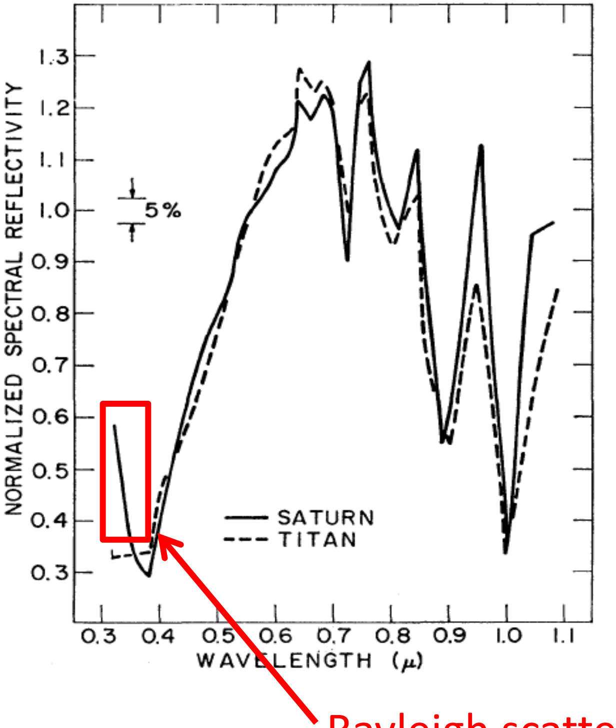


CH4



Rayleigh scattering

Very similar spectra for Titan and Saturn except in UV => 2 different models for Titan

- low density atmosphere => Rayleigh scattering is not efficient.

- Rayleigh scattering exists but is masked by an UV absorber = haze.

If an UV absorber exists = > deposition of energy at high altitude => T ↗ with height

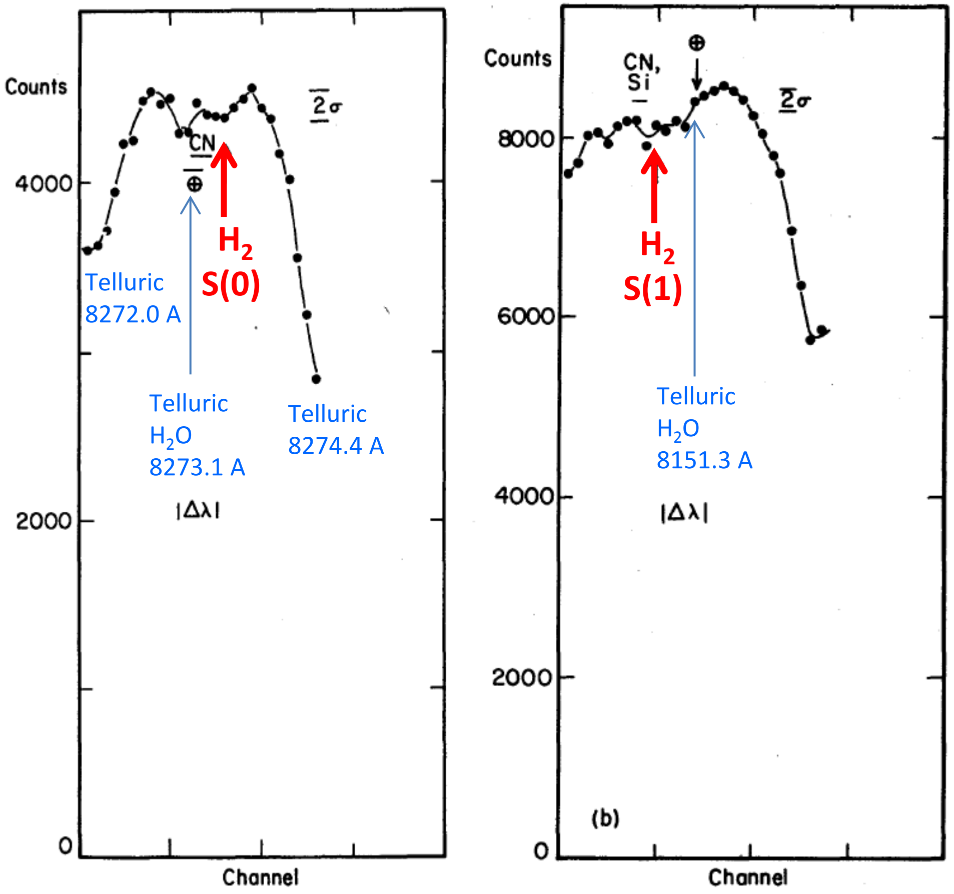
Titan’s spectroscopy: reflected light

- **Possible detection of H_2: unexpected from Jean’s escape calculations**

1972 : possible detection of H_2 by Trafton et al.
McDonald Observatory (2 m)

1975 : confirmation of the detection of the S(1) band by Trafton et al.

=> presence of another gas that would inhibit H_2 escape.



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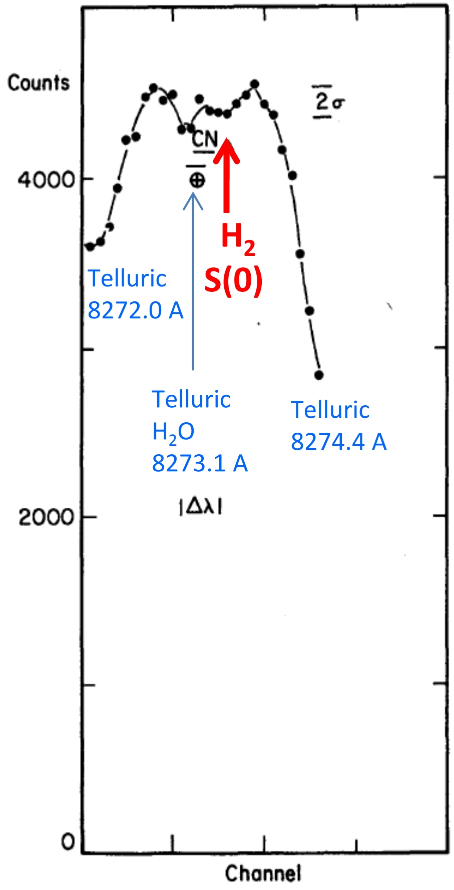

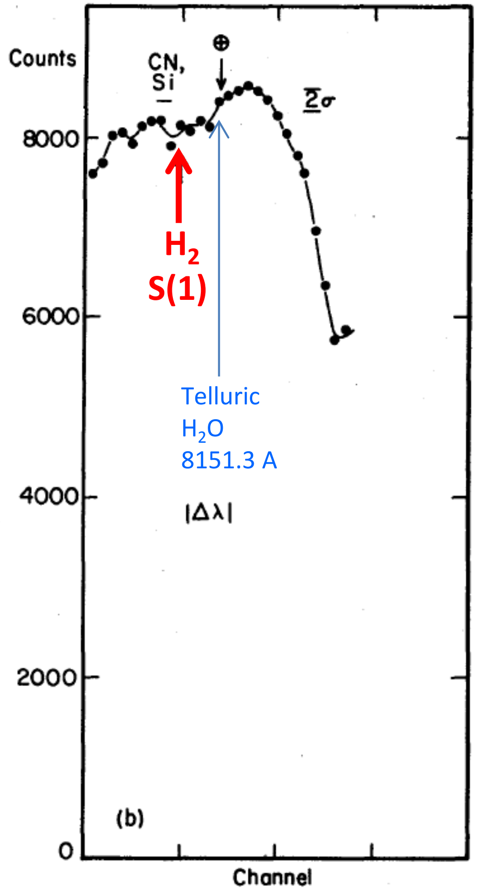

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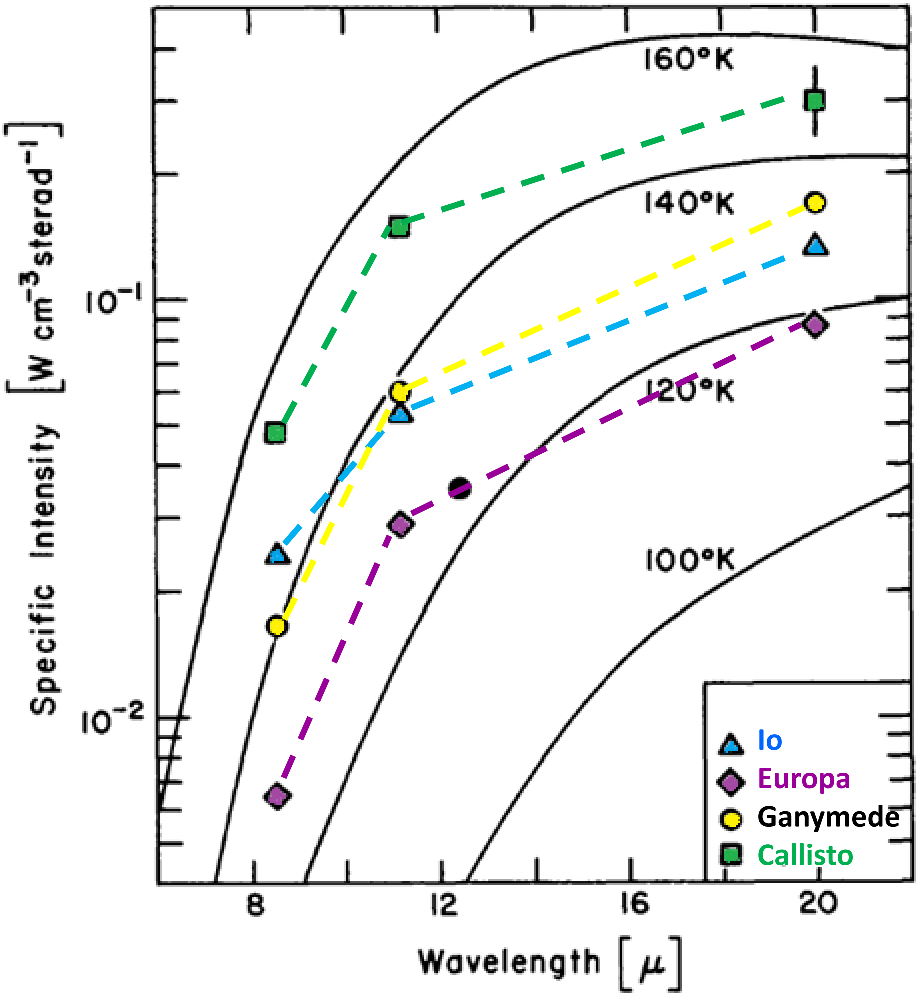
Rmq: In 1981, Trafton et al. mentioned that their 1972 and 1975 H_2 observations were mostly due to CH_4 .

Titan’s photometry: thermal emission (12 - 20 µm)



Jupiter satellites (no atmosphere) temperatures : close to BB emission (Gillet et al., 1970).

Titan : farther from the Sun, A_b= 0.29
=> Titan’s equilibrium temperature should be 82 K.

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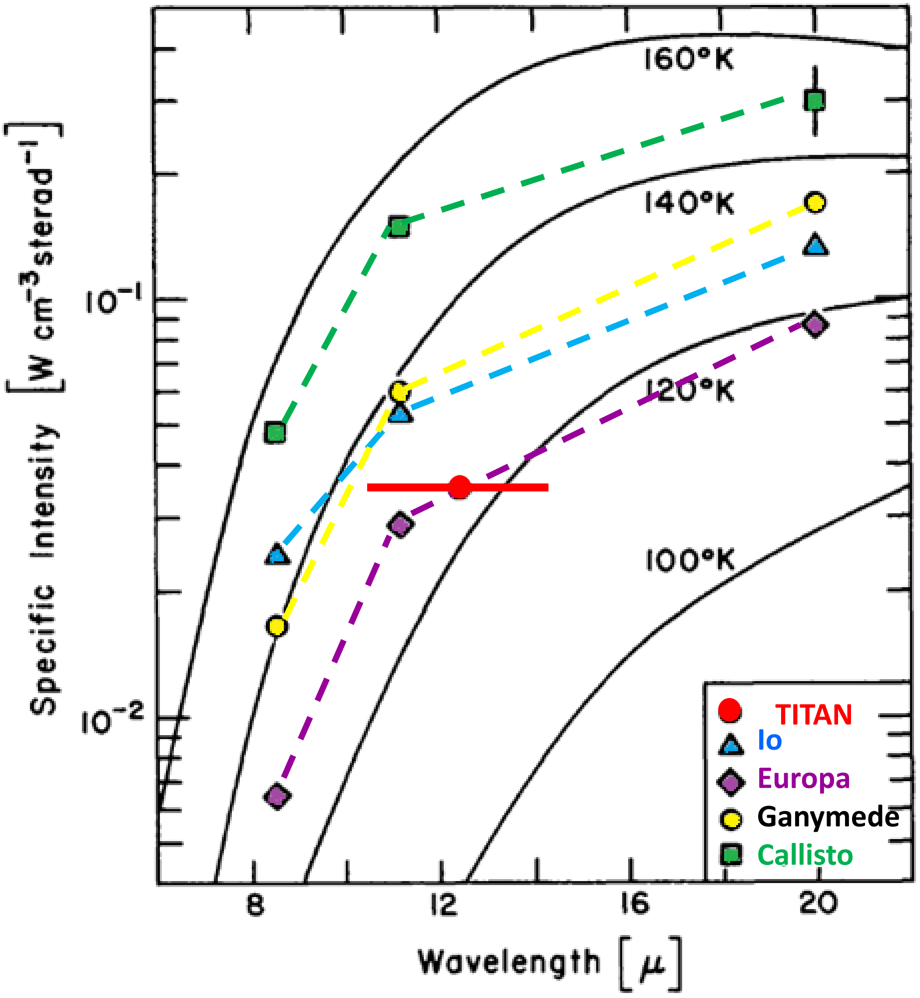

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used O’Brien Observatory (76 cm)
→ T_b = 125 ± 5 K (hyp: R_{Titan} = 2405 km)
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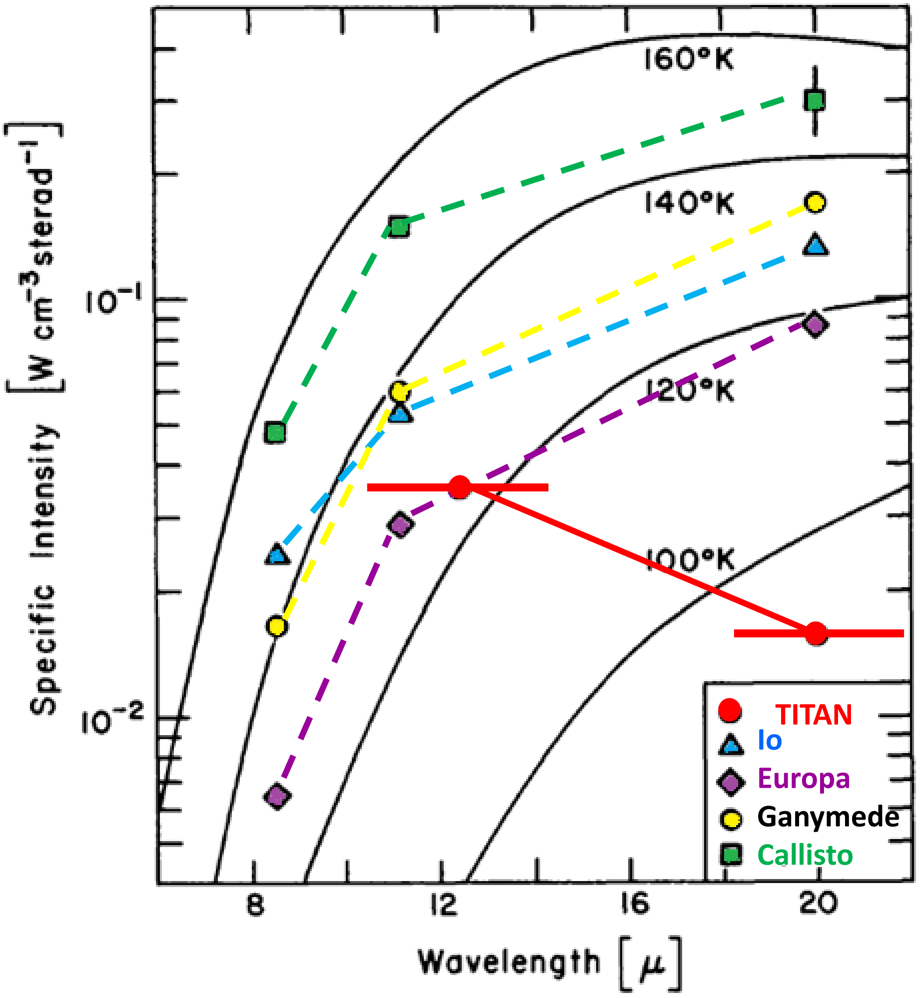

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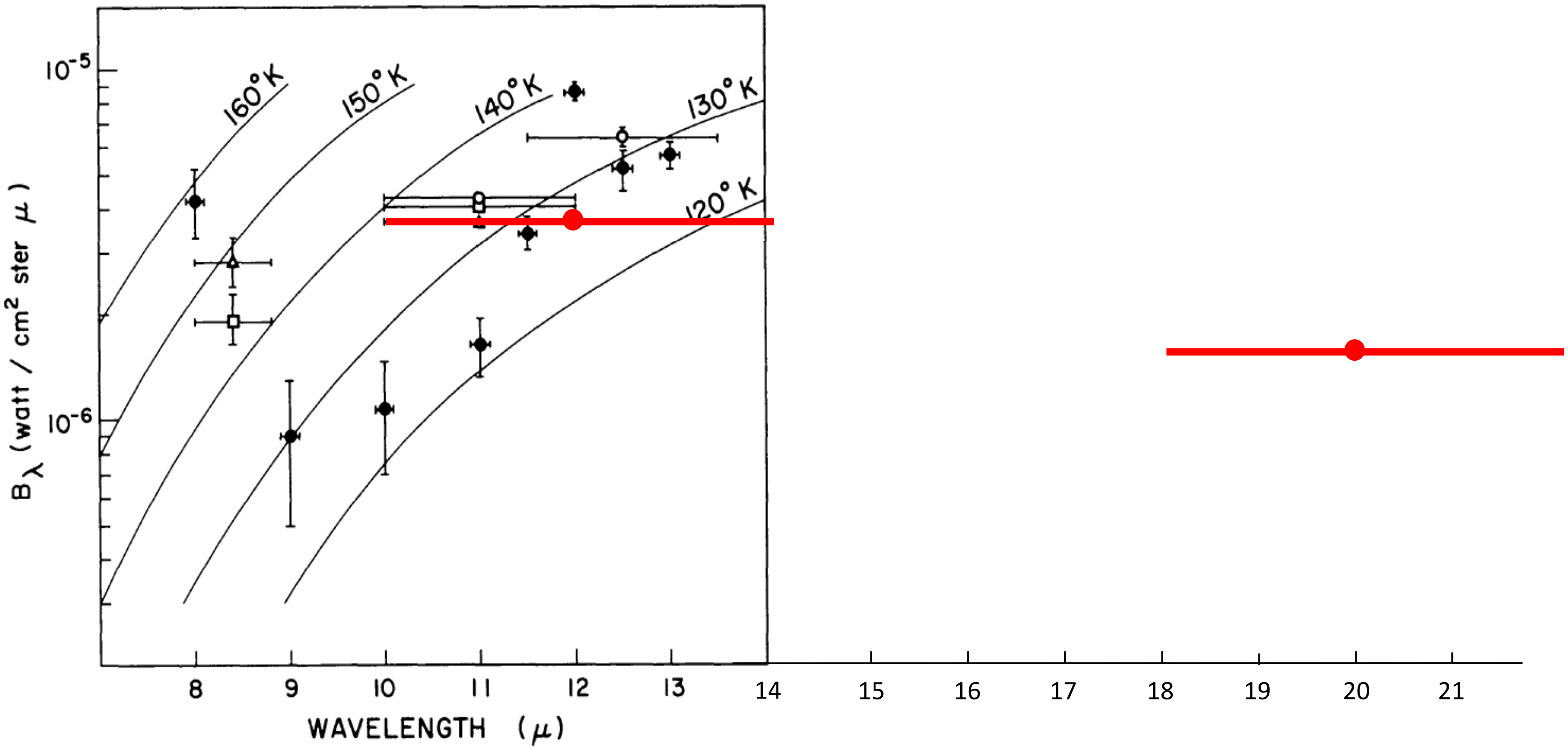
Titan at 20 µm (Morrison et al., 1972) :
Mauna Kea observatory (2.24 m).
interesting because = peak of the BB emission
→ T_b = 93 K, puzzling! (R_{Titan} = 2550 km)

2 possibilities : - surface emissivity is very low
- opacity of the atmosphere very high at 20 µm → possibly H_2 (collision induced), then the surface pressure should be ~1 atm

Titan’s spectroscopy: thermal emission (8 - 13 µm)



Gillet et al., (1973) : observations at Mount Lemmon (152 cm)

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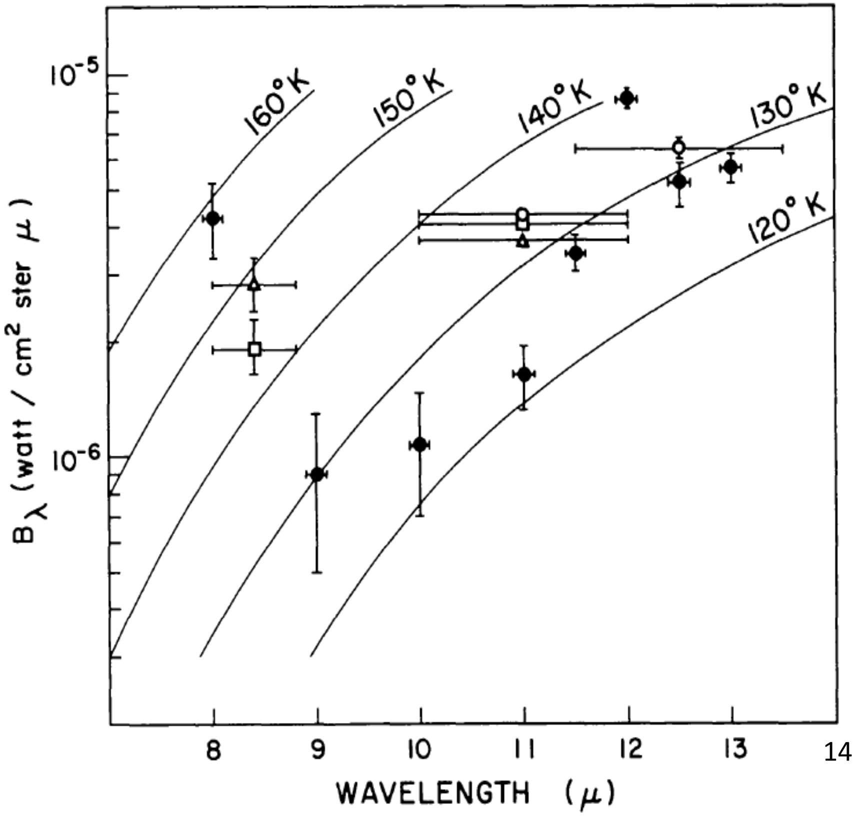


Gillet et al., (1973) : observations at Mount Lemmon (152 cm), assumed : R_{Titan} = 2440 km.

2 possible interpretations :

- If T ↘ with height => strong absorber around 10 µm : NH_3 (10.5 µm) ?

- If T ↗ with height => strong emission features in the 8 µm and 12.5 µm regions : CH_4 (7.7 µm), C_2H_6 (12.2 µm)

Need of a better spectral resolution

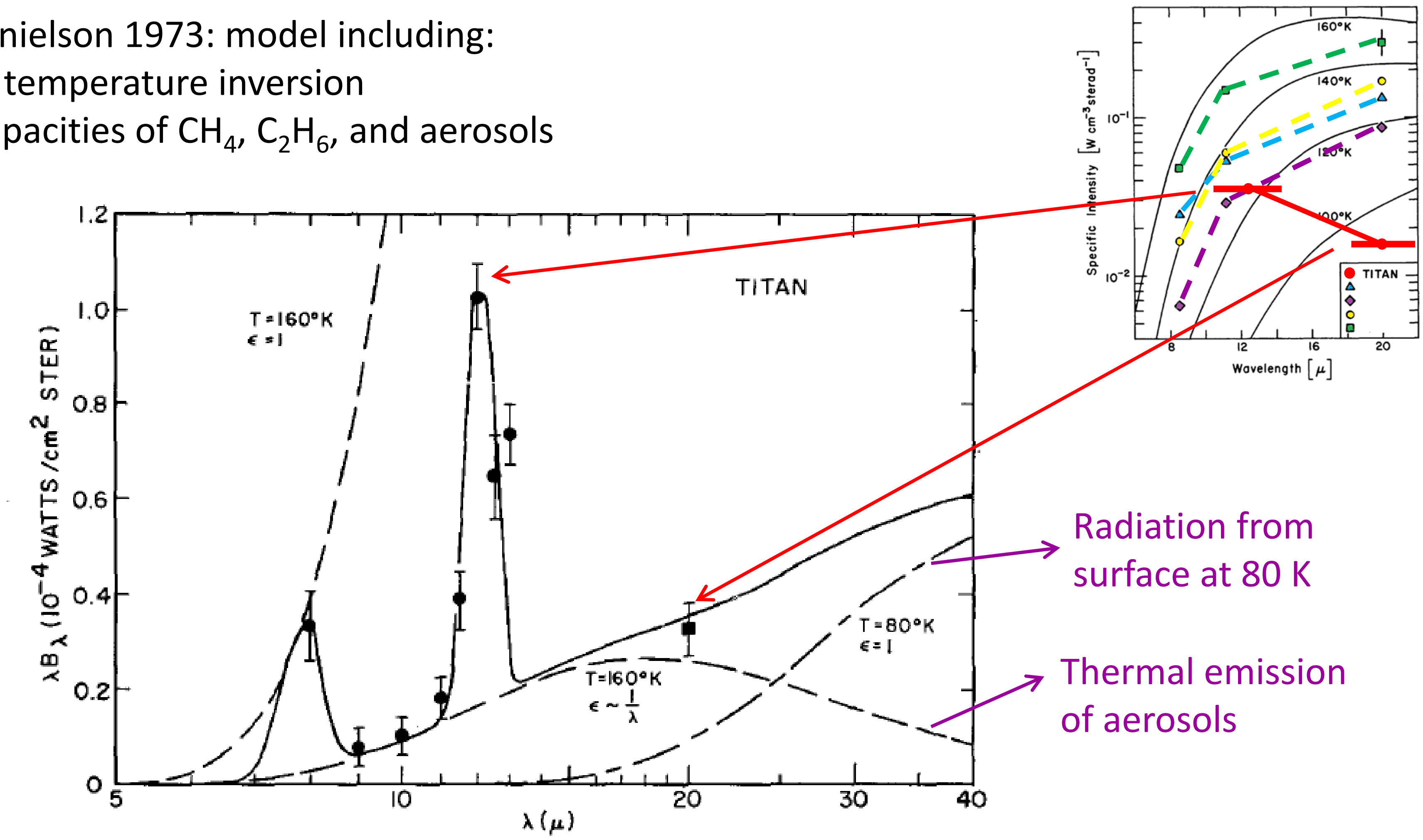
Titan’s atmosphere: the first models

- Greenhouse effect in a massive atmosphere (Pollack, 1973)
- Strong atmospheric inversion in a much less massive atmosphere (Danielson et al., 1973)
- Greenhouse effect + inversion (Low and Rieke, 1974)

- Photochemical models (Strobel, 1974)

Titan: confirmation of a temperature inversion

Danielson 1973: model including:
- a temperature inversion
- Opacities of CH_4, C_2H_6, and aerosols

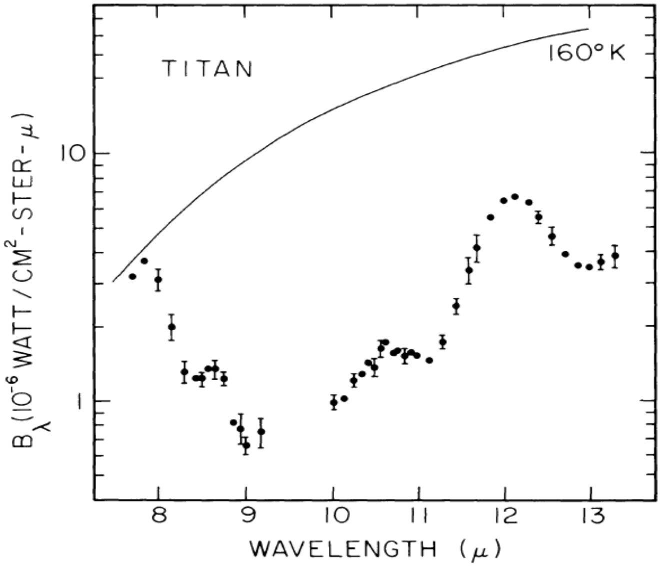


Radiation from surface at 80 K

Thermal emission of aerosols

Thermal emission of the UV-absorbing aerosols explain the observations at 10 and 20 µm.

Titan’s thermal emission (8-13 µm): a better resolution



Gillett et al, 1975: observations at Kitt Peak (2.1 m and 4 m), assumed : R_{Titan} = 2900 km.

They fitted the data with a model including a temperature inversion at 160 K (stratosphere)
- q_{C2H6} = 0.5 atm-cm
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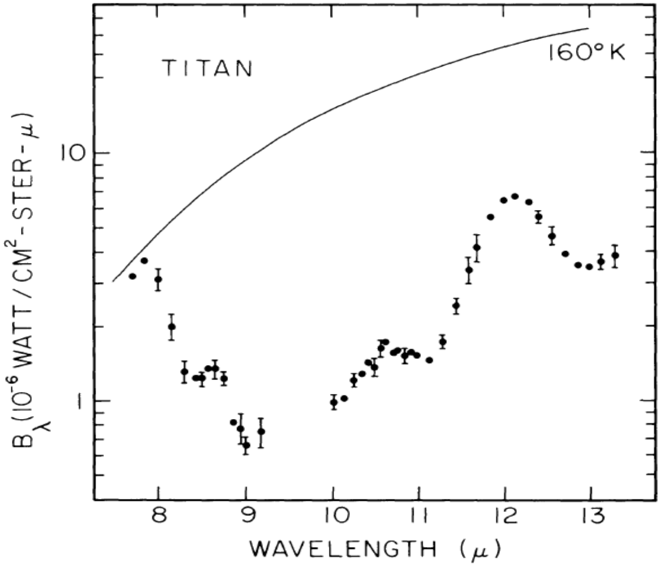

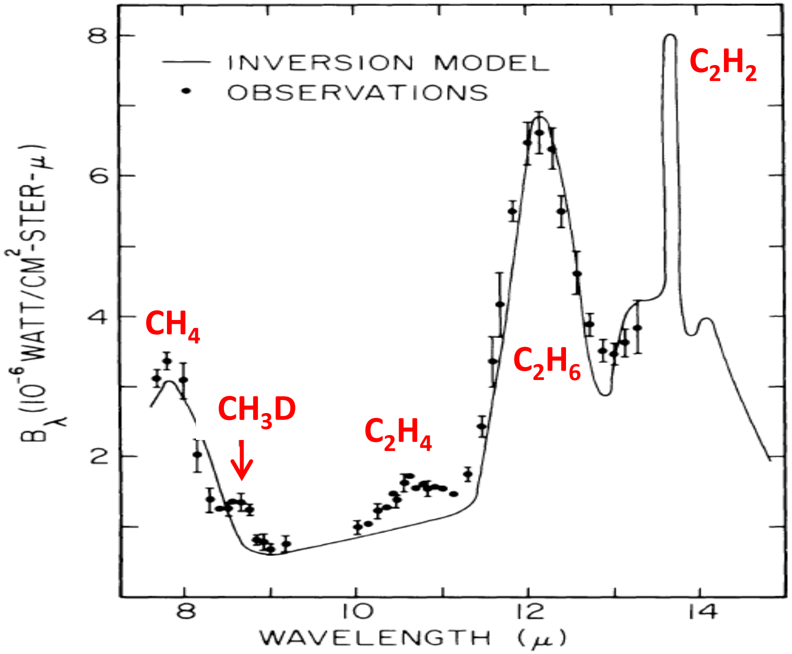

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- q_{C2H4} = 0.002 atm-cm (in agreement with photochemical model)
- q_{CH3D} ~ 0.5 atm-cm

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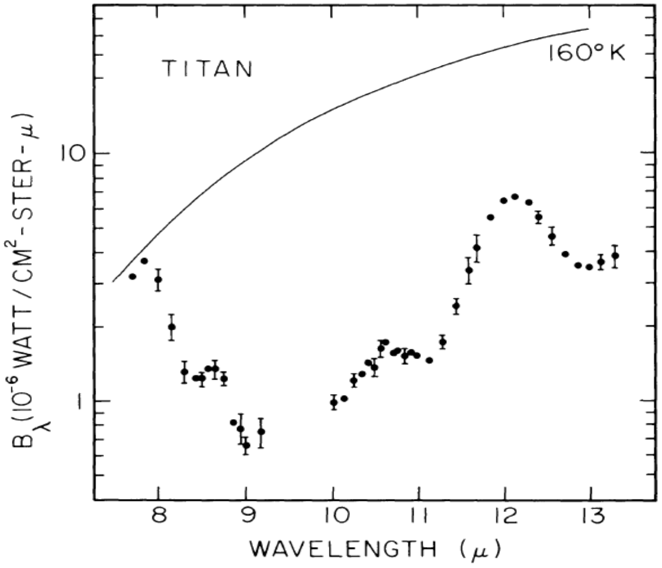

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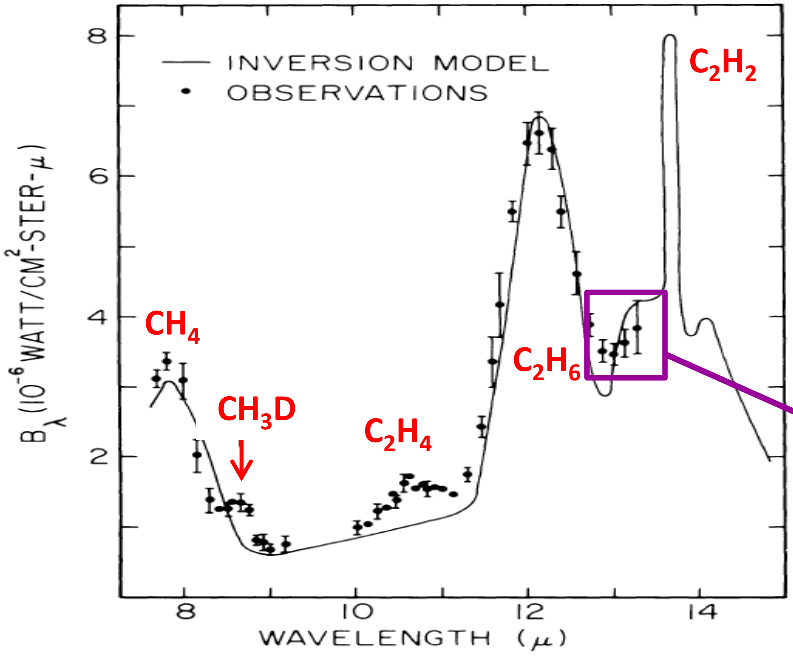

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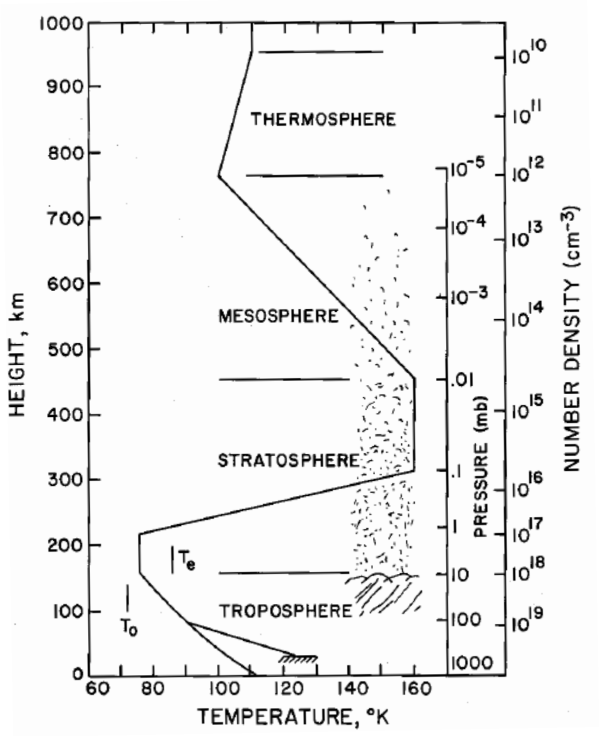
Increase towards higher wavelength
-> suggest C_2H_2, needed confirmation.

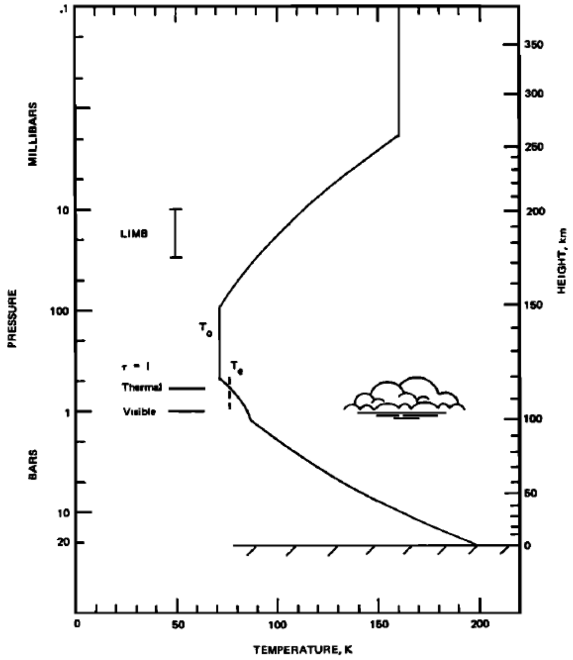
Titan's thermal profiles: models

- atmosphere of CH_4 in equilibrium with a solid CH_4 surface with T_{surf} = 86 K and P_{surf} = 20 mbar (Calwell, 1978).
- atmosphere of N_2 (CH_4 = minor constituent) with T_{surf} = 200 K and P_{surf} = 20 bars (Hunten, 1978) = greenhouse model due to pressure-induced absorption in N_2.

Atmosphere of CH_4, m=16



Atmosphere of N_2, m=28



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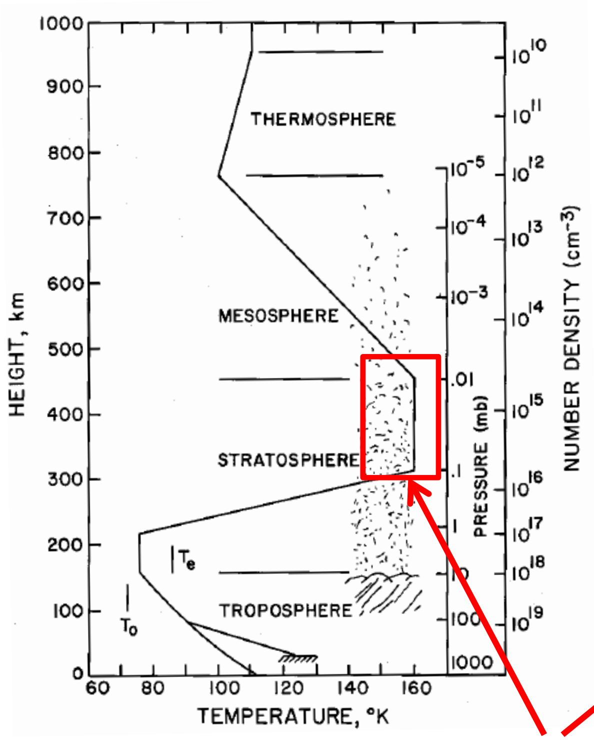

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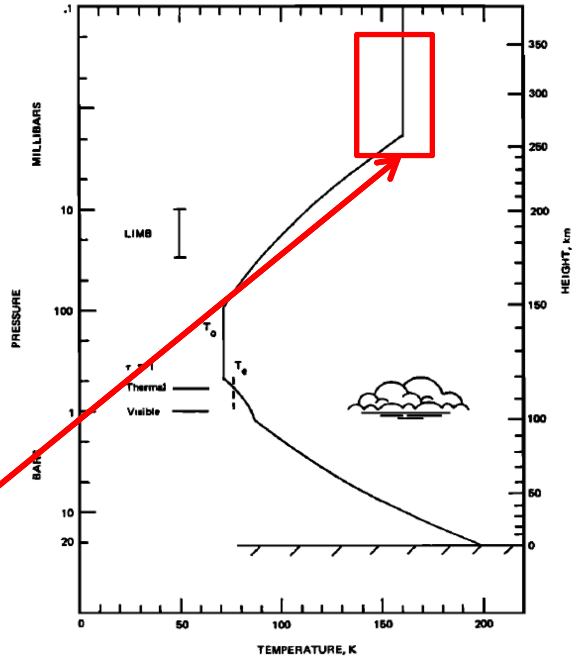


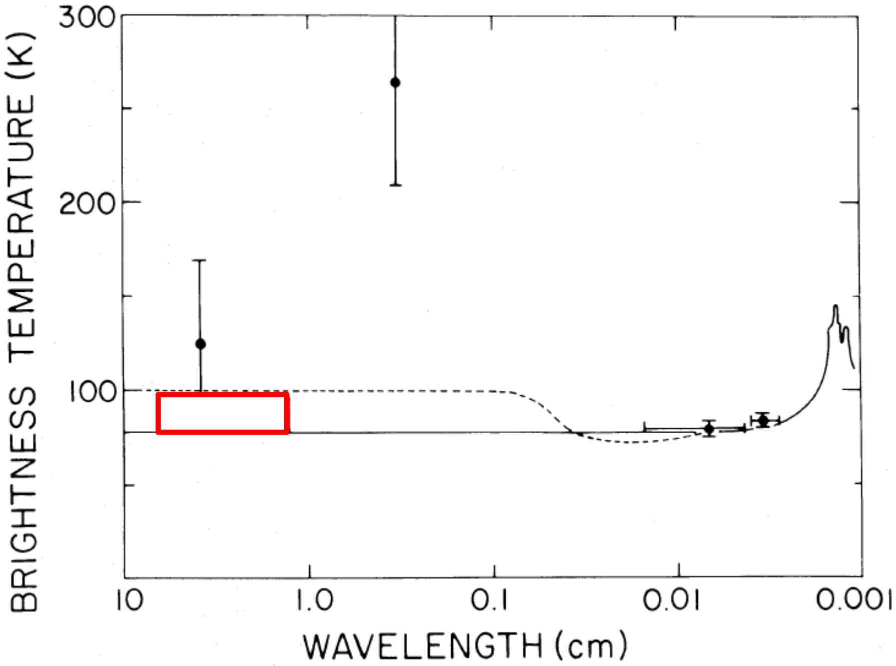
Consensus: T inversion with ~160 K (from the thermal emission of CH_4 at 7.7 µm)

Titan in far IR (0.3- 6 cm): surface temperature

Radio wavelength -> no gas absorption in this spectral region, except NH_3, but was not detected in Titan's atmosphere => should probe the surface temperature

- Jaffe et al., 1980 : observation with the VLA (interferometer) at 1.3, 2 and 6 cm.

-> derived $T_b = 87 \pm 9$ K



Knowledge on Titan's atmosphere before space probes

- Molecular gas detected : CH_4, C_2H_6, C_2H_2, CH_3D, C_2H_4 and maybe H_2
  -> poor constrains of their column densities.
- Aerosols absorbing in UV => heating of the stratosphere = temperature inversion.
- Thermal emission of CH_4 at 7.7 µm => stratosphere temperature = 160 K.
- Cold surface temperature < 100 K.

Uncertainty on the main composition:

- atmosphere of CH_4
- atmosphere of N_2 (CH_4 = minor constituent)

Some photochemical models => based on CH_4 + H_2 photochemistry

Titan’s atmosphere derived from Voyager 1 & 2 (1980, 1981)

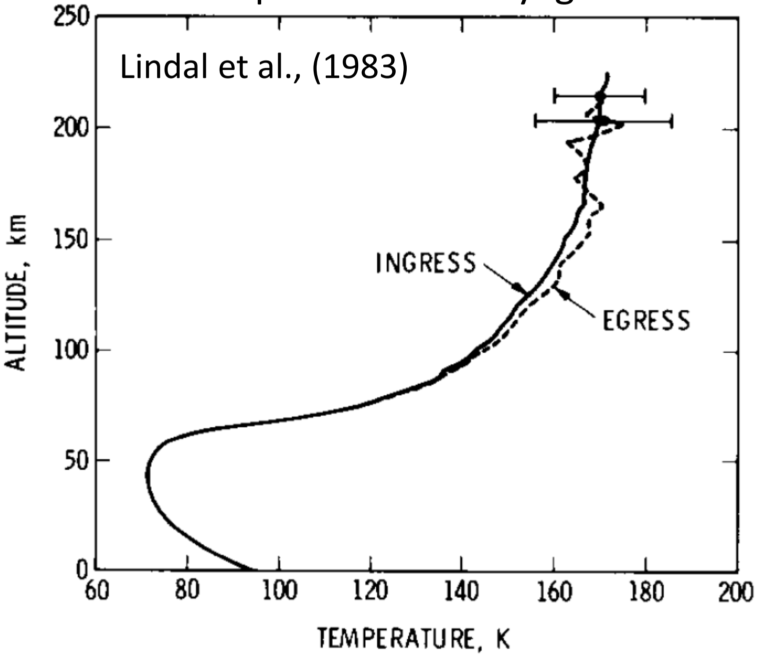
Thermal profile

Inferred from radio occultation measurements (Lindal et al., 1983)

- Radio occultation measurements => T/m profile
- Mid-IR spectrometry at 540 cm^{-1} => T_{surf} = 94-97 K

m ~ 28 amu => atmosphere of N_2 or CO

T profile from Voyager



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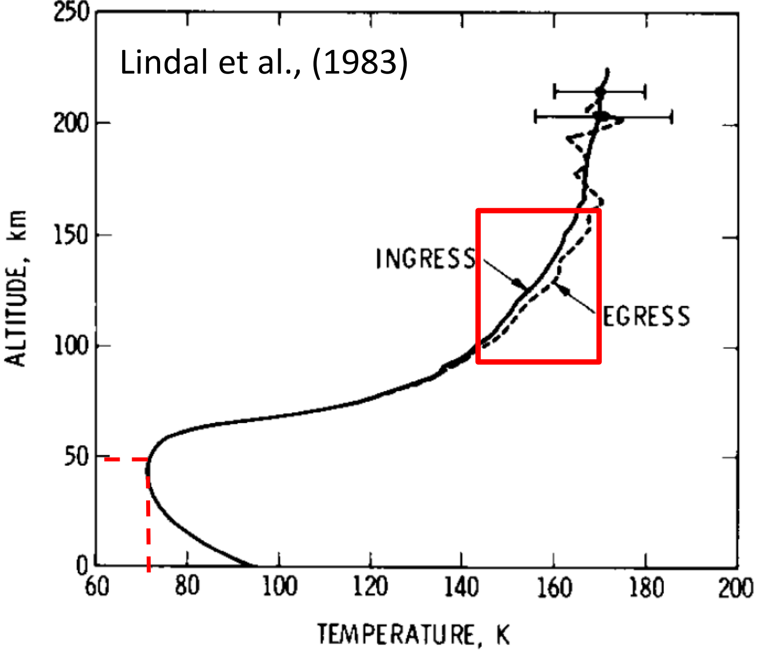
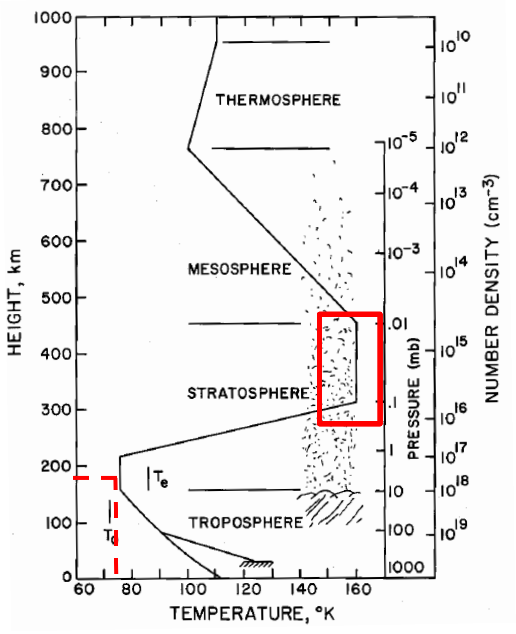

Lindal et al., (1983)

Before Voyager (Hunten, 1978)



The predicted surface and tropopause temperature were close to the Voyager observations.
The tropopause was thought to be 150 km higher than observed.
Stratospheric temperature were correct.

Titan’s atmosphere derived from Voyager 1 & 2 (1980, 1981)

- **Composition**

- **UVS solar occultations and airglow measurements**: emission lines of N and N_2
  => N_2 is the major component (82-95 %)
  => CH_4 is a minor constituent (6% varying with altitude)

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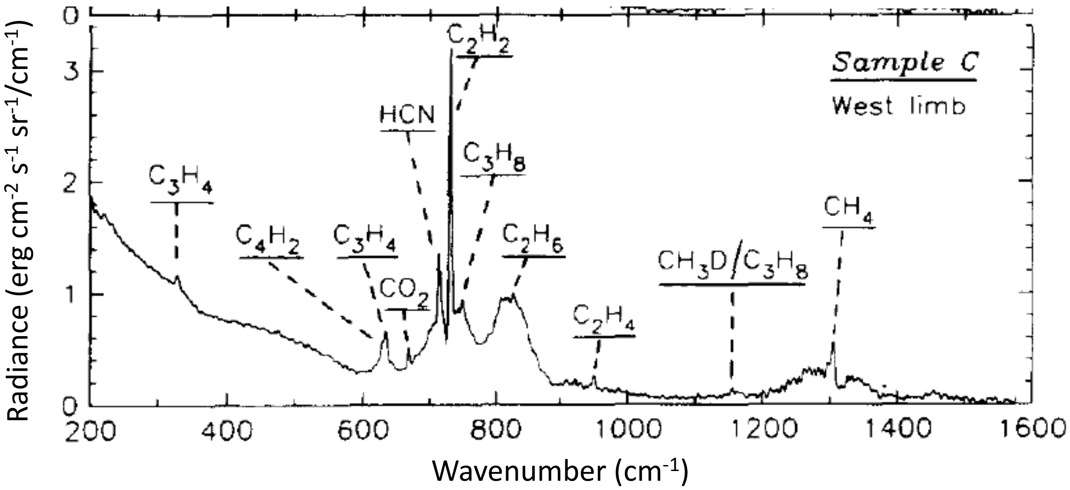
- **Thermal emission in mid-IR**

- In the deep atmosphere (troposphere) : detection of N_2, CH_4 and H_2 (collision-induced absorption)

- In the stratosphere, detection of the emission bands of:
hydrocarbons: CH_4, CH_3D, C_2H_2, C_2H_6, C_2H_4, C_3H_8, CH_3C_2H, C_4H_2
nitriles: HCN, HC_3N, C_2N_2
oxygen compound: CO_2

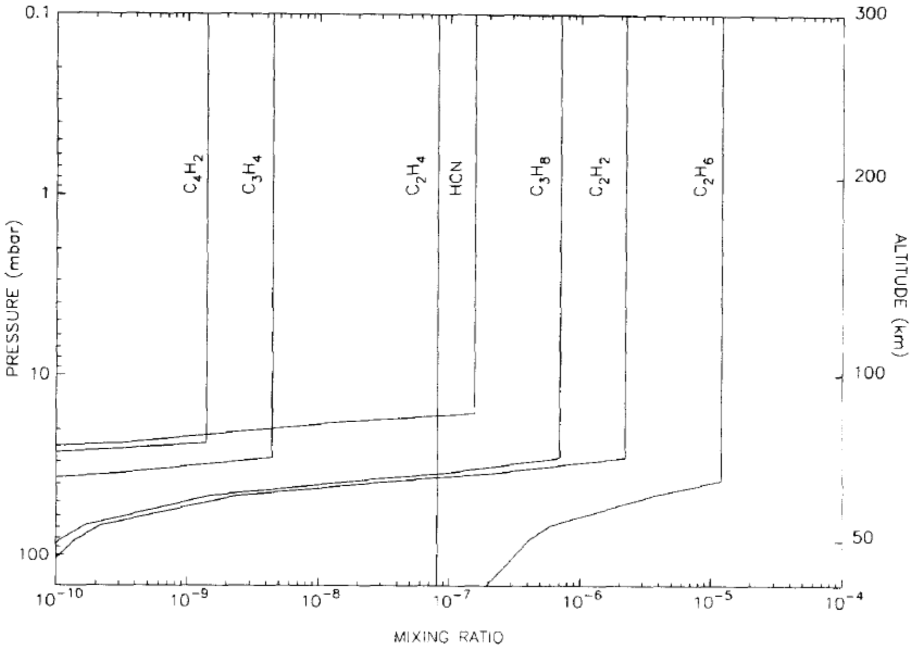
Coustenis et al., (1989)



Titan’s atmosphere derived from Voyager 1 & 2 (1980, 1981)

- **Composition**

As the thermal profile was known => constrains of the molecular abundances with radiative transfer models.
But nadir observations => no vertical resolution



1995 : first General Circulation Model of Titan’s atmosphere => explanation of the spatial distribution of molecules

After Voyager: ground-based observations

- **Observation in near IR**

- 1983: CO detection at 4.5 µm, $q_{CO} = 6 \times 10^{-5}$ (Lutz et al 1983)

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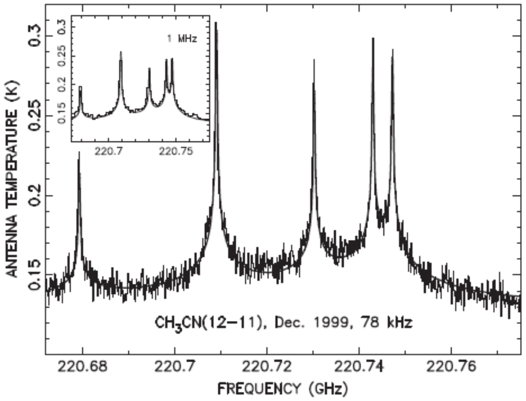
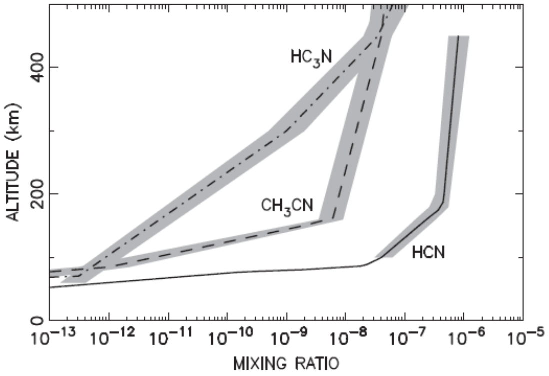
- **Observations in mm/submm : very high resolution**

- Detection of CH_3CN
- Vertical profiles of nitriles outside the Voyager range (from the line profile)
- $^{15}N/^{14}N$ in HCN, $^{18}O/^{16}O$ in CO
- Wind speed from the Doppler shifts of the lines .





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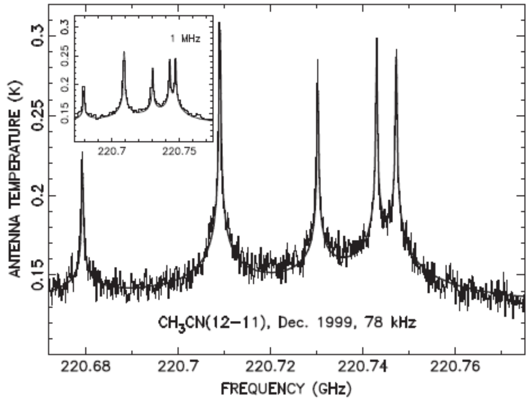
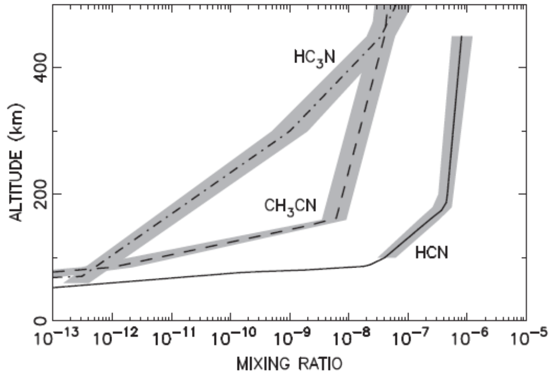


- **Observations in mm/submm : very high resolution**

- Detection of CH_3CN
- Vertical profiles of nitriles outside the Voyager range (from the line profile)
- $^{15}N/^{14}N$ in HCN, $^{18}O/^{16}O$ in CO
- Wind speed from the Doppler shifts of the lines



- **Observations in infrared**

- High resolution ground based observations:

-> thermal profile from CH_4 lines at 7.7 µm in the 300-600 km range (higher than Voyager)

-> wind velocity from Doppler shift from C_2H_6 lines at 12 µm

After Voyager: ground-based observations

- **Observation in near IR**

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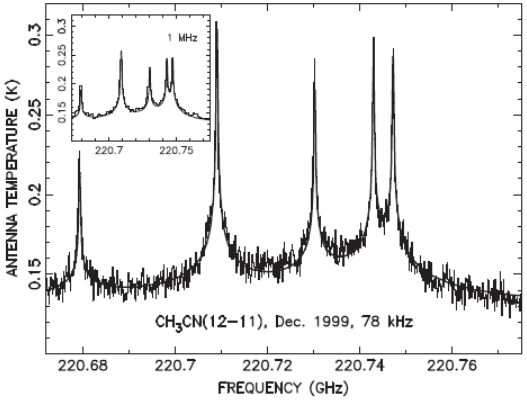

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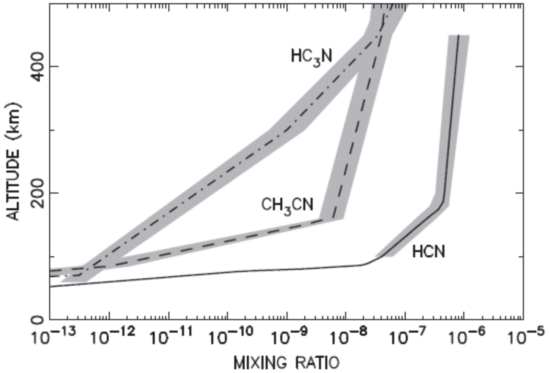


- **Space observations (ISO)**

detection of H_2O and C_6H_6 (Coustenis et al., 1998, 2003).

Titan’s composition: before and after space probes

	Before Voyager	Voyager	Ground/satellites	Cassini
CH_4	1 - 2 km. Am			
H_2	< 2 km.Am			
C_2H_2	1 cm. Am			
C_2H_6	0.5 cm. Am			
C_2H_4	$2. 10^{-3}$ cm.Am			
C_3H_8				
CH_3C_2H				
HCN				
HC_3N				
CH_3CN				
CO_2				
CO				
H_2O				
C_6H_6				

- the main component was unknown
$\Rightarrow$ impossible to infer abundances
- the level probed for each molecule is unknown:
column density ratio ≠ abundances ratio

Before Voyager : only column densities inferred for CH_4, H_2, C_2H_2, C_2H_6 and C_2H_4.
Coupling between T and composition -> importance of the thermal profile observed with Voyager

Titan’s composition: before and after space probes

	“Before” Voyager (a)	Voyager	Ground/satellites	Cassini
CH_4	1.3-2.6 %	6% (alt. var.)		4.9% surf, 1.48% atm.
H_2	< 2.6 %	0.2 %		0.1 %
C_2H_2	1×10^{-5}	2.2×10^{-6}	5.5×10^{-6} (ISO)	2.0×10^{-6}
C_2H_6	2×10^{-6}	1.3×10^{-5}	2.0×10^{-5} (ISO)	1.0×10^{-5}
C_2H_4	3×10^{-10}	$9 \pm 5 \times 10^{-8}$	1.2×10^{-7} (ISO)	1.0×10^{-7} (alt. var.)
C_3H_8				
CH_3C_2H				
HCN				
HC_3N				
CH_3CN				
CO_2				
CO				
H_2O				
C_6H_6				

(a)Derived from column densities and Voyager results

Before Voyager : only column densities inferred for CH_4, H_2, C_2H_2, C_2H_6 and C_2H_4.
coupling between T and composition -> importance of the thermal profile observed with Voyager .
After Voyager: very good constraints because the T profile was known from Voyager

Titan’s composition: before and after space probes

	“Before” Voyager [a]	Voyager	Ground/satellites	Cassini
CH_4	1.3-2.6 %	6% (alt. var.)		4.9% surf, 1.48% atm.
H_2	< 2.6 %	0.2 %		0.1 %
C_2H_2	1 x 10^{-5}	2.2 x 10^{-6}	5.5 x 10^{-6} (ISO)	2.0 x 10^{-6}
C_2H_6	2 x 10^{-6}	1.3 x 10^{-5}	2.0 x 10^{-5} (ISO)	1.0 x 10^{-5}
C_2H_4	3 x 10^{-10}	9 ± 5 x 10^{-8}	1.2 x 10^{-7} (ISO)	1.0 x 10^{-7} (alt. var.)
C_3H_8	-	7± 4 x 10^{-7}	2 x 10^{-7} (ISO)	1.0 x 10^{-7}
CH_3C_2H	-	4 ± 2 x 10^{-9}	1.2 x 10^{-8} (ISO)	8 x 10^{-9}
HCN	-	1.6 x 10^{-7}	5 x 10^{-7} (alt. var.)	1 x 10^{-7}
HC_3N	-	< 1.5 x 10^{-9}	10^{-12} -10^{-8} (alt.var.)	1 x 10^{-9}
CH_3CN	-	-	1 x 10^{-8} (alt. var.)	-
CO_2	-	1.4 x 10^{-8}	2.0 x 10^{-8} (ISO)	1.6 x 10^{-8}
CO	-	-	6 x 10^{-5} (near IR)	4.7 x 10^{-5}
H_2O	-	-	8 ± 5 x 10^{-9} (ISO)	4 x 10^{-10}
C_6H_6	-	-	4 x 10^{-10} (ISO)	4 x 10^{-10}

(a)Derived from column densities and Voyager results

Before Voyager : only column densities inferred for CH_4, H_2, C_2H_2, C_2H_6 and C_2H_4.
coupling between T and composition -> importance of the thermal profile observed with Voyager .

After Voyager: very good constraints because the T profile was known from Voyager

Saturn

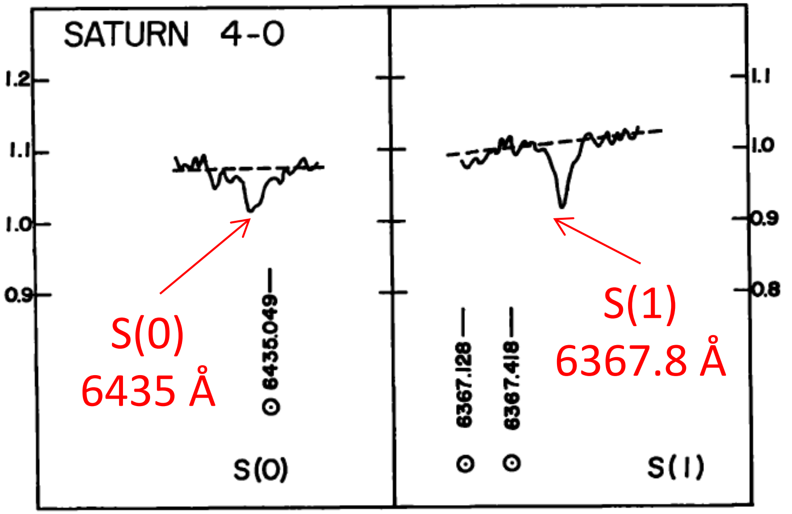
Saturn’s composition: before space probes flybys

- 1932: identification of CH_4 and NH_3

- 1962: first observation of H_2 from S(1) and S(0) lines in the (4-0) band (Spinrad et al., 1962)

From the line width:

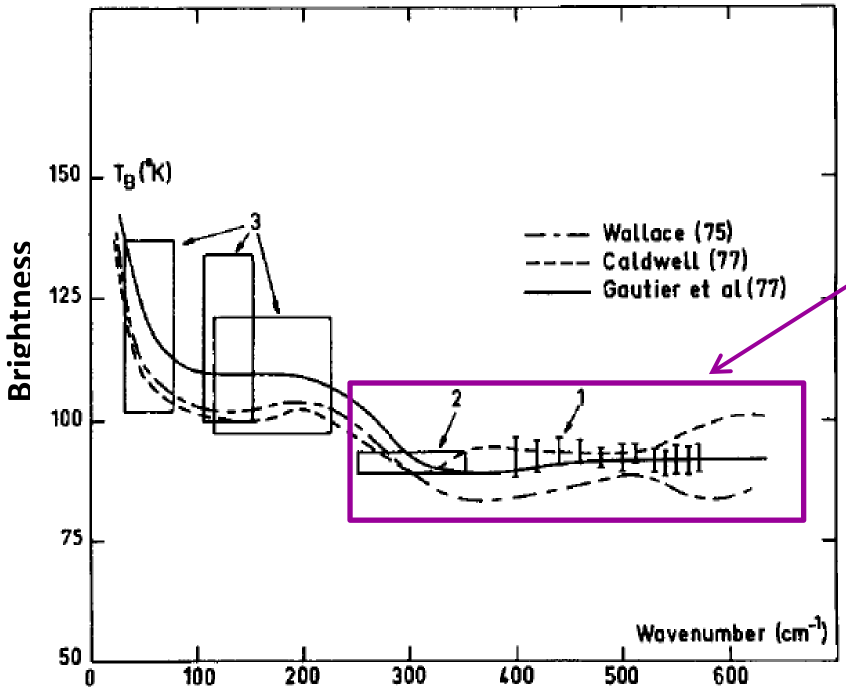
a_{H2}= 76±20 km.Am (encrenaz 1973)



H_2 detection by Encrenaz et al., 1973

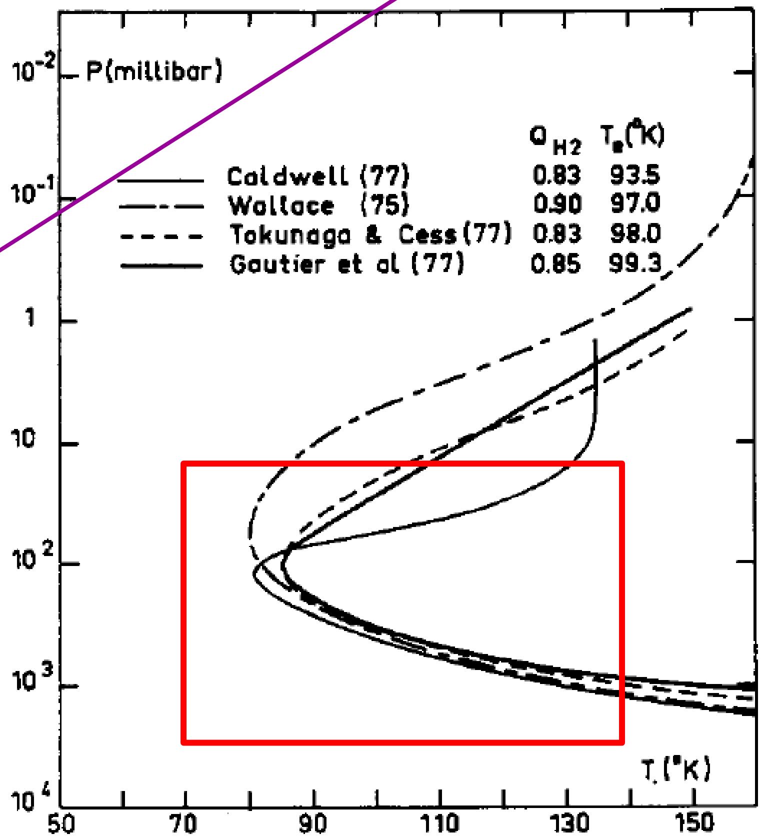
Saturn’s thermal profile before space probes flybys

Fit of the H_2-H_2 and H_2-He collision-induced absorption between 250 and 800 cm^{-1} (40-12 µm) => constraints of T in the deep atmosphere



Gautier et al. 1977

q_{H2} = 0.7, 0.85, 1.0

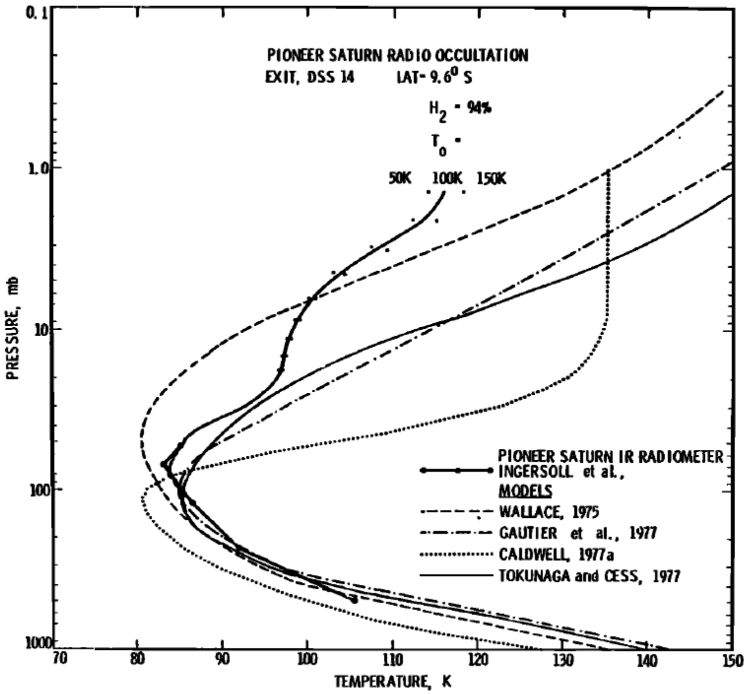


But the equilibrium temperature of Saturn should be 75 K (including ring shadowing)

⇒ Internal source of heating

Saturn’s temperature: comparison with probes results

Pioneer flyby (Sept. 1979)



Saturn’s temperature: comparison with probes results

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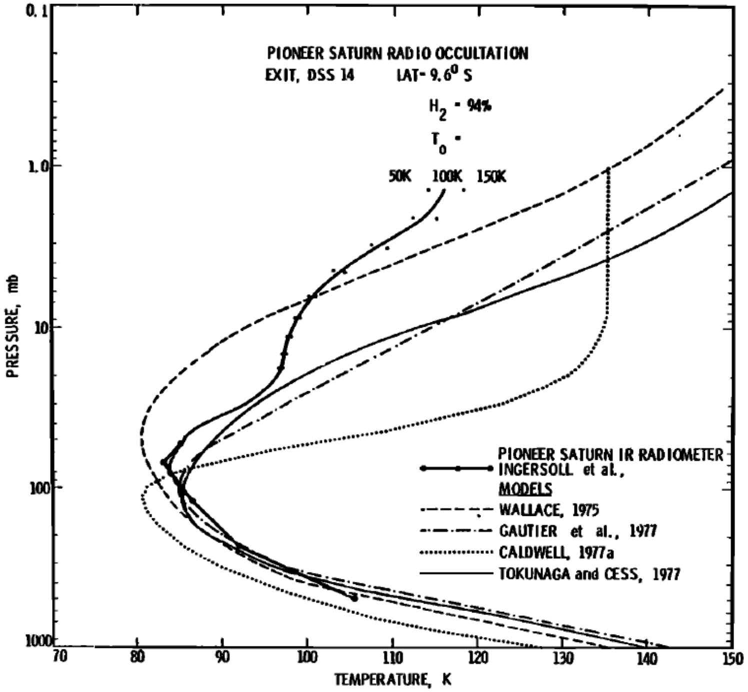
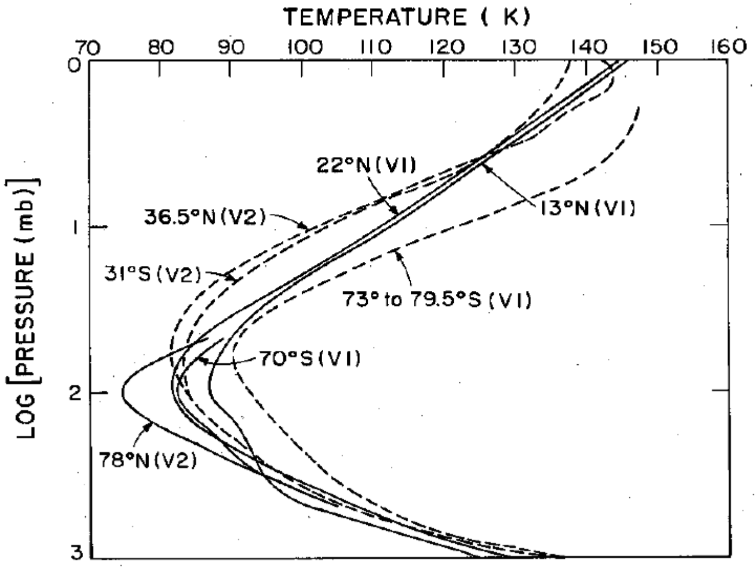


Voyager 1 (V1) and Voyager 2 (V2) flybys

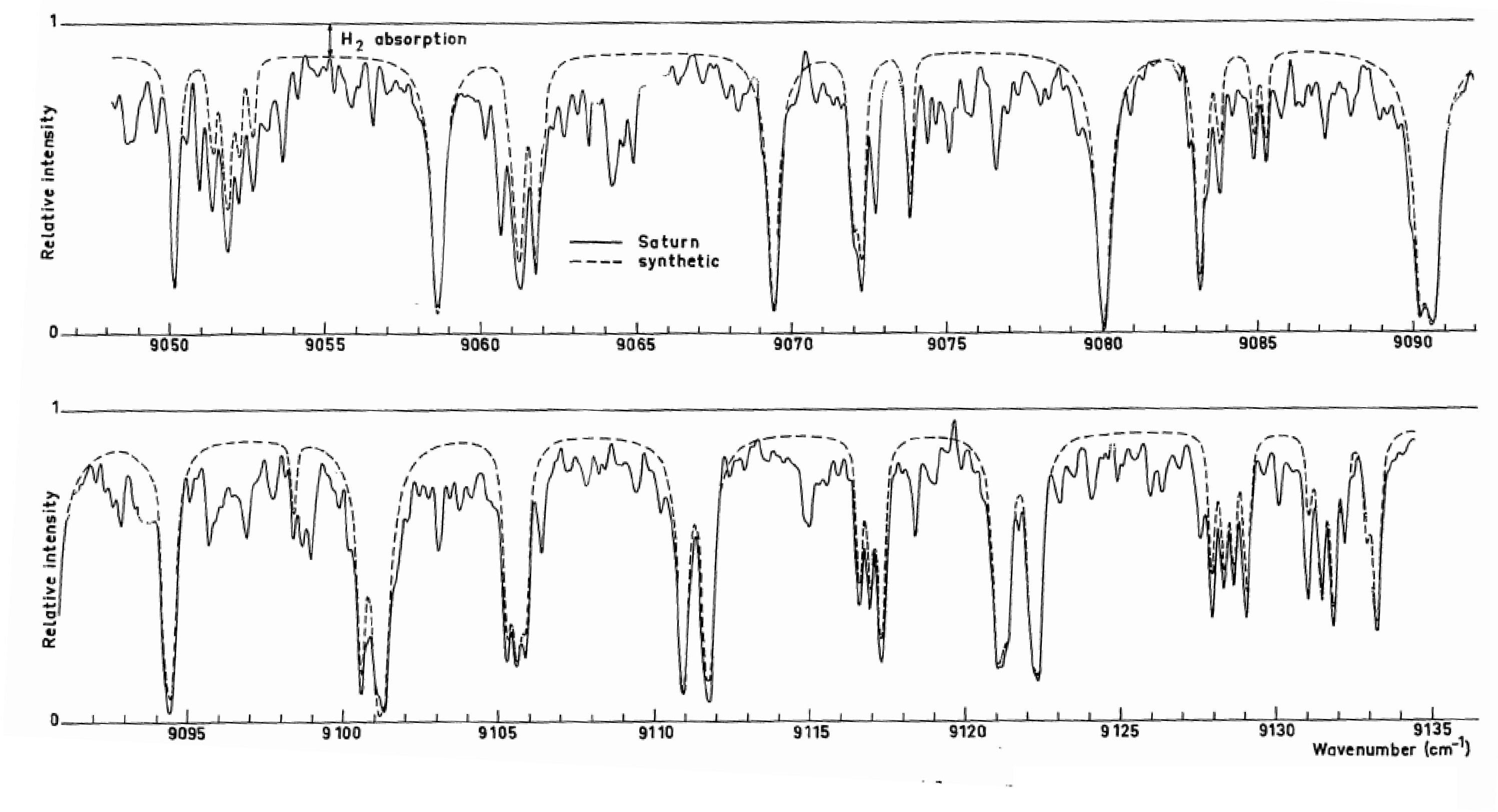


Good constraints on the deep thermal profile from H_2-H_2 and H_2-He collision-induced absorption spectrum

-> independent from the “insitu” spacecraft measurements

Saturn’s composition: constraints before the probes

- **Case of CH_4 and H_2** from the $3\nu_3$ CH_4 band (0.83 - 1.67 µm) -> many CH_4 lines over a continuum due to H_2 pressure-induced absorption



Buriez and deBergh (1981)
=> $CH_4/H_2 = (4 \pm 2).10^{-3}$

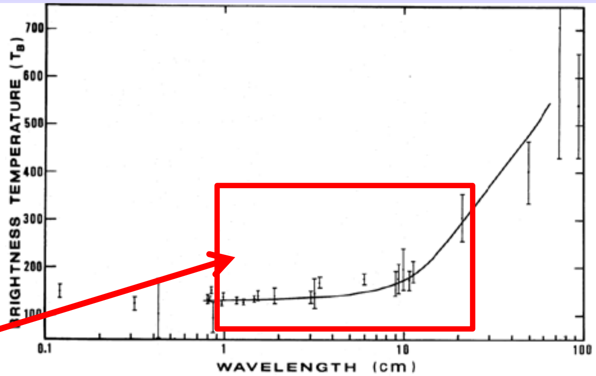
From Voyager: $(2 - 4).10^{-3}$
From Cassini: $(4.7 \pm 0.2).10^{-3}$

H_2 and CH_4: Good constraints from ground-based observations

Saturn’s composition: constraints before the probes

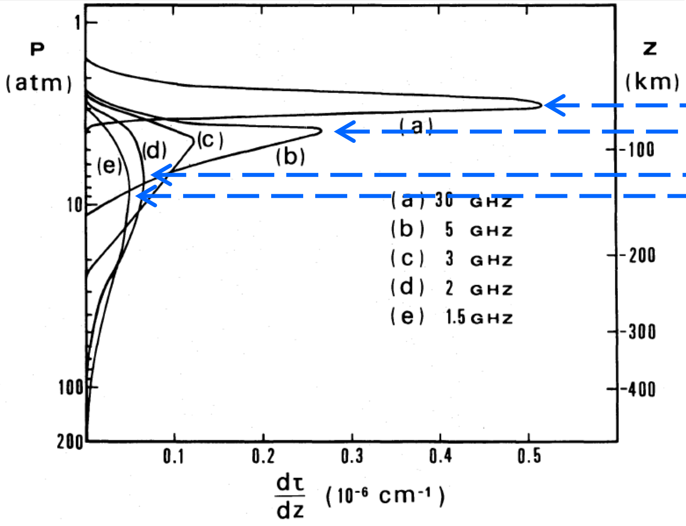
- **Case of NH_3**

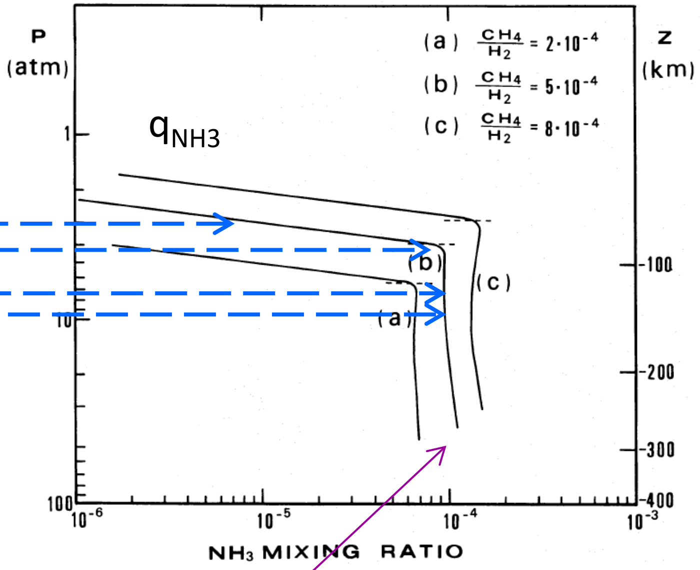
from its absorbing 1.25 cm band (Ohring et al., 1976)
No constraints of the tropospheric temperature
→ assumed adiabatic extrapolations, CH_4/H_2=5 10^{-4}



They inverted the 1.5 – 30 cm spectral region

Weighting functions



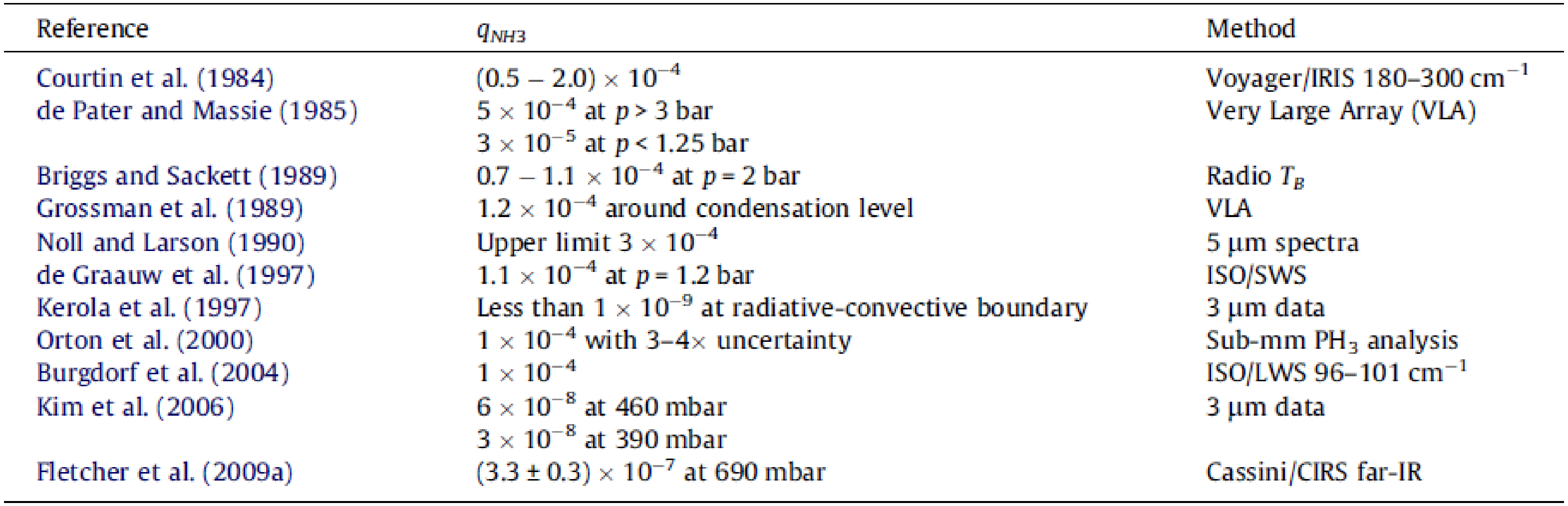


First vertical profile of NH_3: q= 1.10^{-4} below the condensation level
From Voyager : (0.5 - 2) x 10^{-4} , Courtin et al. (1984)
From Cassini : 1 - 3 bar : q_{NH3} = (1.4 - 5).10^{-4} with latitudinal variations, Fletcher et al. (2011)

Saturn’s composition: constraints before the probes

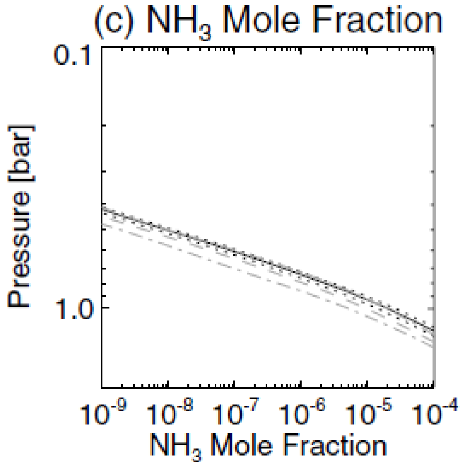
Case of NH_3

Many other constrains from the ground and with ISO and Herschel satellites



Reference	q_{NH3}	Method
Courtin et al. (1984)	$(0.5 - 2.0) \times 10^{-4}$	Voyager/IRIS 180–300 cm^{-1}
de Pater and Massie (1985)	5×10^{-4} at $p > 3$ bar 3×10^{-5} at $p < 1.25$ bar	Very Large Array (VLA)
Briggs and Sackett (1989)	$0.7 - 1.1 \times 10^{-4}$ at $p = 2$ bar	Radio T_B
Grossman et al. (1989)	1.2×10^{-4} around condensation level	VLA
Noll and Larson (1990)	Upper limit 3×10^{-4}	5 μm spectra
de Graauw et al. (1997)	1.1×10^{-4} at $p = 1.2$ bar	ISO/SWS
Kerola et al. (1997)	Less than 1×10^{-9} at radiative-convective boundary	3 μm data
Orton et al. (2000)	1×10^{-4} with 3–4× uncertainty	Sub-mm PH_3 analysis
Burgdorf et al. (2004)	1×10^{-4}	ISO/LWS 96–101 cm^{-1}
Kim et al. (2006)	6×10^{-8} at 460 mbar 3×10^{-8} at 390 mbar	3 μm data
Fletcher et al. (2009a)	$(3.3 \pm 0.3) \times 10^{-7}$ at 690 mbar	Cassini/CIRS far-IR

Vertical profile from the Herschel satellite : Fletcher et al., 2012



NH_3: good constraints from the ground-based and Earth satellites, independently of Saturn’s probes.

Saturn’s composition: hydrocarbons

- **C_2H_6**

\- From ground or Earth satellites :

q_{C2H6} = 1.8 x 10^{-6} , 12.2 µm Tokunaga et al. (1975)
(6±1) x 10^{-6} < 20 mbar, IUE (UV satellite), Winkelstein et al. (1983)
(1.3 ±0.3) x 10^{-5} at 0.5 mbar, ISO/SWS (infrared satellite), Moses et al. (2000)
(1.5 ±0.5) x 10^{-5} at 0.5 mbar, IRTF, Greathouse et al. (2005)

\- From spacecrafts:

Voyager: (3±1) x 10^{-6} < 20 mbar, Voyager/IRIS, Courtin et al. (1984)
Cassini: (1.4±0.2) x 10^{-5} at 1 mbar

☺ C_2H_6: agreement between ground-based and spacecraft measurements

Saturn’s composition: hydrocarbons

- **C_2H_6**

\- From ground or Earth satellites :

q_{C2H6} = 1.8 x 10^{-6} , 12.2 µm Tokunaga et al. (1975)
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🙂 C_2H_6: agreement between ground-based and spacecraft measurements

- **Other hydrocarbons:**

🙂 **C_2H_2**: many measurements with IUE, TEXES/IRTF, SWS/ISO, Celeste/IRTF
😕 **C_3H_8**: (2.6 ±0.8) x 10^{-6} with TEXES/IRTF while (0.9 – 1.5) x 10^{-7} from Cassini/CIRS
🙂 **CH_3C_2H**: 1 measurement with SWS/ISO , in agreement with Cassini/CIRS
🙂 **C_4H_2**: 1 measurement with SWS/ISO , in agreement with Cassini/CIRS
C_6H_6 : only detection with SWS/ISO, no detection from probes

Saturn’s composition

Oxygen compounds

- **CO :** detection in submm but not with the probes

🙂 - **CO_2 :** 1 measurement from ISO/SWS (3.0×10^{-10} at 0.3-10 mbar), agrees with Cassini/CIRS

☹ - **H_2O :**

1.5×10^{-7} at 2 mbar from IUE (UV)

6.0×10^{-9} at 2 mbar from SWS/ISO (2.4 – 45 µm)

H_2O was not detected by Saturn’s probes (because of bad S/N ratio)

Saturn's composition

Oxygen compounds

- **CO :** detection in submm but not with the probes
- **CO_2 :** 1 measurement from ISO/SWS (3.0×10^{-10} at 0.3-10 mbar), agrees with Cassini/CIRS
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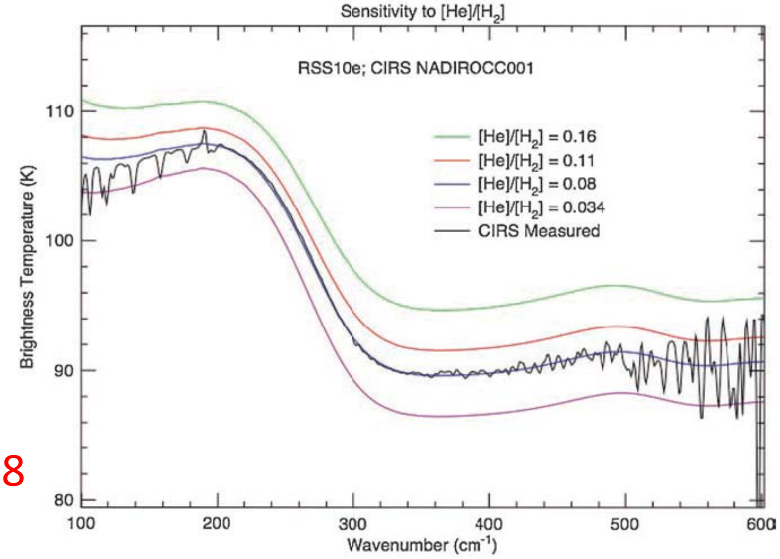
6.0×10^{-9} at 2 mbar from SWS/ISO (2.4 – 45 µm)

H_2O was not detected by Saturn's probes (because of bad S/N ratio)

Helium

Determined from Voyager and Cassini, impossible from the ground because of bad S/N ratio



From Cassini/CIRS: [He]/[H2]=0.08

Jupiter

Jupiter knowledge before probes flybys

1932: detection of $\mathbf{CH_4}$ and $\mathbf{NH_3}$ (Wildt, 1932)
1960: detection of $\mathbf{H_2}$ (Kiess et al.)

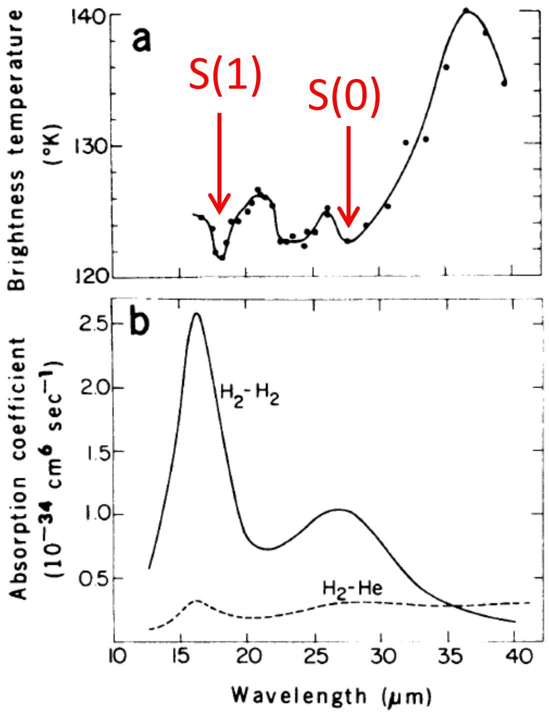
Helium was presumed because of the theory of the primitive solar nebula composition

Jupiter knowledge before probes flybys

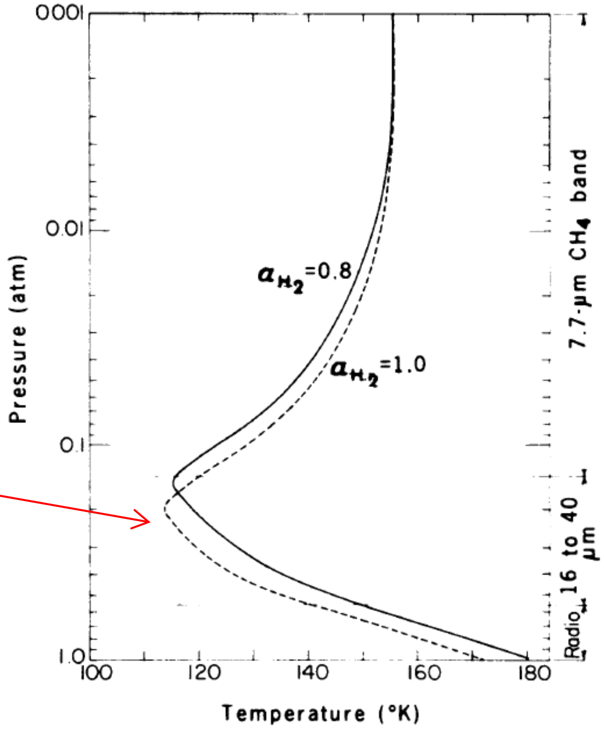
1932: detection of **CH_4** and **NH_3** (Wildt, 1932)
1960: detection of **H_2** (Kiess et al.)

Helium was presumed because of the theory of the primitive solar nebula composition

- **Thermal profile**
  constrained from H_2-H_2 and H_2-He collision induced absorptions (Houck et al., 1975)



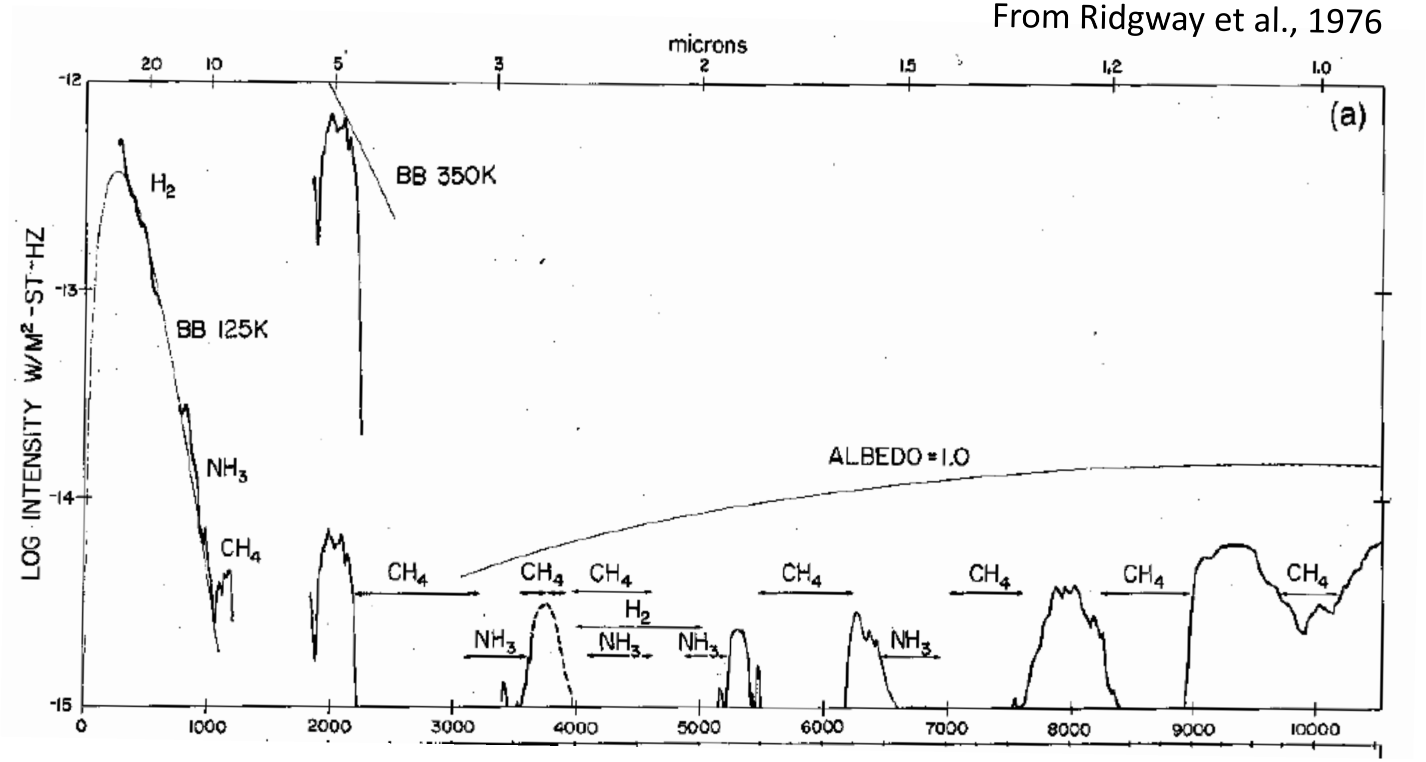
Results:
- q_{H2} = 0.89 ± 0.11
- tropospheric temperature



Jupiter knowledge before probes flybys

1975 : Jupiter’s infrared spectrum

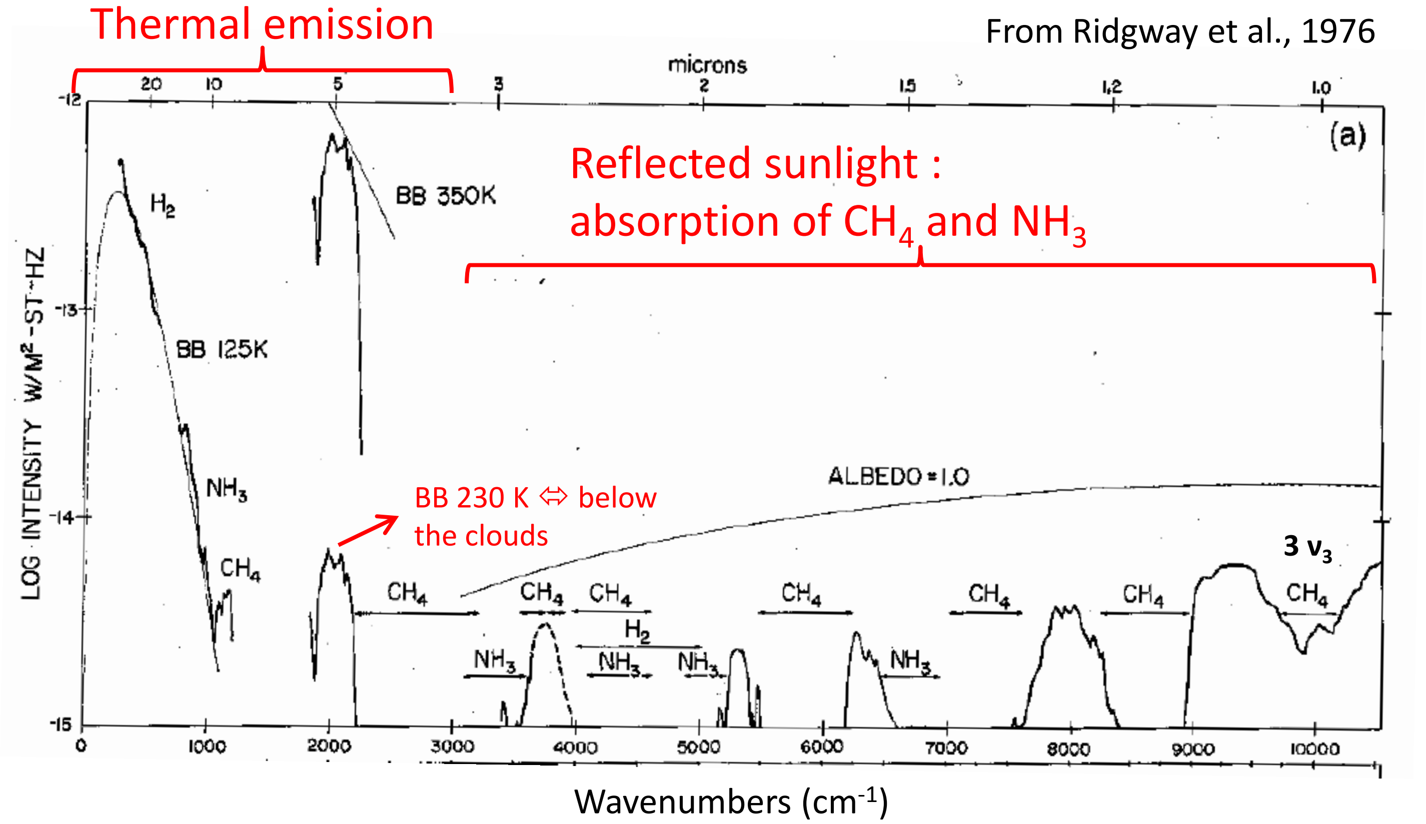
From Ridgway et al., 1976



Wavenumbers (cm^{-1})

Jupiter knowledge before probes flybys

1975 : Jupiter’s infrared spectrum



Thermal emission

From Ridgway et al., 1976

Reflected sunlight : absorption of CH_4 and NH_3

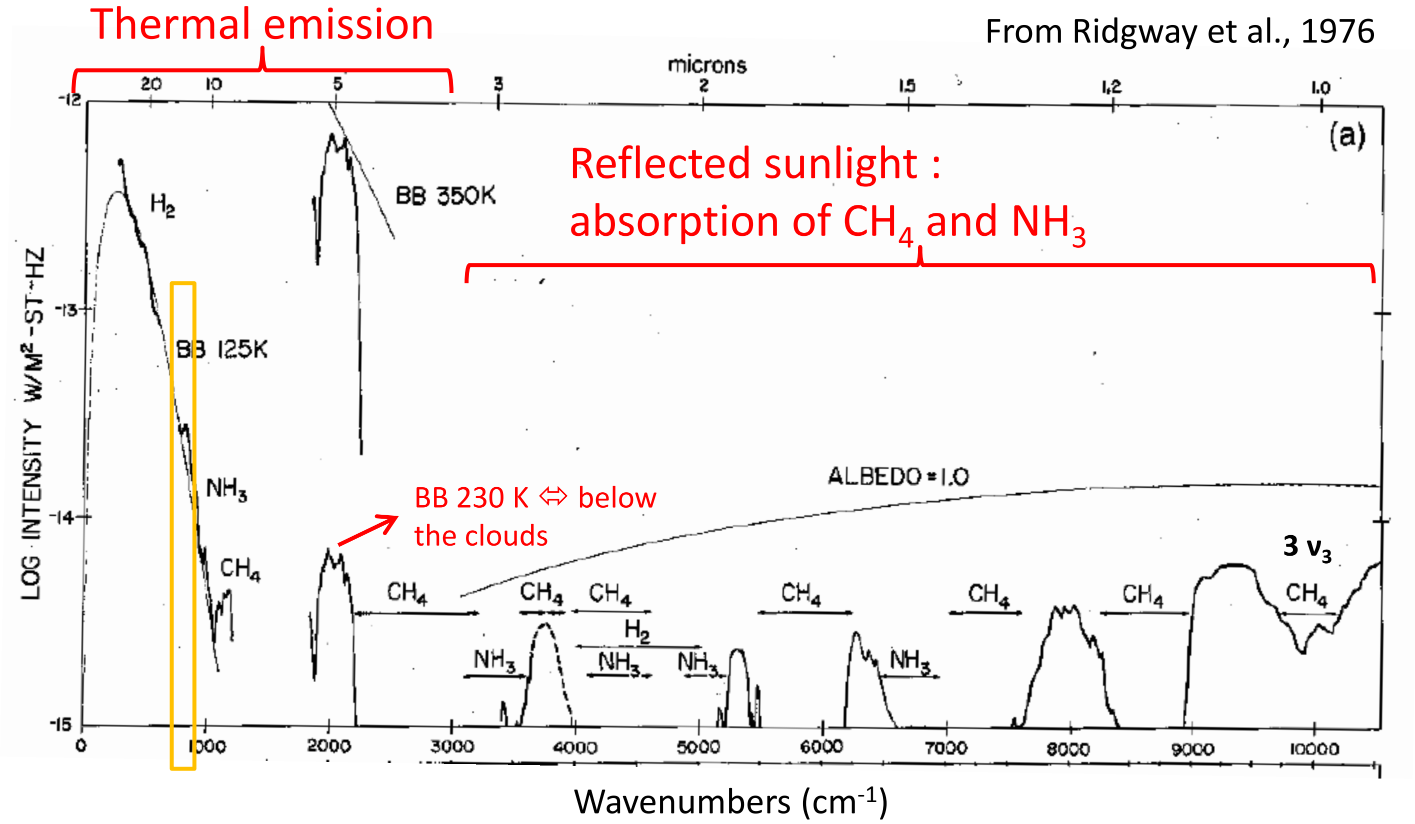
BB 230 K ⇔ below the clouds

$3\ \nu_3$

Detection of CH_4, NH_3, H_2 from the IR spectrum.

Jupiter knowledge before probes flybys

1975 : Jupiter's infrared spectrum



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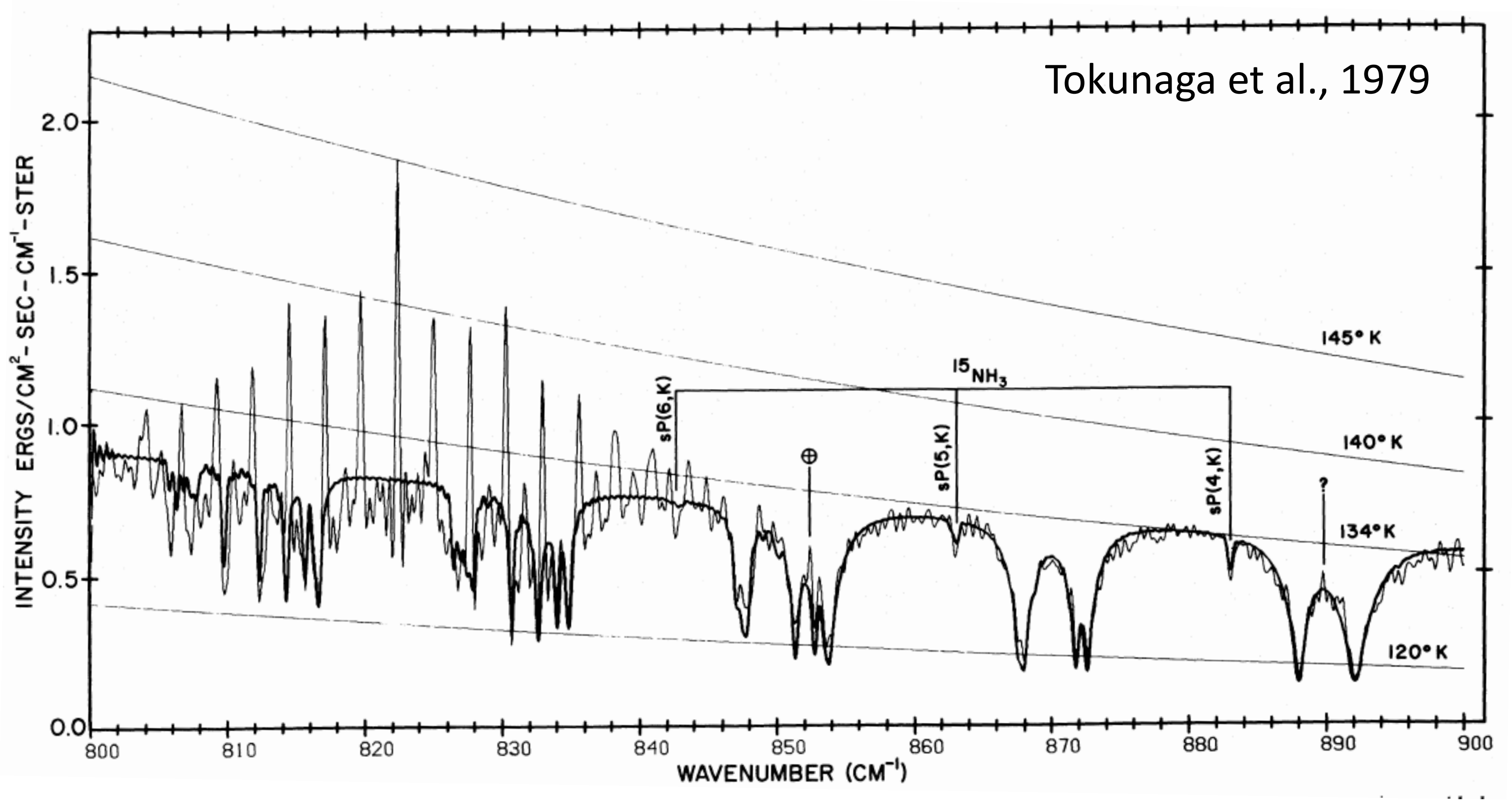
Reflected sunlight : absorption of CH_4 and NH_3

BB 230 K ⇔ below the clouds

Detection of CH_4, NH_3, H_2 from the IR spectrum.

Jupiter composition before probes flybys

- **High spectral resolution observations in IR**


Tokunaga et al., 1979

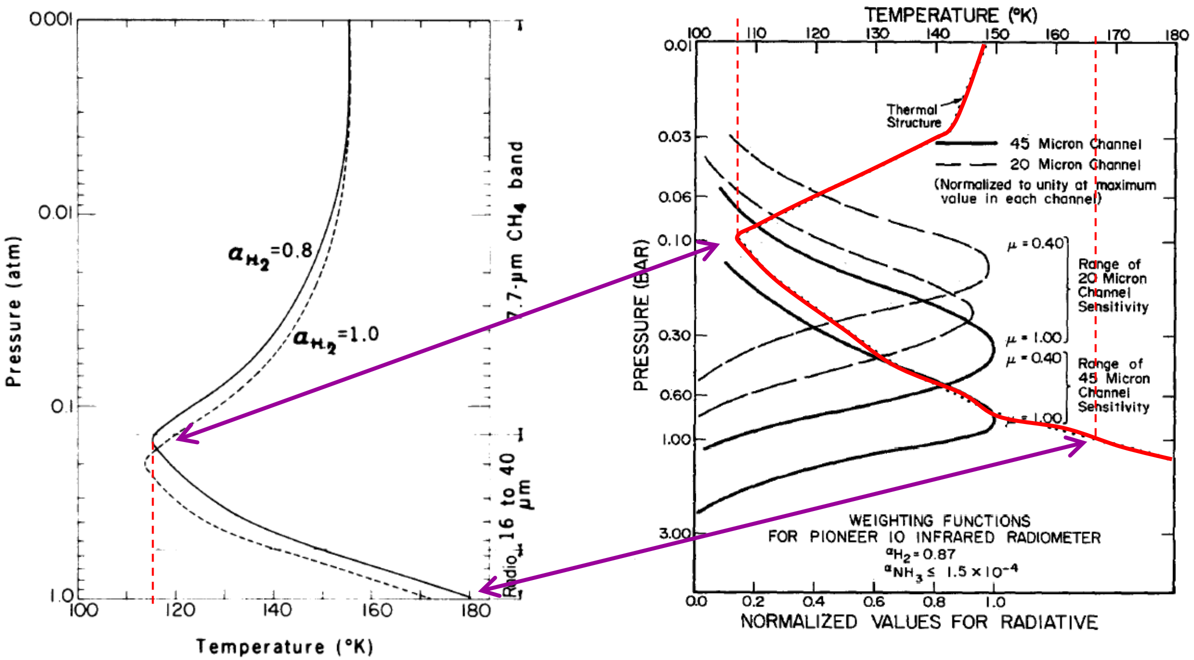
- line profile of NH_3 absorption lines => sensitivity to different levels , while continuum is sensitive to the NH_3 cloud deck
- C_2H_6 observed in emission => emission comes from a region where T ↗ with height

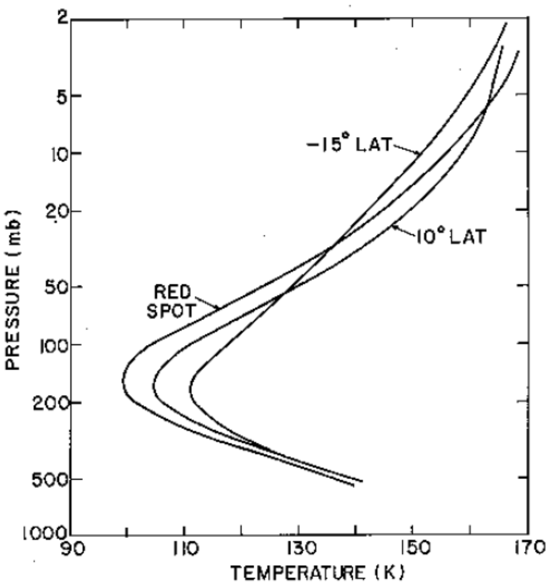
Jupiter thermal profile: comparison with probes

Before Pioneer, 1975

From Pioneer, Orton 1975

From Voyager, Hanel 1979





Good agreement from ground-based observations and Pioneer spacecraft

Jupiter composition: comparison with probes

- **Abundances, some examples**

		Before spacecrafts (Ridgway, 1976)	From spacecrafts (Taylor, 2004)
🙂	H_2	0.89	0.86
🙂	He	0.05 – 0.15	0.136
🙂	CH_4	7×10^{-4}	1.8×10^{-3}
🙂	NH_3	2×10^{-4}	7.0×10^{-4}
😕	H_20	1×10^{-6}	$> 5.0 \times 10^{-4}$
	Non equilibrium gas		
🙂	CO	2×10^{-9}	1.5×10^{-9}
🙂	PH_3	4×10^{-7}	5×10^{-7}
	Photochemical products		
☹	C_2H_6	4×10^{-4}	3×10^{-6}
☹	C_2H_2	8×10^{-5}	2×10^{-8}

Disagreement mostly come from the thermal profiles

Conclusions regarding the solar system observations

- **Giant planets**

Main composition = H_2 (~ 90%) and He (~ 10 %).

T in the troposphere can be constrained by the absorption-induced bands of H_2 = most reliable probe for temperature sounding for giant planets.

$\Rightarrow$ Good estimation of the molecular abundances in the troposphere

$\Rightarrow$ But for photochemical product emitting in the stratosphere, constrains are poorer

-> need of high spectral resolution observations to probe higher.

Conclusions regarding the solar system observations

- **Giant planets**

Main composition = H_2 (~ 80%) and He (~ 20 %).

T in the troposphere can be constrained by the absorption-induced bands of H_2 = most reliable probe for temperature sounding for giant planets.

$\Rightarrow$ Good estimation of the molecular abundances in the troposphere

$\Rightarrow$ But for photochemical product emitting in the stratosphere, constrains are poorer

-> need of high spectral resolution observations to probe higher.

- **Telluric planets**

Very difficult … because the main composition is a priori unknown.
Large spectral coverage => constrains on the T at several level: e.g. surface temperature in radio and stratospheric temperature in mid-IR.

The knowledge of the T profile from Voyager observations was crucial in the knowledge of Titan's composition.

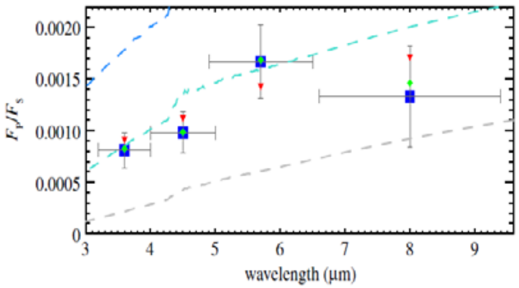
Perspectives: 2 promising methods for hot Jupiters

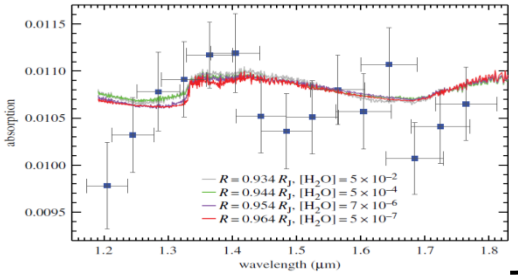
- **Use of primary transit and secondary transit spectra simultaneously** (Griffith et al., 2014)

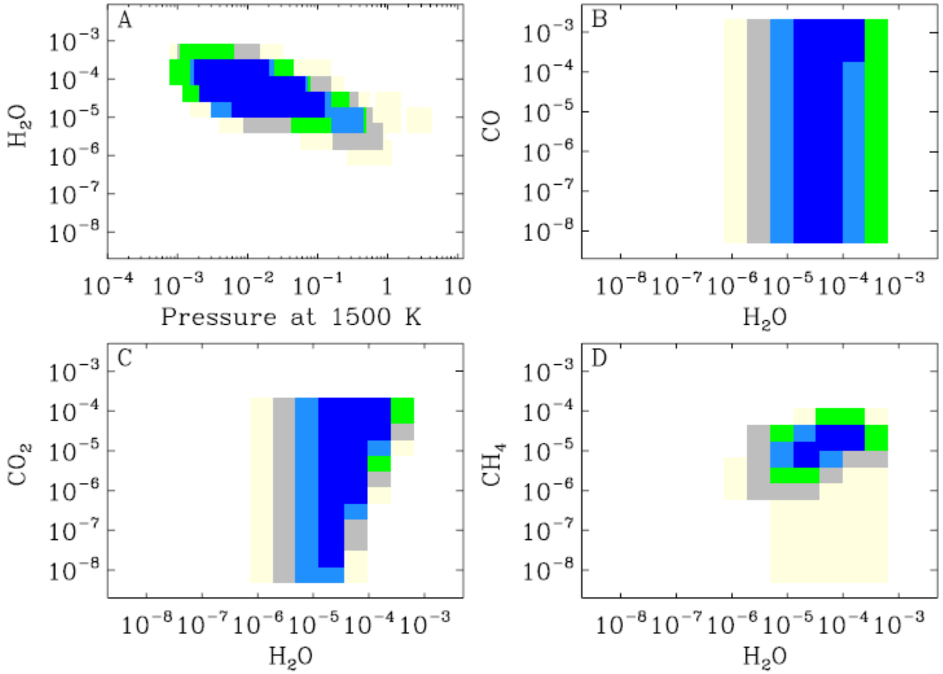
  - Primary transit -> terminator, absorption of the stellar light => sensitive to the planet composition and not so much to the T profile

  - Secondary transit -> day side, stellar light diffusion + thermal emission => sensitive to the composition and the T profile

Fit of the secondary transit + primary transit of XO-2b (include H_2O, CH_4, CO, CO_2)


Spitzer secondary transit


HST primary transit spectrum



Need of large spectral range and high resolution to decouple T and composition.

Perspectives: 2 promising methods for Hot Jupiters

- **Detection of a molecule from high resolution spectra** (Snellen et al. 2010)

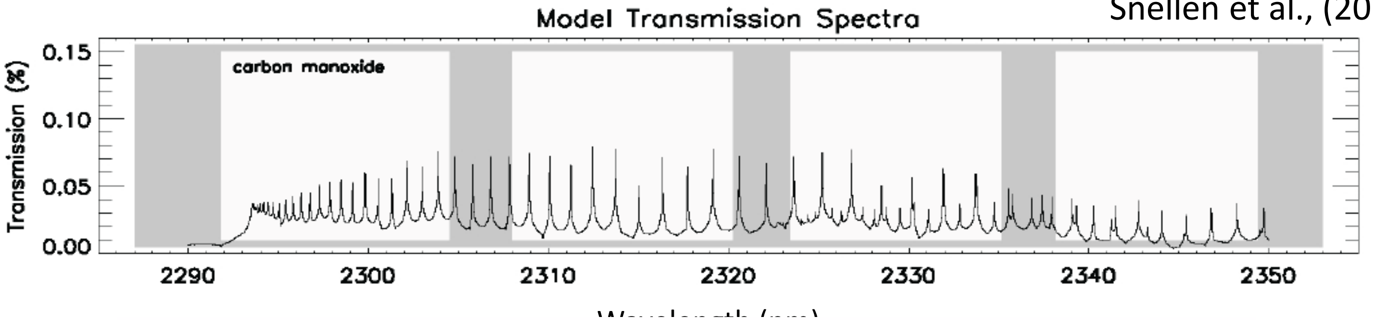
High spectral resolution observation of exoplanets with VLT/CRIRES (R = 100 000)

Principle: molecular lines are Doppler shifted while the planet is moving on its orbit, whereas the stellar spectrum is not.

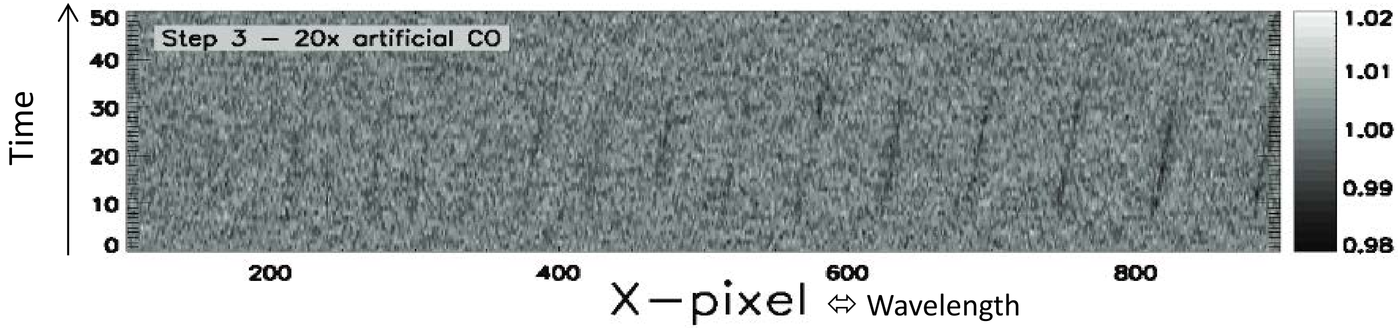
=> Case of CO in HD209458b, observation during the primary transit

Snellen et al., (2010)

Model of the CO band at 2.3 µm



Doppler shifted lines during the transit



⇔ Wavelength

Detection of CO in transit: HD209 and HD189

outside transit: τ -Boo and 51 Peg