HITRAN Conference
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Titan's neutral atmospheric chemistry from the astronomical point of view

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Titan, the largest kronian satellite…

Physical parameters:

$R = 2\ 575$ km

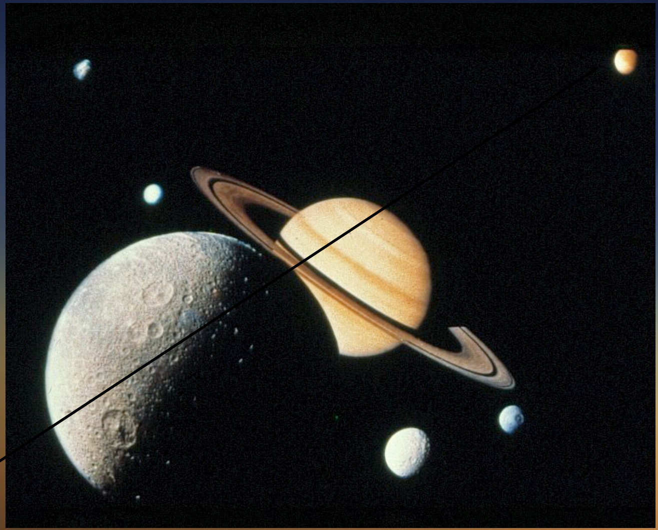
$m = 1{,}831\ M_{Moon}$

Orbital parameters:

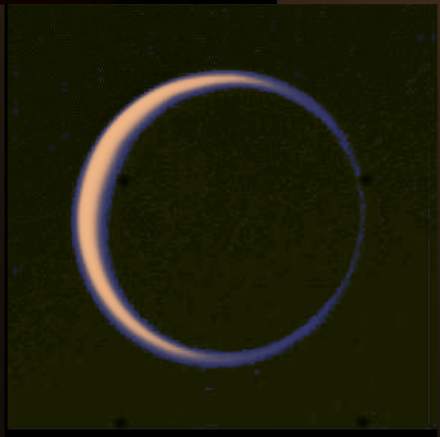
$a = 1\ 221\ 830$ km $\sim 20\ R_{Saturn}$

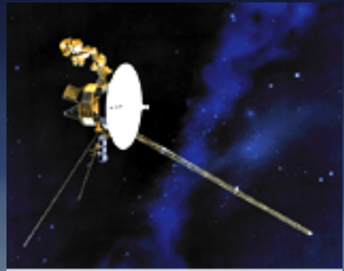
$P = 15{,}95$ j

$e = 0{,}0292$

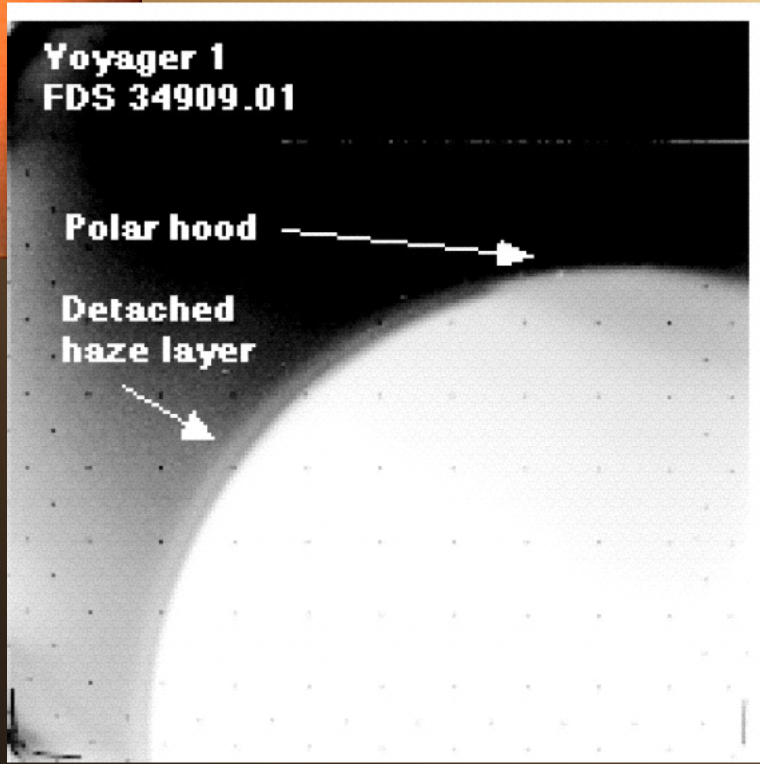


Titan's atmosphere seen by Voyager

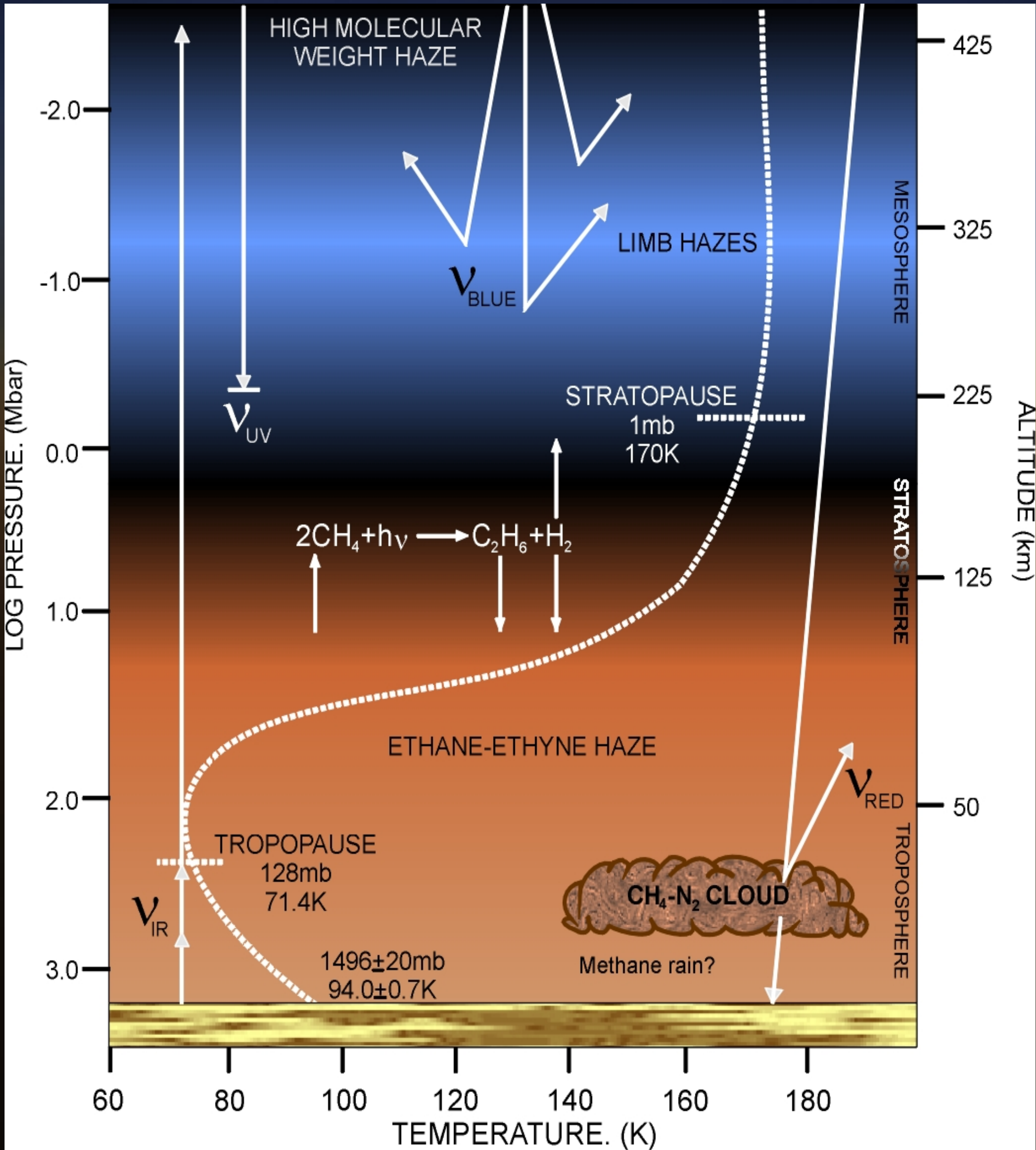




Voyager 1 Launch to Jupiter/Saturn
Sept. 5, 1977



Titan



Temperature inversion

By greenhouse effect below 40 km in altitude

Composition of the atmosphere :

* N_2 is the major component (~97%)
* CH_4 & other hydrocarbons
* H_2
* nitriles

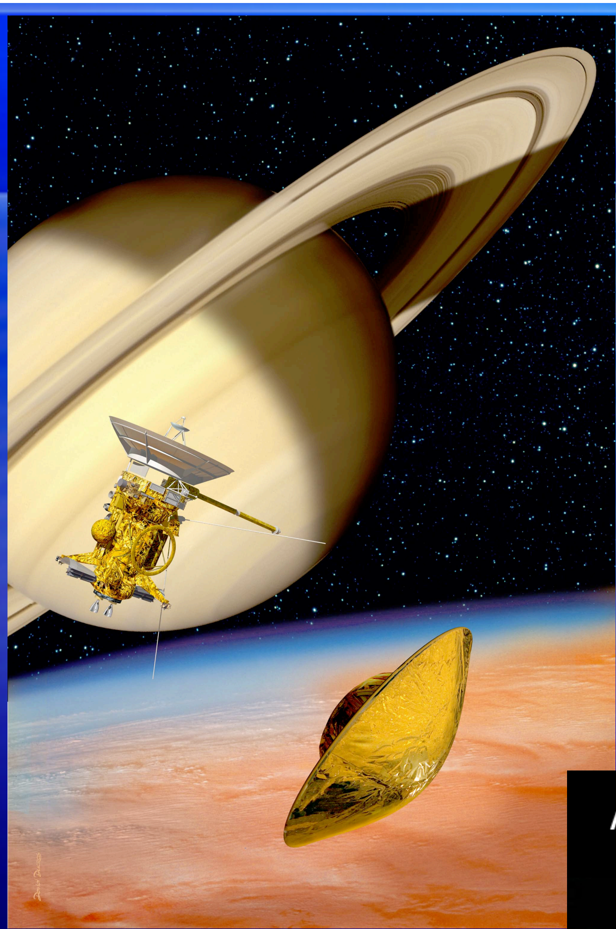
• Little oxygen: H_2O, CO, CO_2

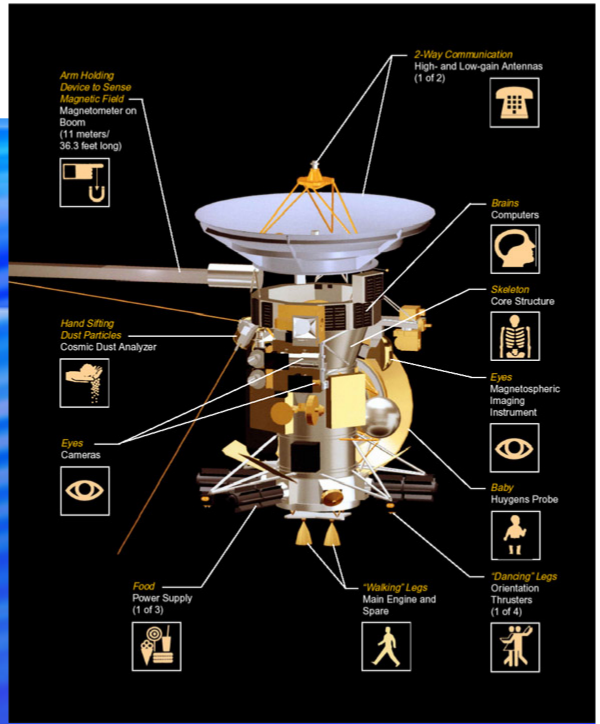
Huygens et Cassini

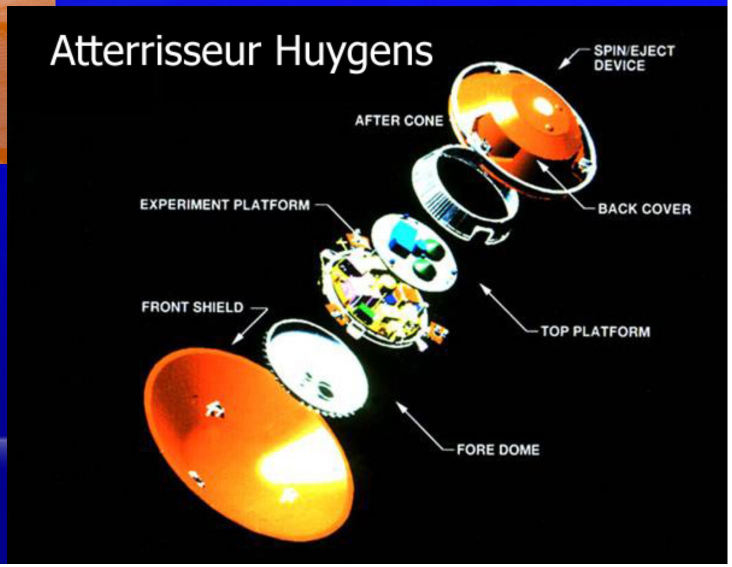
•*Thermal and chemical structure in the stratosphere of Titan* from IR spectra of **CIRS** on the orbiter.

•**HASI** determined *temperature, pressure and density in the whole atmosphere* during the Huygens descent.

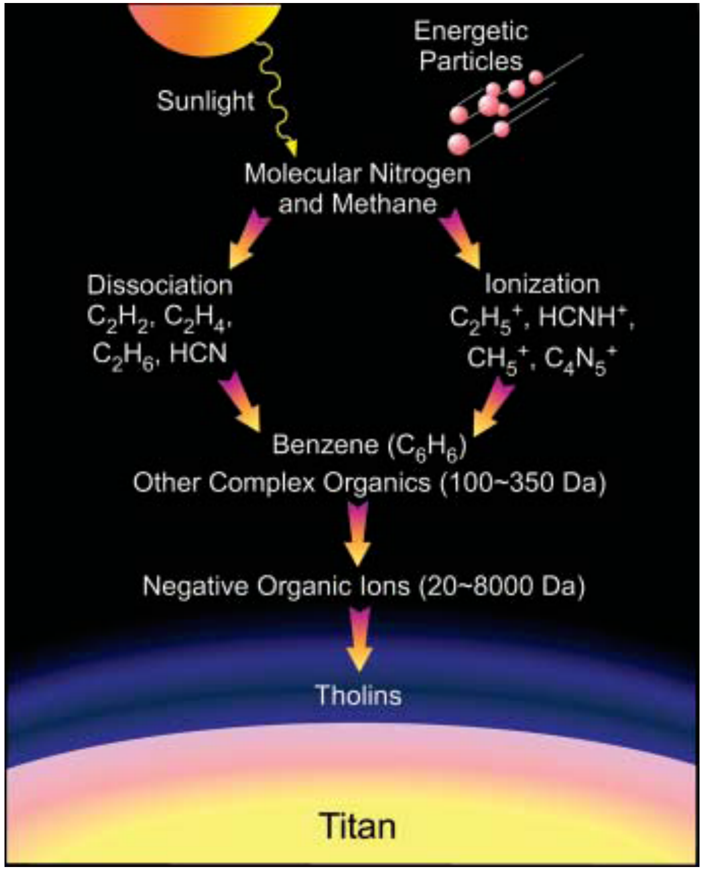
•Spectra and images taken by **DISR**, give information on the *composition of the surface and constrain the distribution of the aerosols on Titan.*



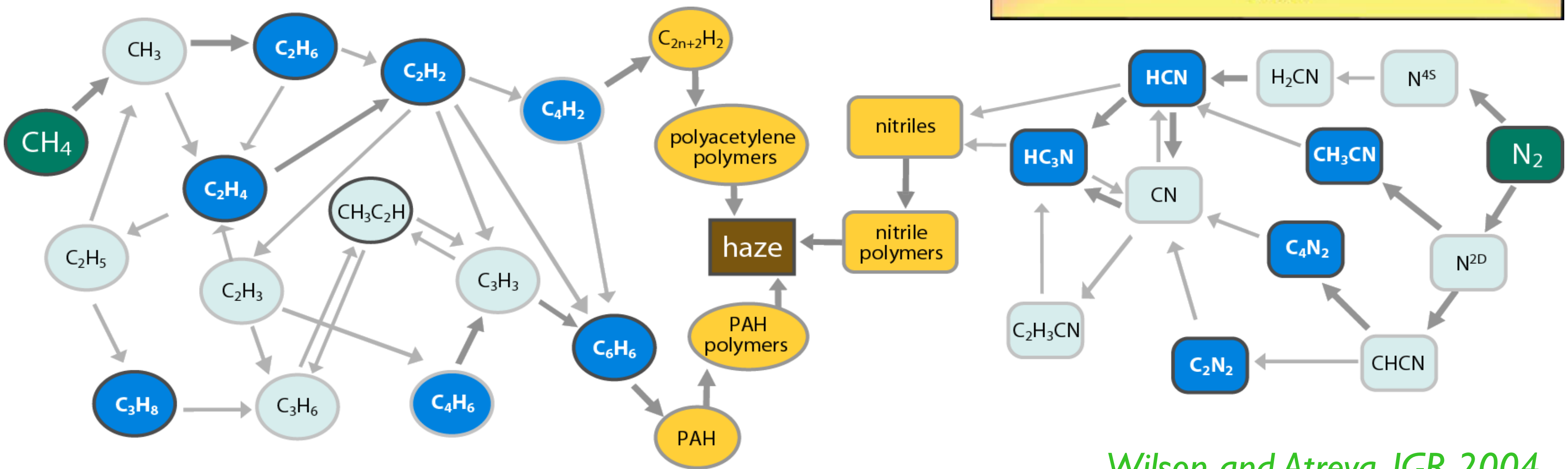




Organic chemistry on Titan



Cassini/INMS on Titan: Waite et al (2006)



Wilson and Atreya, JGR 2004

Gas		Mole fraction		Comments-Ref.
Major components				
Nitrogen	N_2	0.97		Inferred indirectly
Methane	CH_4	$1.4\text{-}1.8\times10^{-2}$		Stratosphere (1,2)
		4.9×10^{-2}		Surface (2,3)
Monodeuterated methane	CH_3D	8×10^{-6}		(4)
Hydrogen	H_2	0.0011		(5)
Argon	^{36}Ar	2.8×10^{-7}		(2)
	^{40}Ar	4.32×10^{-5}		(2)
		Equator	*North Pole*	
Hydrocarbons				
Ethane	C_2H_6	1.3×10^{-5}	1.7×10^{-5}	(4)
Acetylene	C_2H_2	3.7×10^{-6}	4.0×10^{-6}	(4)
Monodeuterated acetylene	C_2HD	2×10^{-9}		
Propane	C_3H_8	6.0×10^{-7}	8.0×10^{-7}	(4)
Ethylene	C_2H_4	1.6×10^{-7}	1.1×10^{-7}	(4)
Methylacetylene	C_3H_4	6.4×10^{-9}	1.2×10^{-8}	(4)
Diacetylene	C_4H_2	1.3×10^{-9}	4.2×10^{-9}	(4)
Benzene	C_6H_6	3.0×10^{-10}	1.1×10^{-9}	(4)
Nitriles				
Hydrogen cyanide	HCN	1.3×10^{-7}	5.5×10^{-7}	(4,6)
Cyanoacetylene	HC_3N	3.0×10^{-10}	2.2×10^{-9}	(4)
Cyanogen	C_2N_2	5×10^{-10}	9×10^{-10}	(6)
Dicyanogen	C_4N_2			Solid form only (7)
Acetonitrile	CH_3CN	1.5×10^{-9}		(8)
Oxygen compounds				
Water vapor	H_2O	8×10^{-9}		(9) at 400 km
Carbon dioxide	CO_2	1.5×10^{-8}	1.9×10^{-8}	(4)
Carbon monoxide	CO	$(2\text{-}4)\times10^{-5}$		Troposphere (10,11)
		$(3\text{-}6)\times10^{-5}$		Stratosphere (1,12)
Isotopic ratios				
$^{13}C/^{14}C$		82.3 ± 1		(2)
$^{14}N/^{15}N$ in HCN		67		(11)
In N_2		183 ± 5		(2)
D/H in CH_3D		1.3×10^{-4}		(4)
in HD		2.3×10^{-4}		(2)
in C2HD		1.7×10^{-4}		(4)

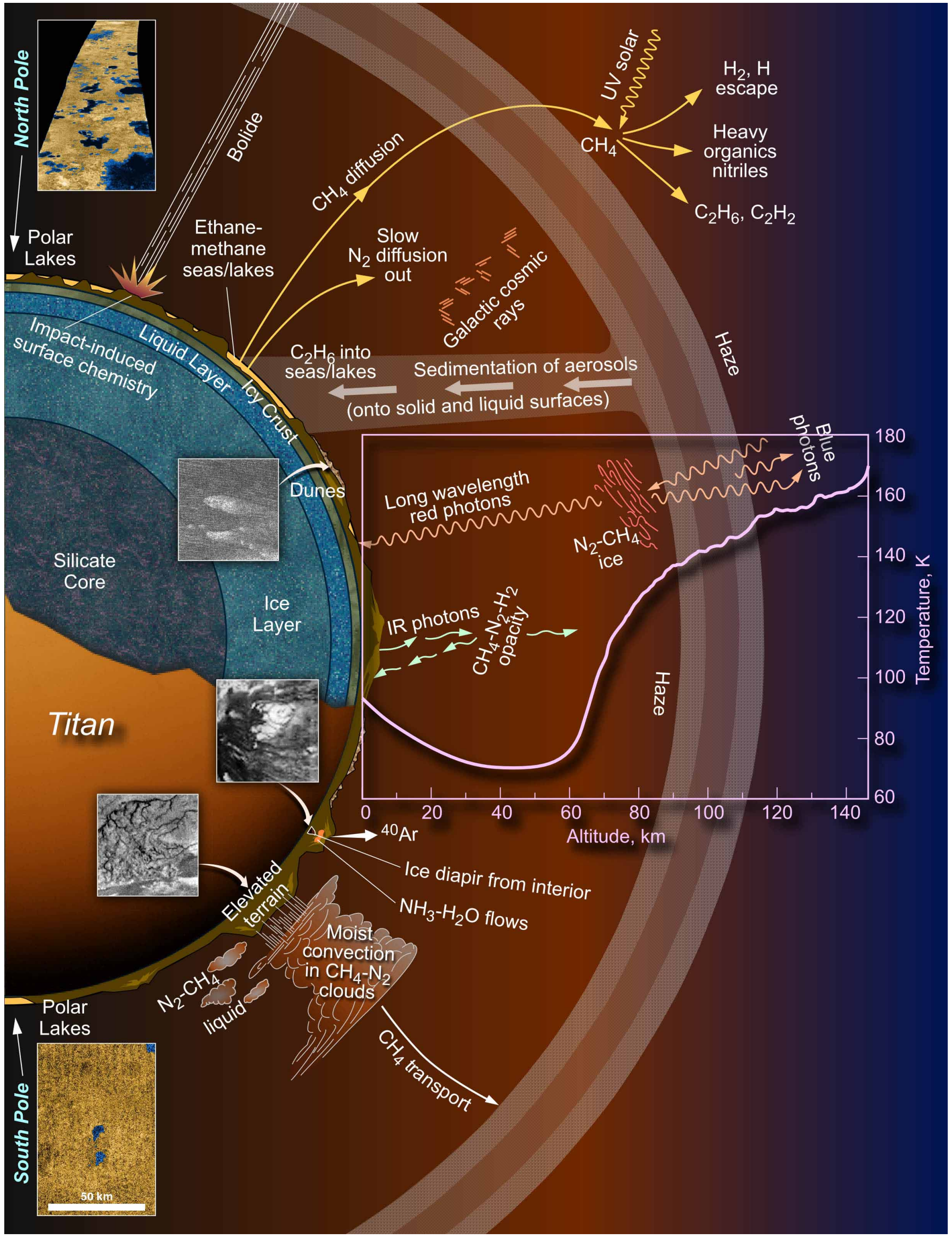
1. Flasar *et al.* (2005) from Cassini/CIRS data
2. Niemann et al. 2005 from Huygens/GCMS data
3. Tomasko et al. (2005) from Huygens/DISR data
4. Coustenis et al. (2007) from Cassini/CIRS data
5. Samuelson *et al.* (1997a) from V1/IRIS data
6. Teanby et al. (2006) from Cassini/CIRS data
7. Samuelson *et al.* (1997b) from V1/IRIS data
8. Bézard *et al.* (1993) from disk-averaged ground-based heterodyne mm observations
9. Coustenis *et al.* (1998) from ISO/SWS data
10. Lellouch *et al.* (2003) from ground-based VLT data at 5 micron
11. Marten *et al.* (2002) from disk-averaged ground-based heterodyne mm observations
12. Gurwell and Muhleman (2000) from disk-averaged mm heterodyne data

From Vuitton, Waite, et al. INMS

Ionospheric species detected by INMS	Neutral mole fractions
H_2	4×10^{-3}
CH_4	3×10^{-2}
C_2H_2	3×10^{-4}
C_2H_4	6×10^{-3}
C_2H_6	1×10^{-4}
C_4H_2	6×10^{-5}
HCN	2×10^{-4}
HC_3N	2×10^{-5}
CH_3CN	1×10^{-5}
C_2H_3CN	1×10^{-5}
C_2H_5CN	5×10^{-7}
NH_3	7×10^{-6}
CH_2NH	$< 1\times10^{-5}$

Coustenis & Taylor 2008 (WSP)

Titan: a world of high interest for planetology and astrobiology studies



Context

Dense planetary atmospheres:

Observations : Voyager, gd-based, ISO and Cassini-Huygens

Titan (N_2, CH_4), 1,5 bar, 94 K on the surface

Long atmospheric paths

scale heights of a few tens of km

Temperatures difficult to achieve in a laboratory

Titan : 70-94 K in troposphere; <200 K in stratosphere

Space exploration and instrumentation:

Observations : Cassini-Huygens : 2004-2017

Thermal IR :

Cassini/CIRS : 7µm-1mm (resolution up to 0.5 cm^{-1})

Near-IR:

Cassini/VIMS : 0,35-5,2 µm (resolution 7-16 nm)

Huygens/DISR : 0,48-1,7 µm (resolution: 5-17 nm)

Context

Goals:

Cartography of the chemical composition with high precision

Detect new components with low abundance levels (including isotopes)

Determine the origin and evolution of the planetary bodies

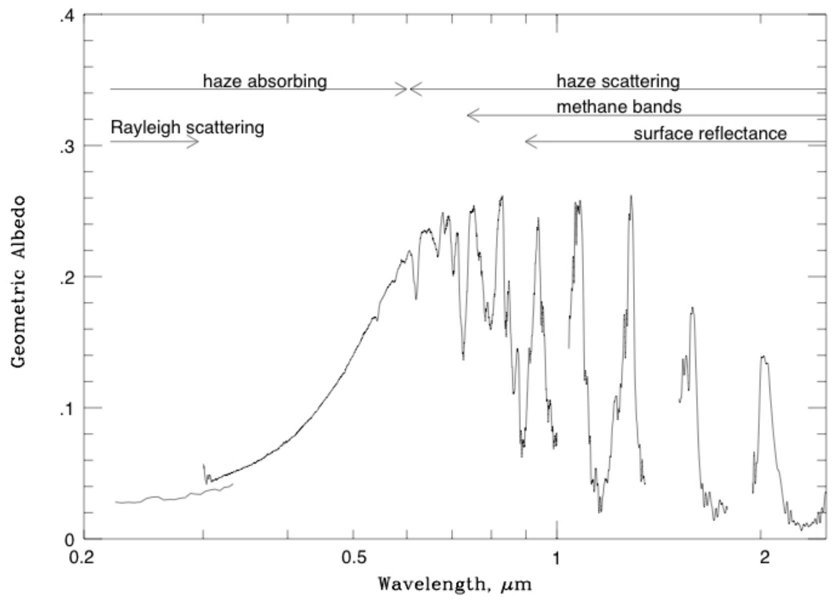
Need for spectroscopic measurements at the right p, T conditions to be able to perform the spectroscopic analysis

We study the physical properties in the atmosphere of the giant planets and Titan with radiative transfer calculations

- **Using a line-by-line code**

solving for

- Opacity sources
  - Chemical abundances (gas and solid)
  - Haze/aerosols
  - clouds
- Temperature structure

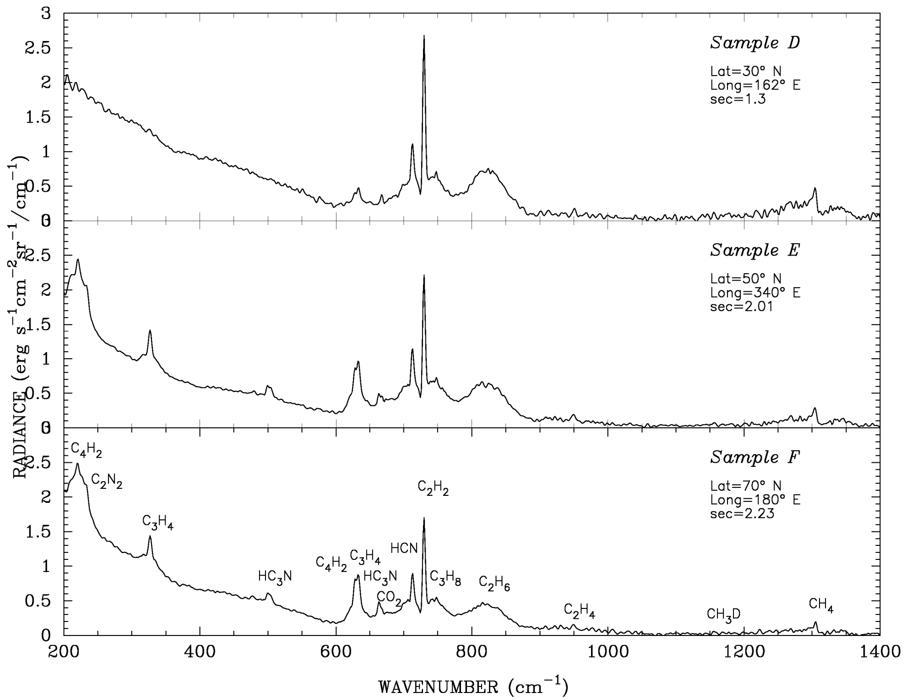


Titan's UV and near-IR spectrum mainly through ground-based measurements (CFHT, UKIRT, IRTF, Keck, VLT, etc), with the exception of HST and ISO from space.

7 -> 50 μm

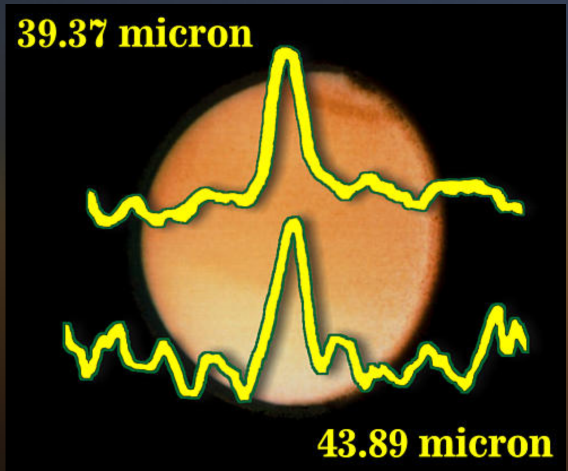
→ 5 μm

Titan's far-IR spectrum mainly through space observations since 1980: Voyager, ISO and Cassini in the future. (Parts thereof were observed from the ground e.g. by Gillett long before that and also since then).



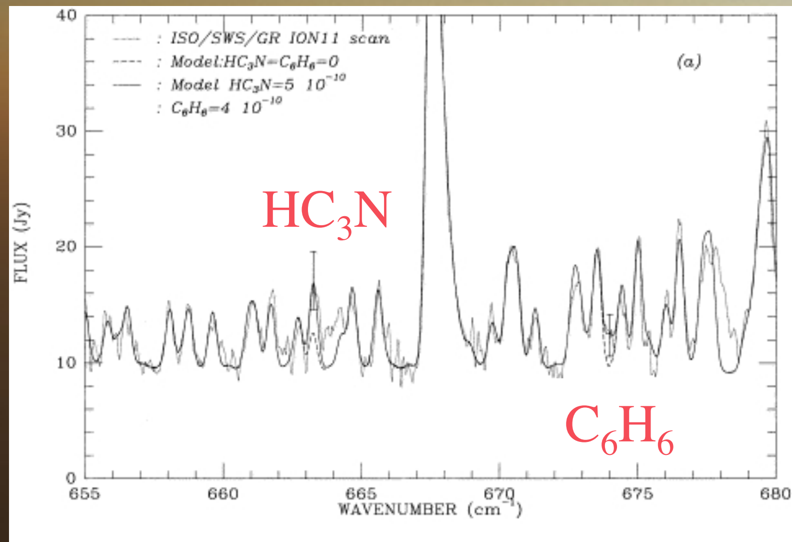
Discoveries on Titan by Infrared Space Observatory (ISO)

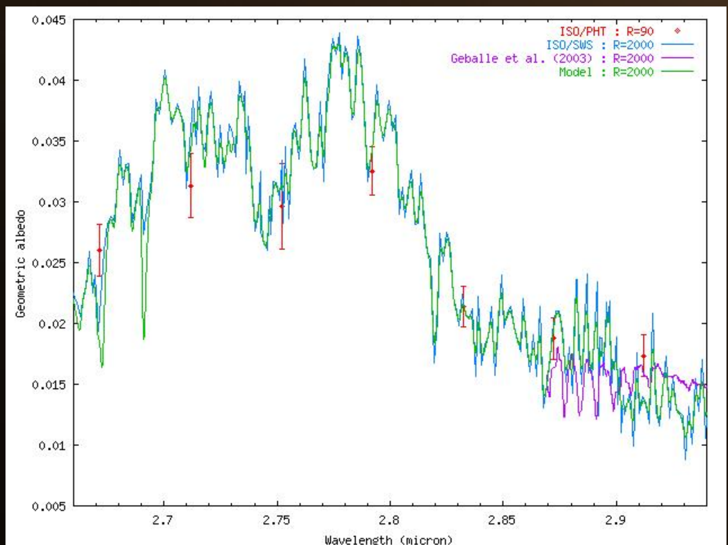
A. Coustenis, A. Salama, B. Schulz, E. Lellouch, Th. Encrenaz, S. Ott, M. Kessler, Th. De Graauw, the ISO Titan Team



Water vapour
(Coustenis et al., 1998)

Benzene (C_6H_6)
(Coustenis et al., 2003)



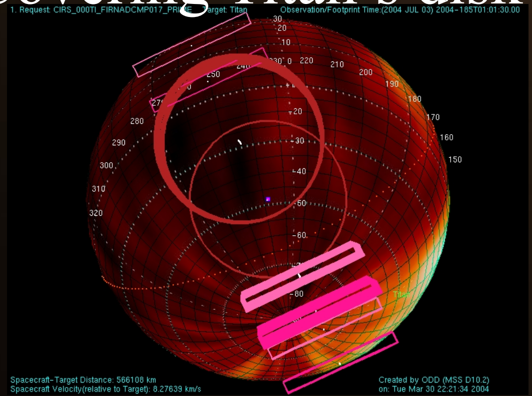


First surface albedo spectrum in the 3 micron methane window
(Coustenis et al., 2004-2005)

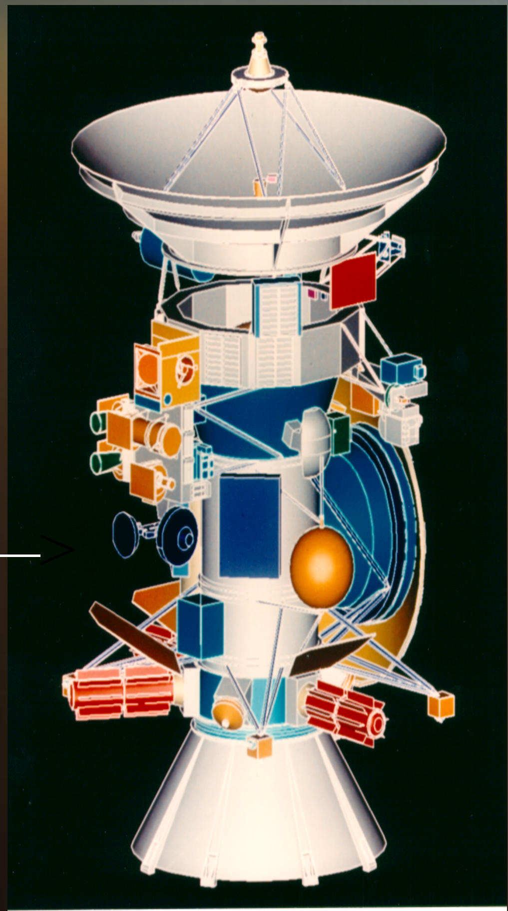
We have analyzed CIRS observations (nadir and limb) covering the

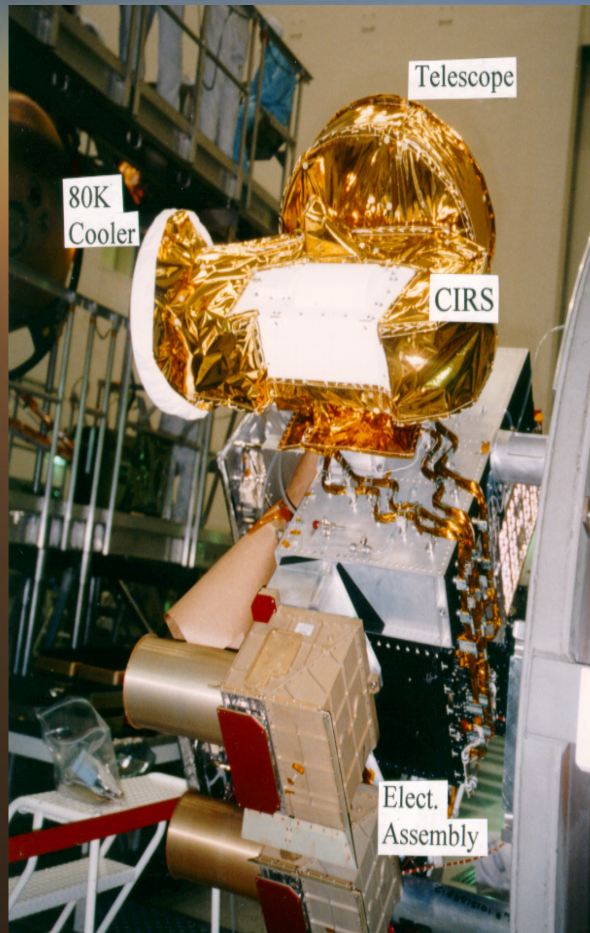
thermal infrared region (10-1500 cm^{-1})

Since July 2, 2004 : TB-T62 flybys
FP3 and FP4 spectra
high resolution apodized (0.53 cm^{-1}) or medium resolution (2.5 cm^{-1})
Covering Titan's disk

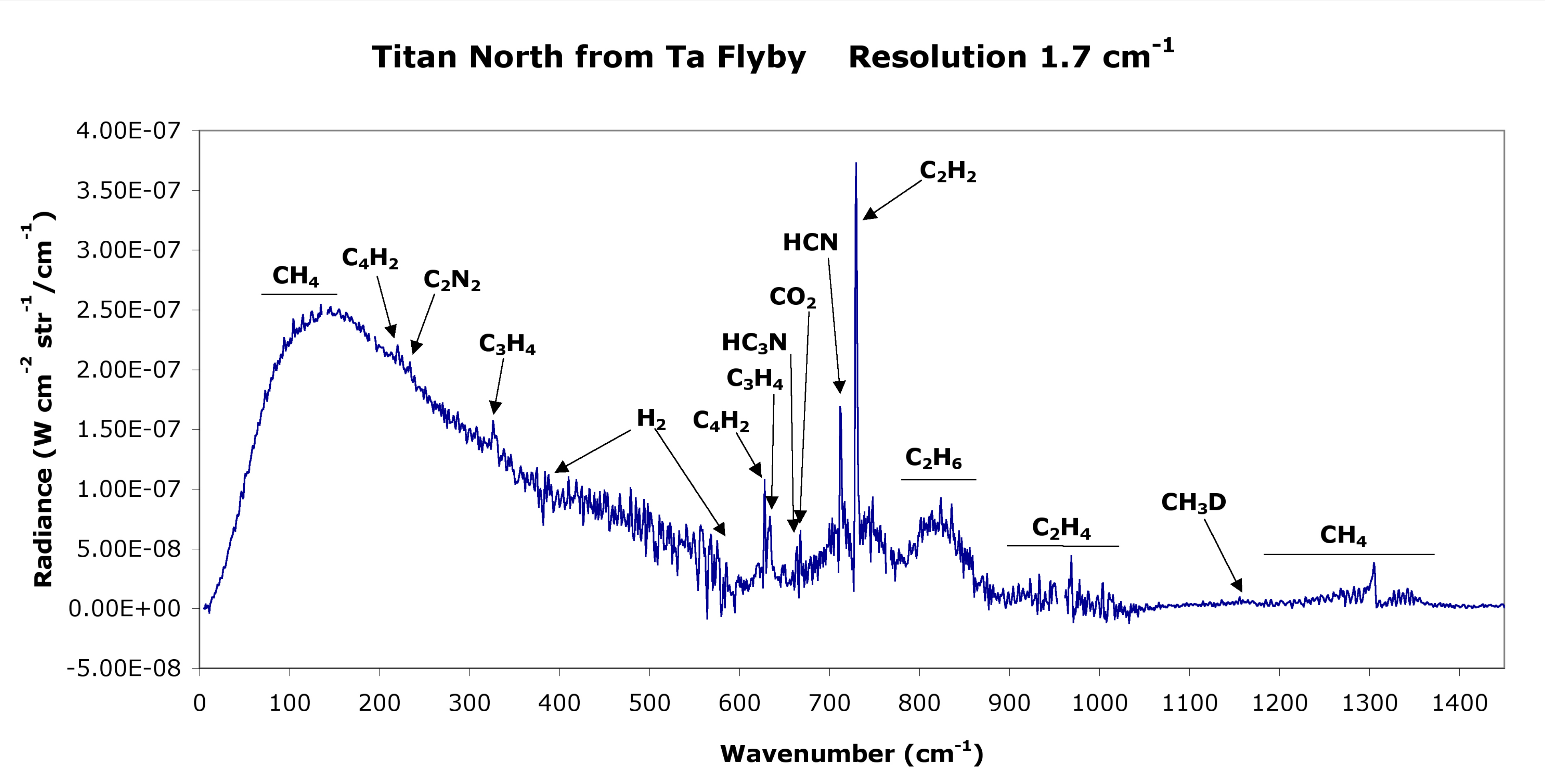


CIRS—

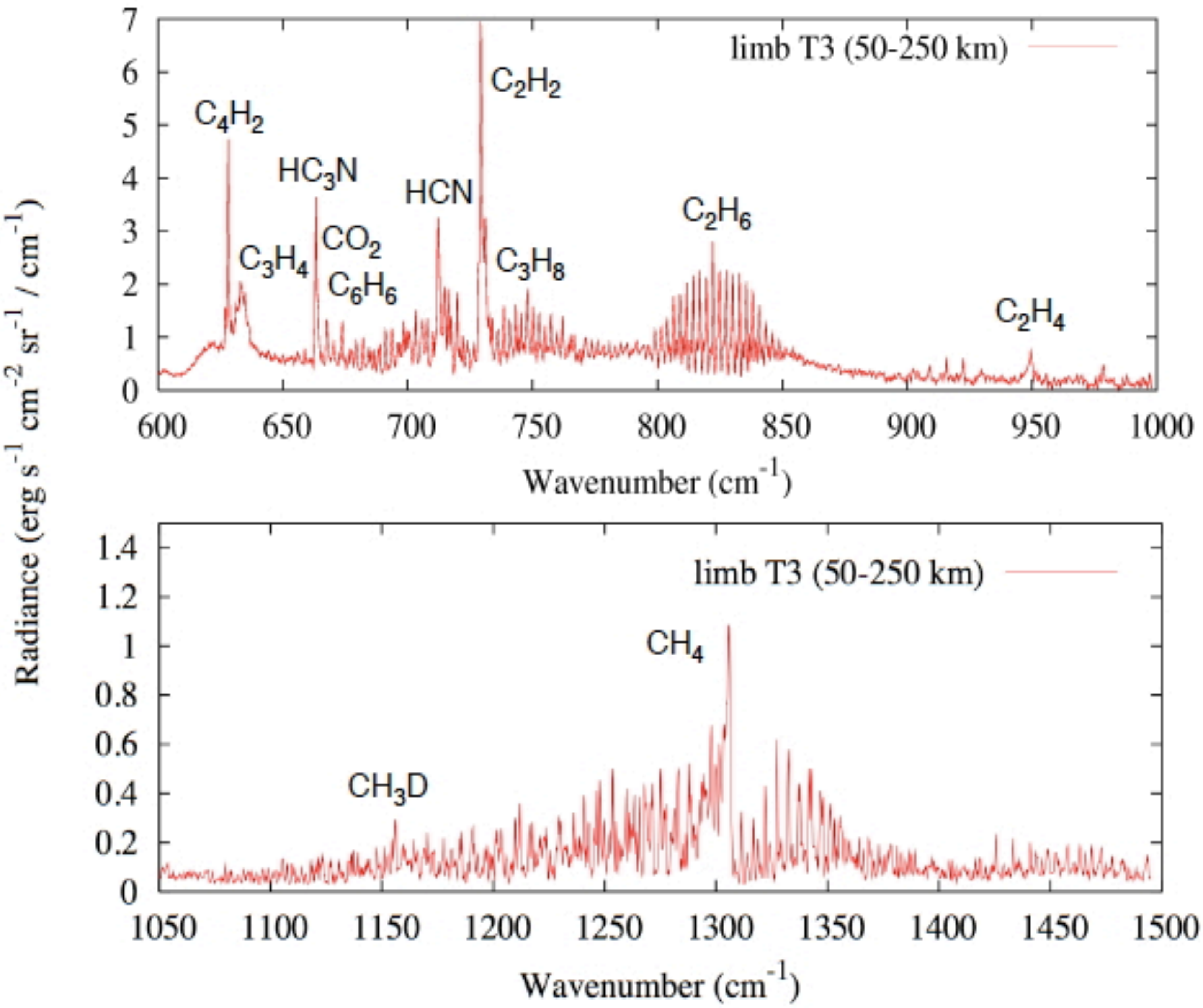




Cassini-CIRS Ta at Titan

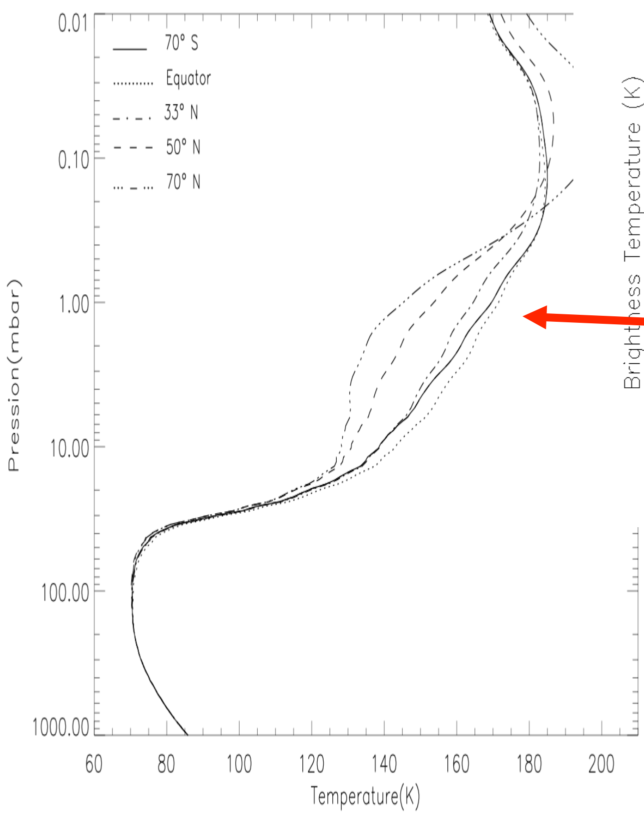


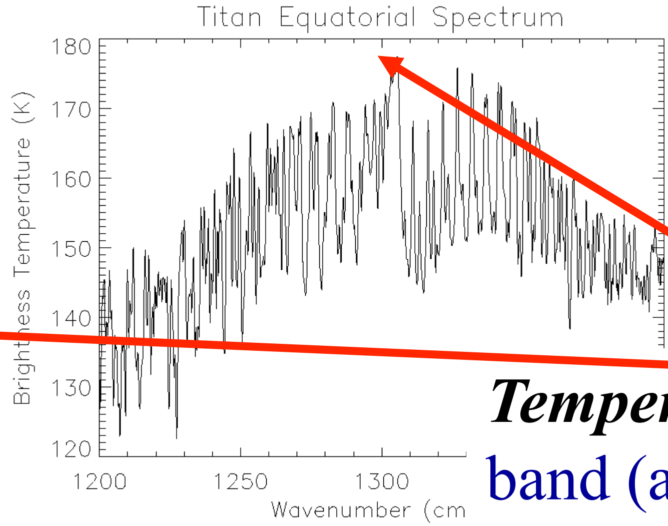
Titan



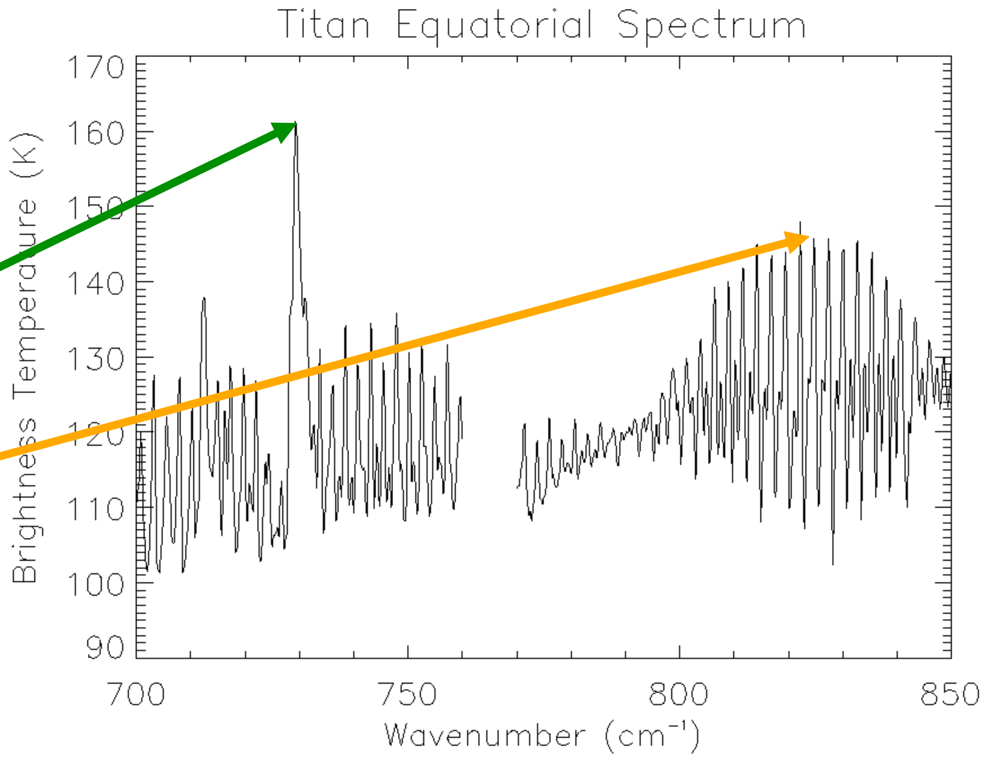
limb T3 (50-250 km)
C_4H_2
C_3H_4
HC_3N
CO_2
C_6H_6
HCN
C_2H_2
C_3H_8
C_2H_6
C_2H_4
Wavenumber (cm^{-1})
Radiance (erg s^{-1} cm^{-2} sr^{-1} / cm^{-1})
limb T3 (50-250 km)
CH_4
CH_3D
Wavenumber (cm^{-1})

Spectral Modelling



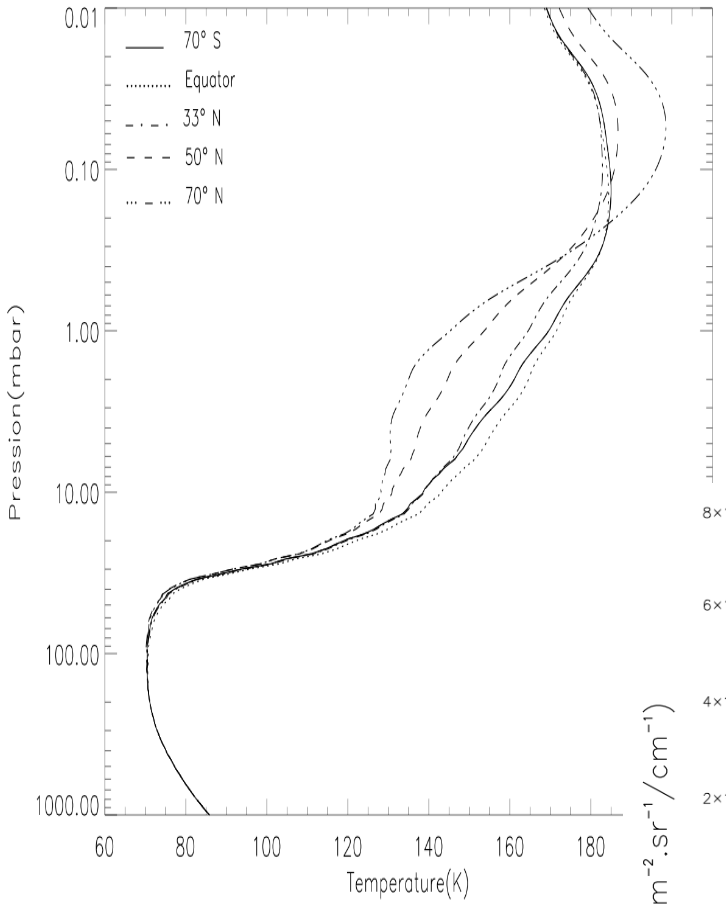


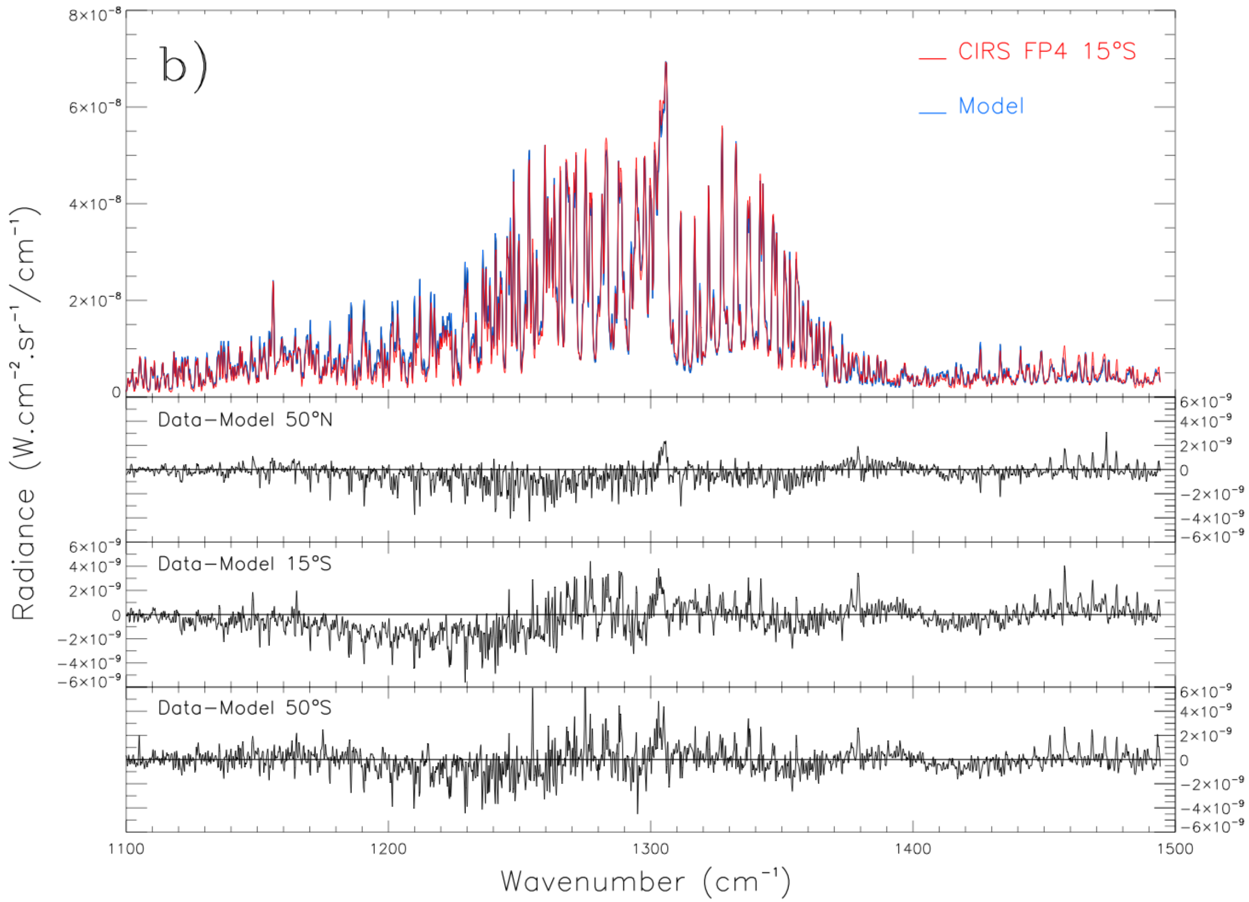
Temperatures from CH_4 ν_4 band (assuming Huygens VMR profile). Can use these to measure…



Abundances from emission bands of $^{13}CH_4$, C_2H_2, $^{13}C^{12}CH_2$, C_2H_6, $^{13}C^{12}CH_6$ - allows calculation of isotopic ratios.

Titan ν_4 CH_4 band with CIRS Gives access to thermal profile

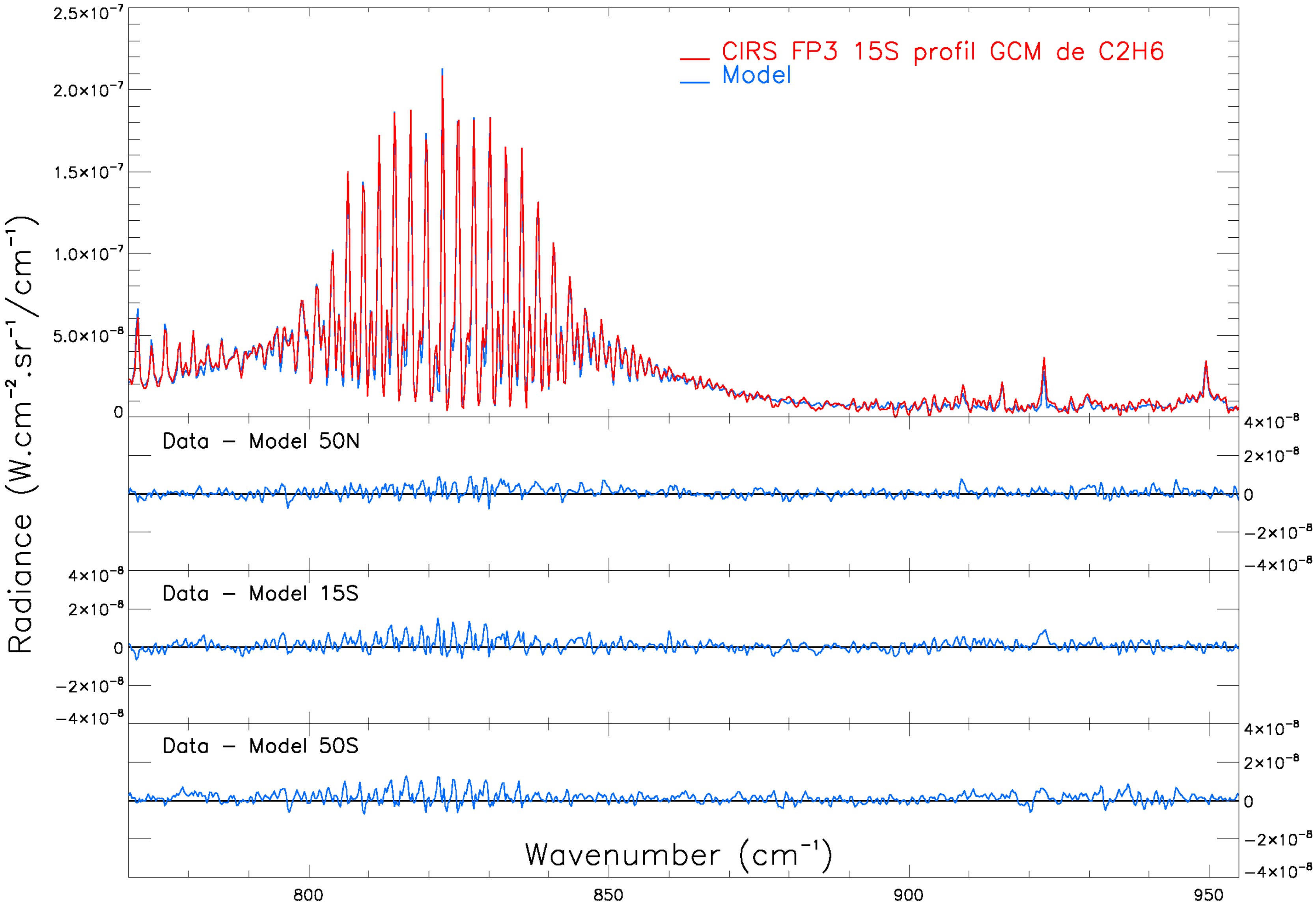




Achterberg et al., 2008

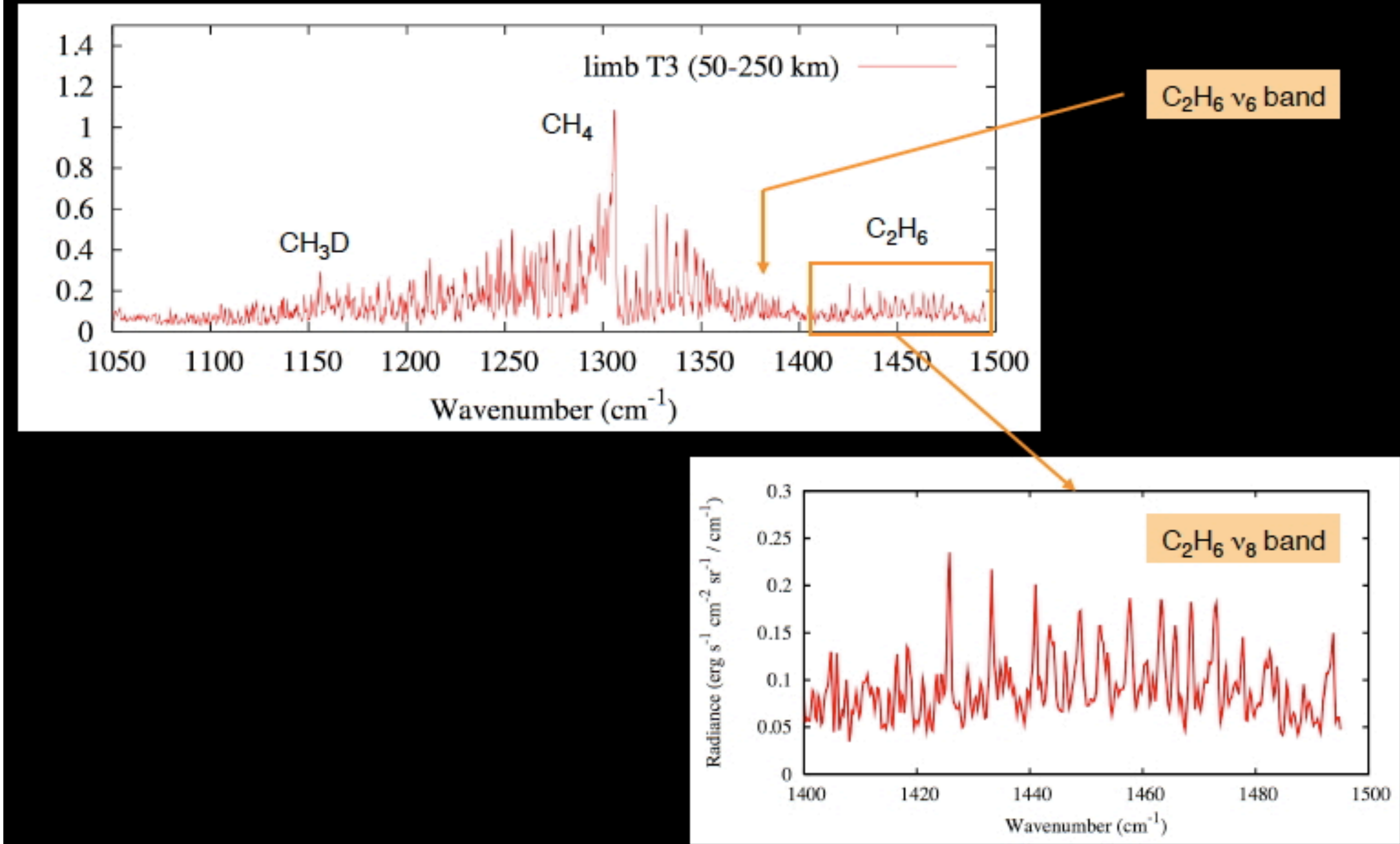
Coustenis et al., 2010

The ν_9 C_2H_6 band at 821 cm^{-1}



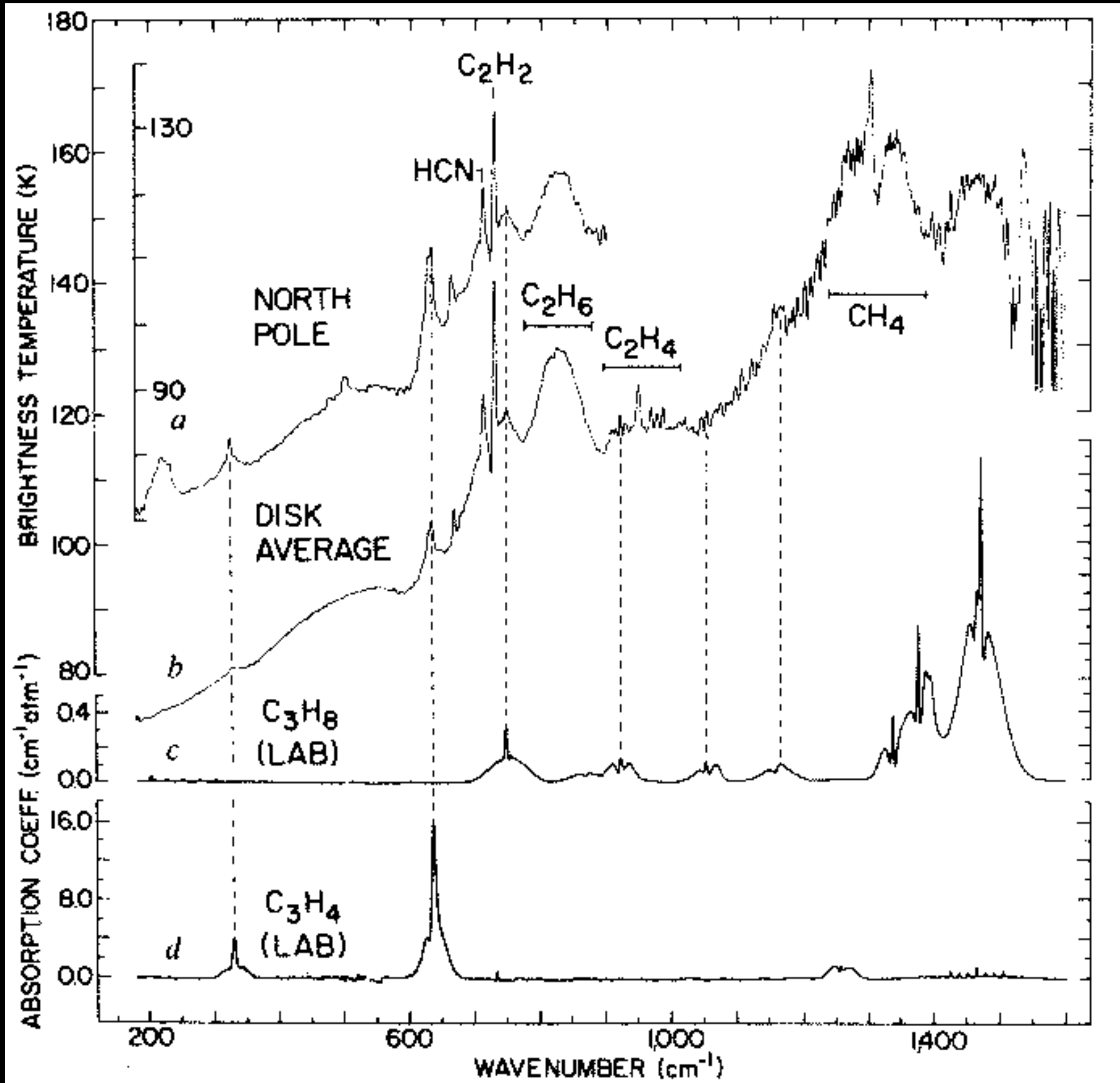
Coustenis et al., 2010 with new spectro data by Jean Vander Auwera

Ethane band

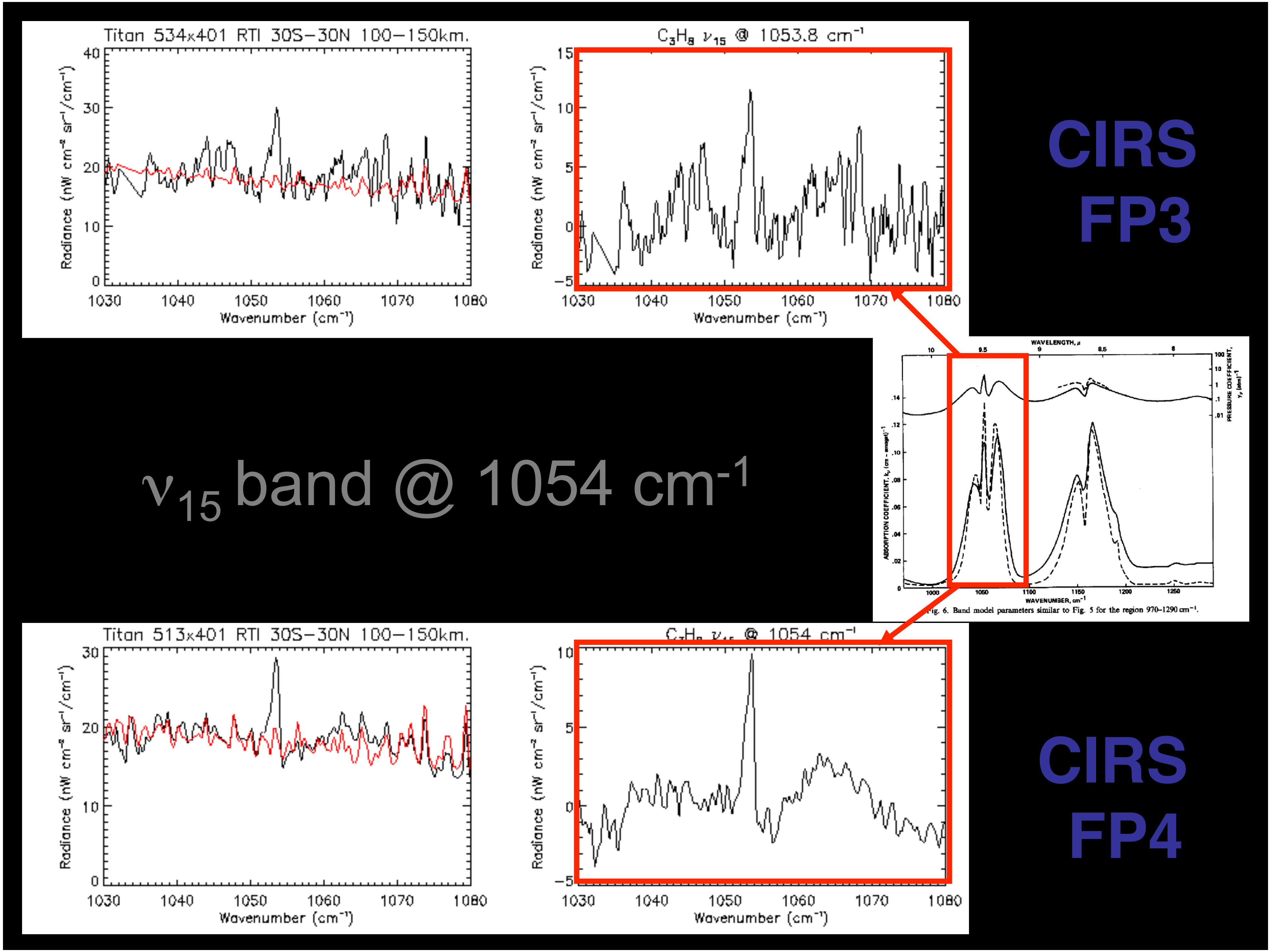


Coustenis *et al.* (2007; 2010)

Propane - Historical Perspective

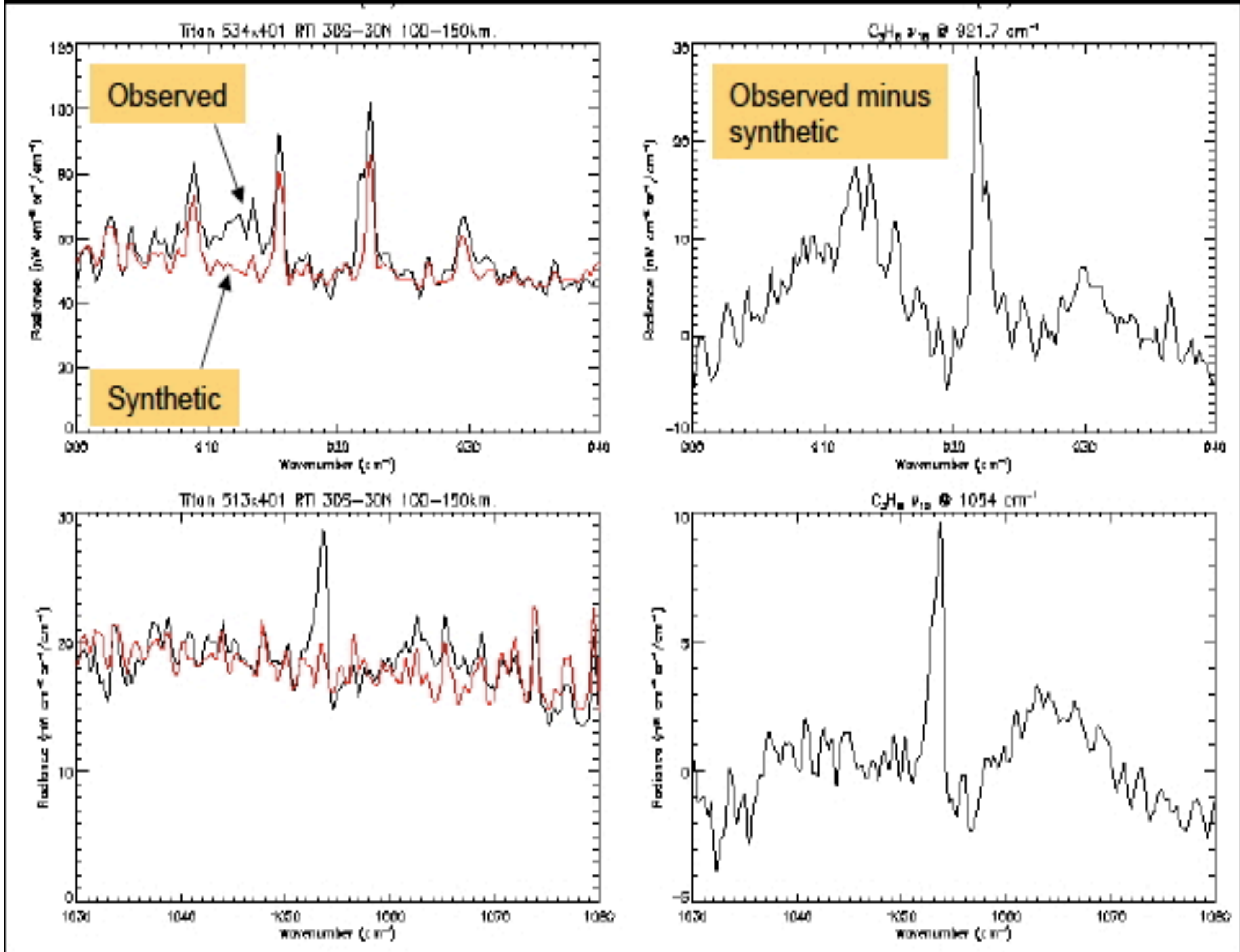


- First identification of C_3H_8 on Titan came from Voyager IRIS (Maguire *et al. Nature,1981)*
- Although multiple bands were identified, the S/N was poor,
- Only the ν_{21} band at 748 cm^{-1} was ever used for VMR determination (papers by Coustenis et al.)



Titan 534x401 RTI 30S–30N 100–150km.
C3H8 ν15 @ 1053.8 cm-1
Radiance (nW cm-2 sr-1/cm-1)
Wavenumber (cm-1)
CIRS
FP3
ν15 band @ 1054 cm-1
WAVELENGTH, μ
ABSORPTION COEFFICIENT
PRESSURE COEFFICIENT
WAVENUMBER, cm-1
Fig. 6. Band model parameters similar to Fig. 5 for the region 970–1290 cm-1.
Titan 513x401 RTI 30S–30N 100–150km.
CIRS
FP4

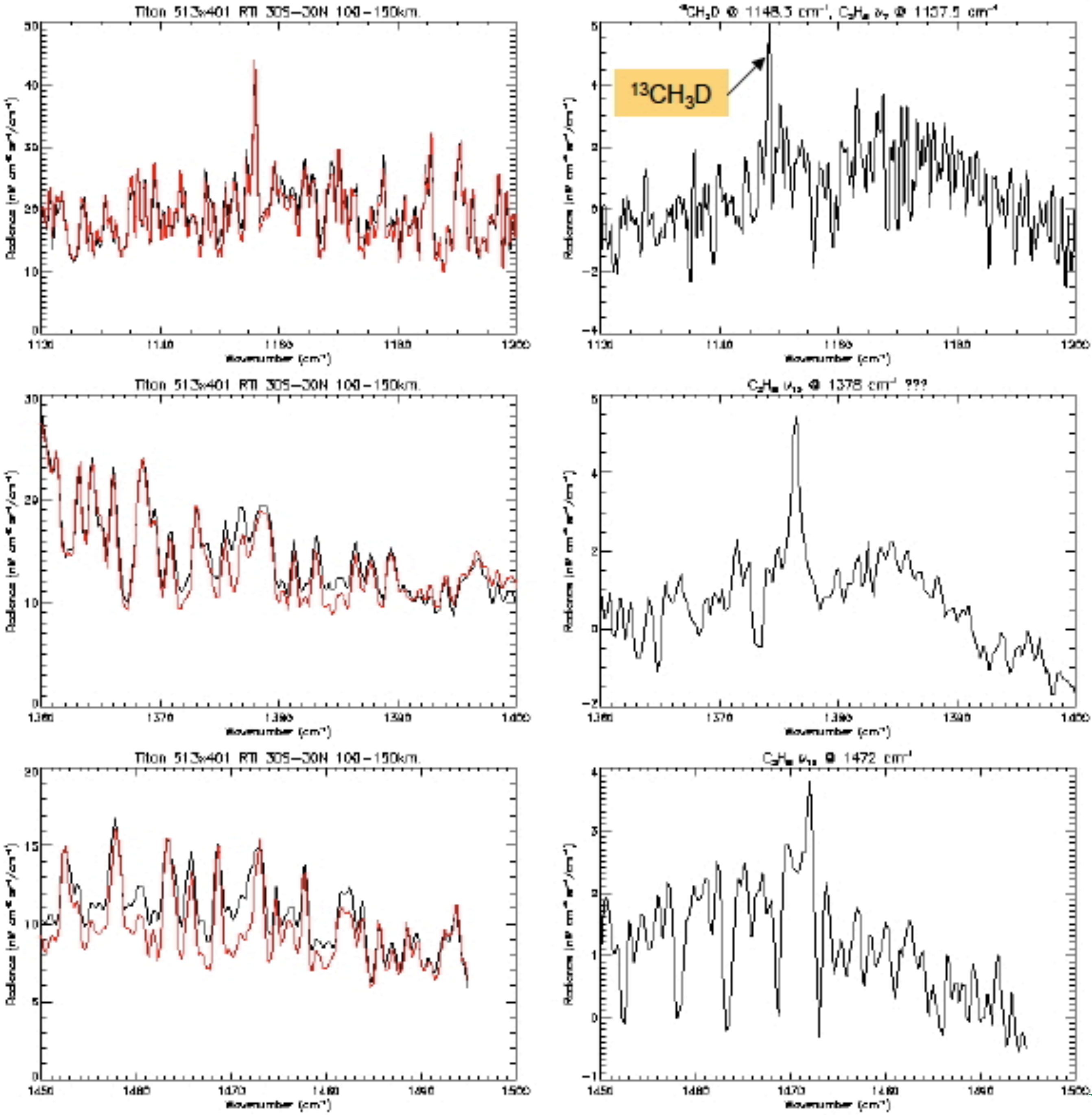
Propane



922 cm^{-1}

1054 cm^{-1}

Coustenis *et al.* (2007; 2010)



1158 cm^{-1}

1377 cm^{-1}

1472 cm^{-1}

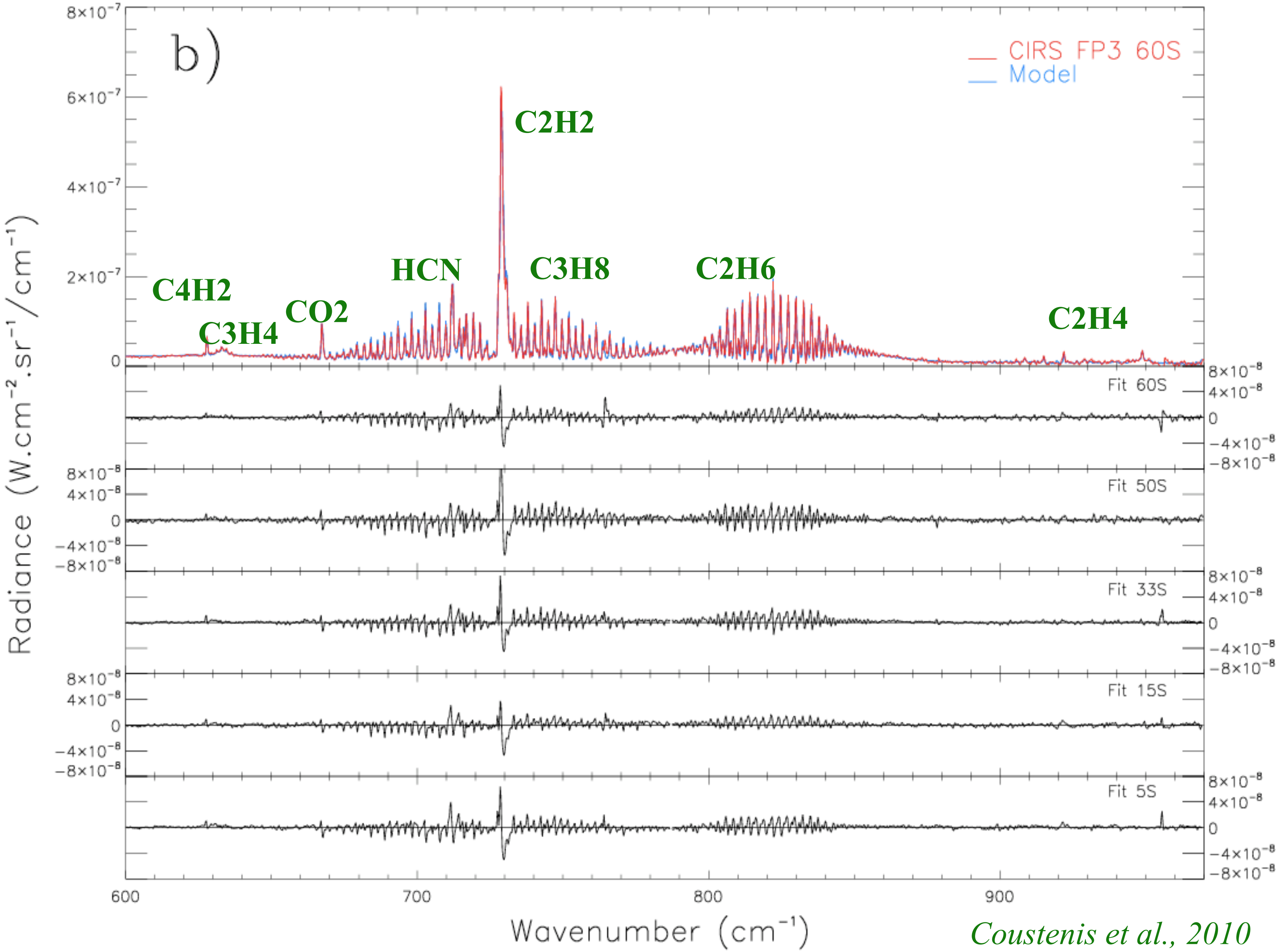
Nixon *et al.* (2007; 2009)

Propane - Summary

- All four bands of propane tentatively identified by IRIS are now clearly seen by CIRS at much higher S/N.
- In addition 2-3 further bands have now been identified on CIRS residuals, enabled by modeling and subtraction of stronger species (CH_4, C_2H_6).

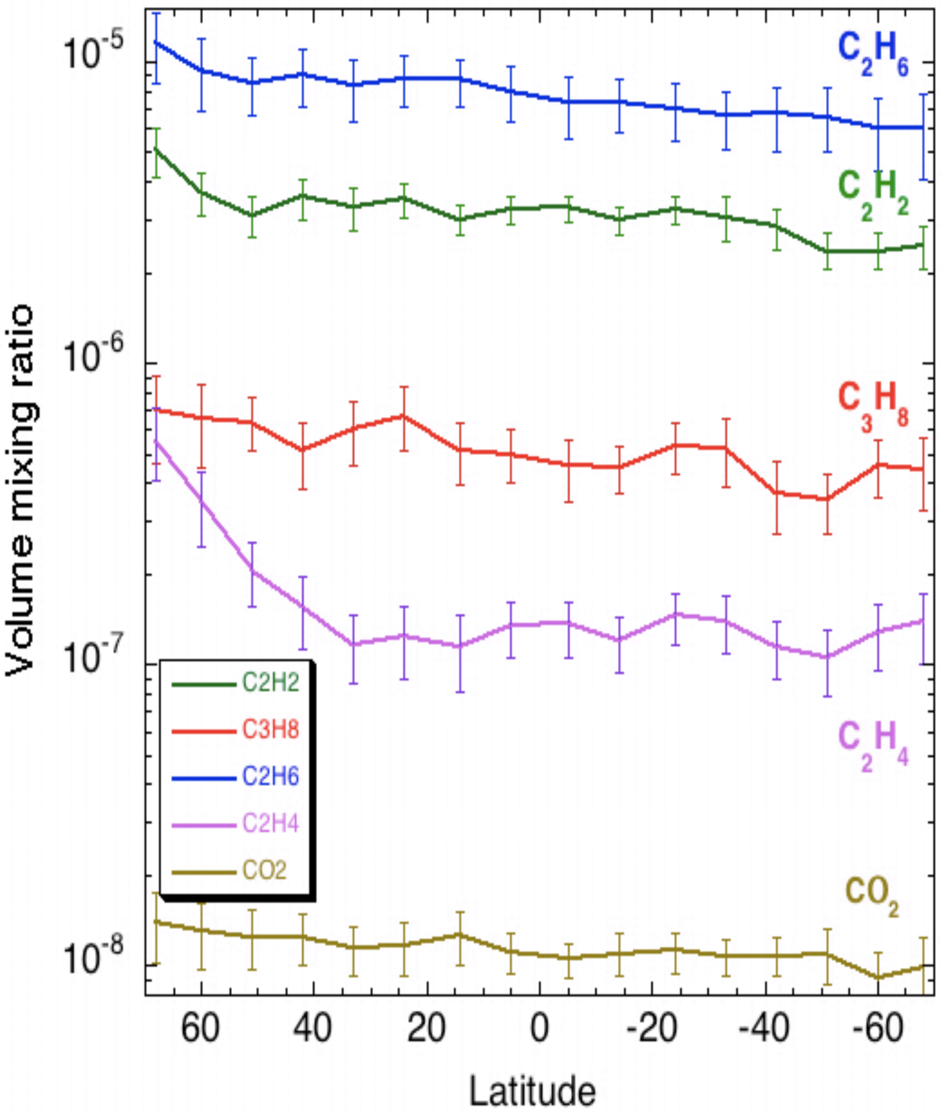
PROPANE BANDS ON TITAN

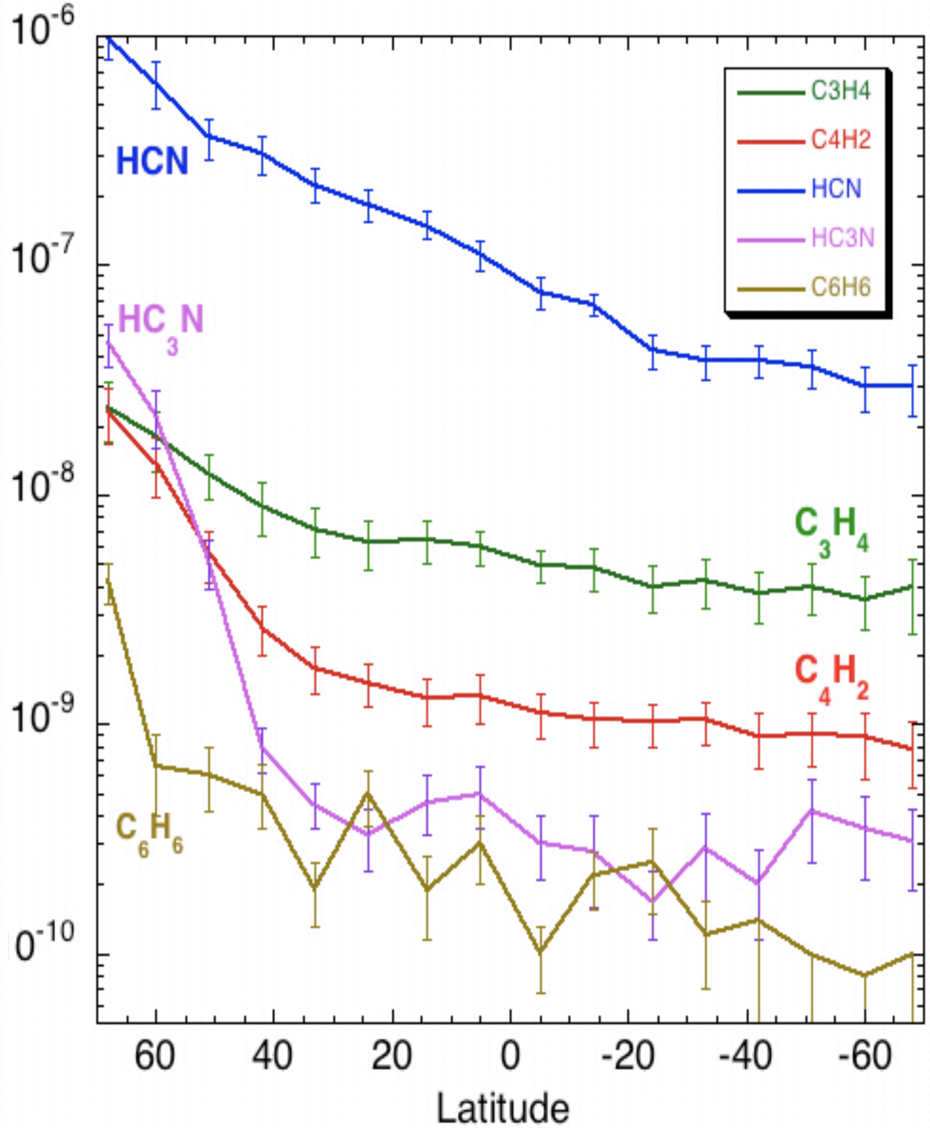
Wavenumber	Band	IRIS	CIRS
748	$\nu21$	Y	Y
860	$\nu8$	N	MAYBE
922	$\nu16$	Y	Y
1054	$\nu15$	Y	Y
1157	$\nu7$	Y	Y
1338	$\nu14$	N	N
1376	$\nu13$	N	Y
1472	$\nu19$	N	Y



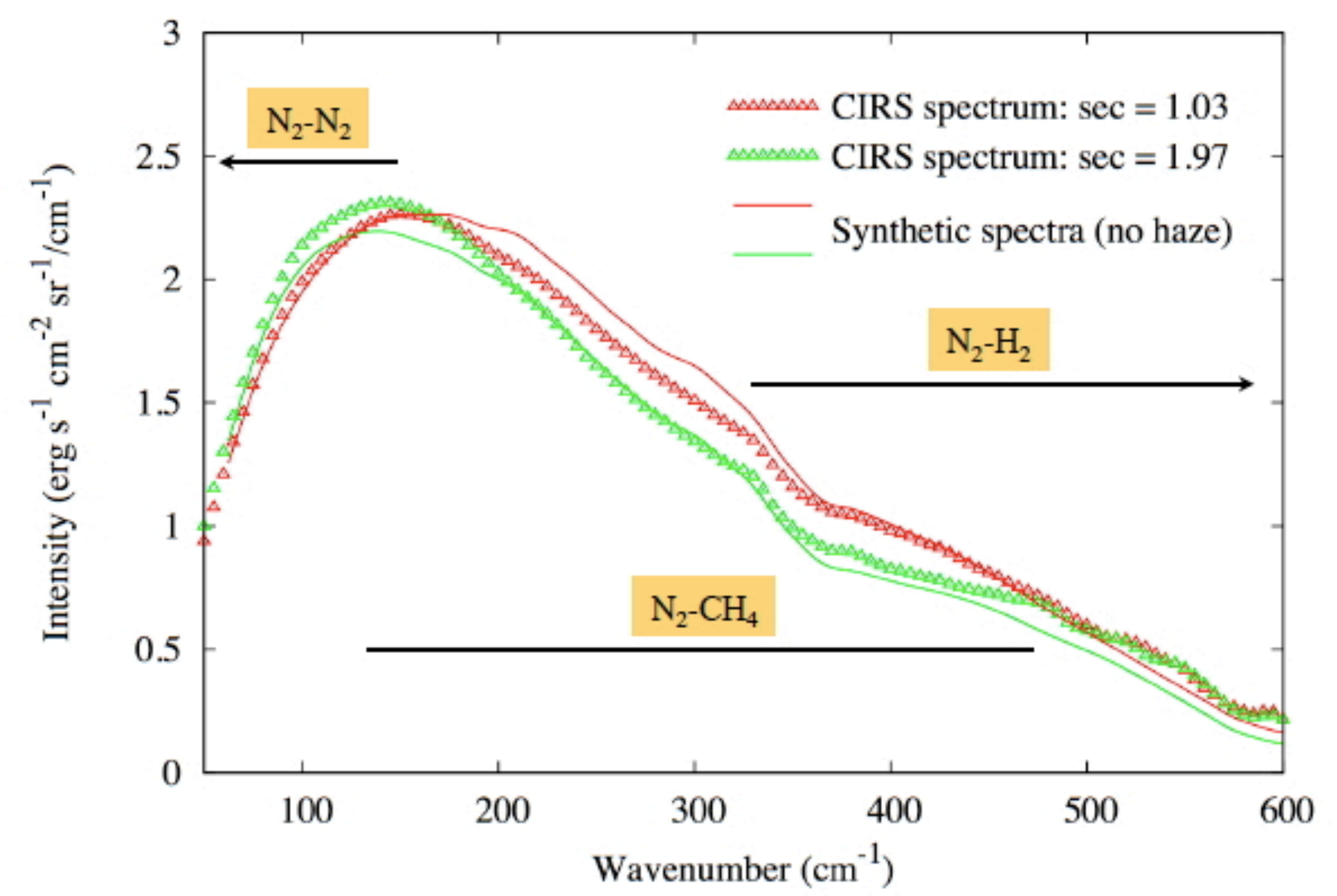
Coustenis et al., 2010

Meridional variations

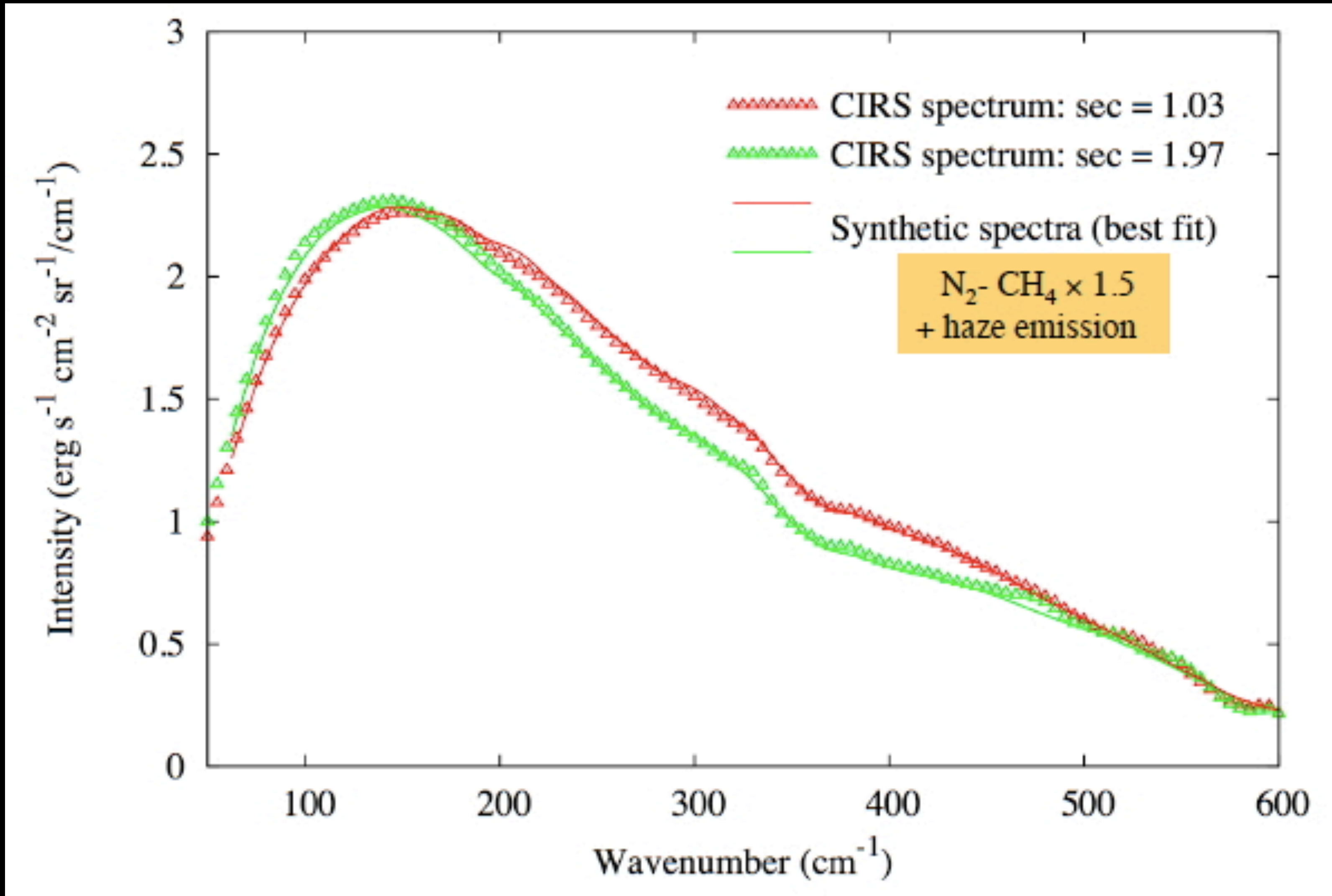




Strong increase in the North : HCN,HC3N,C3H4,C4H2,C2H4,C6H6
Small increase for: C2H2, C2H6

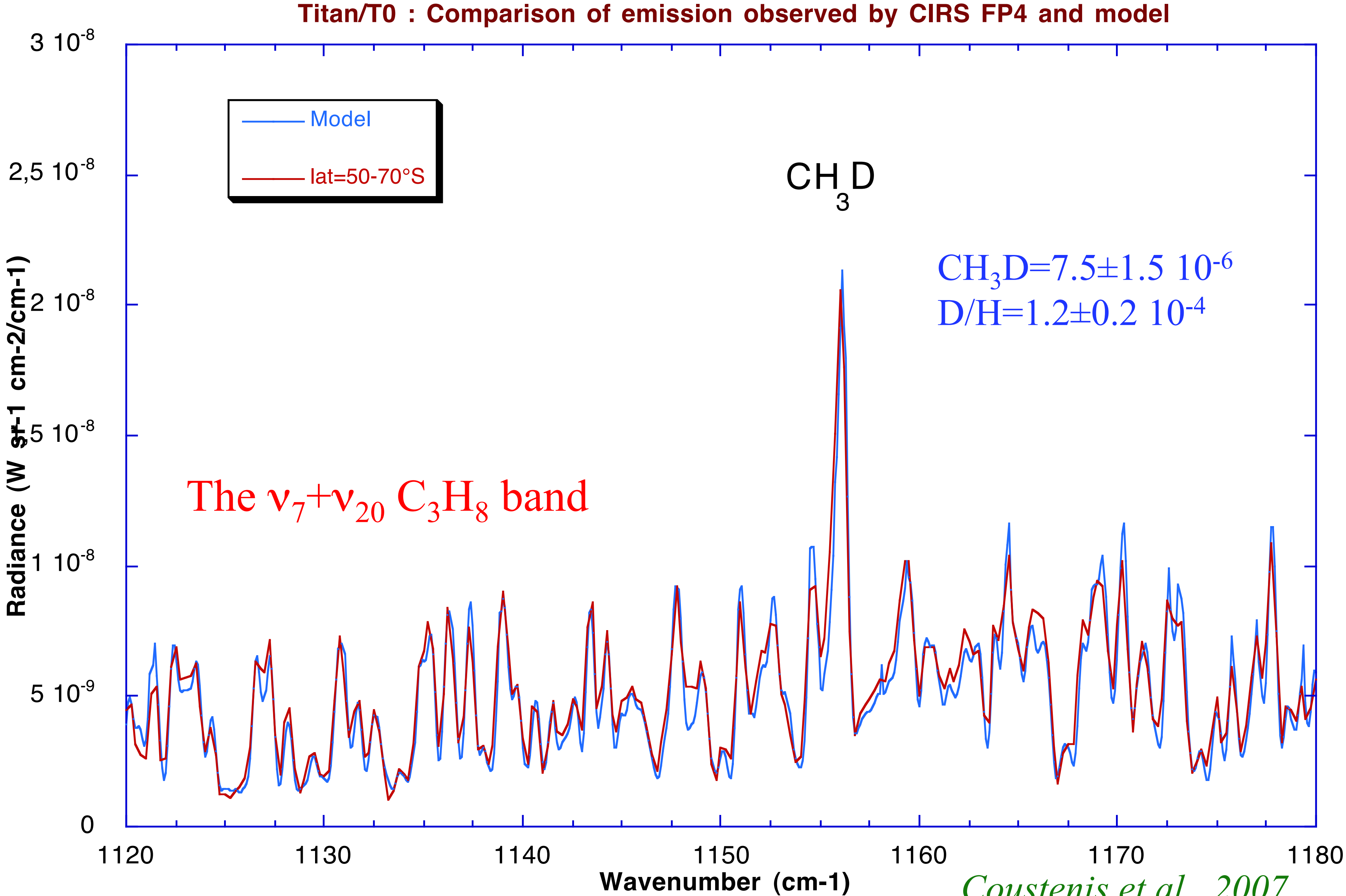


Flasar *et al.* (2005)



Flasar *et al.* (2005)

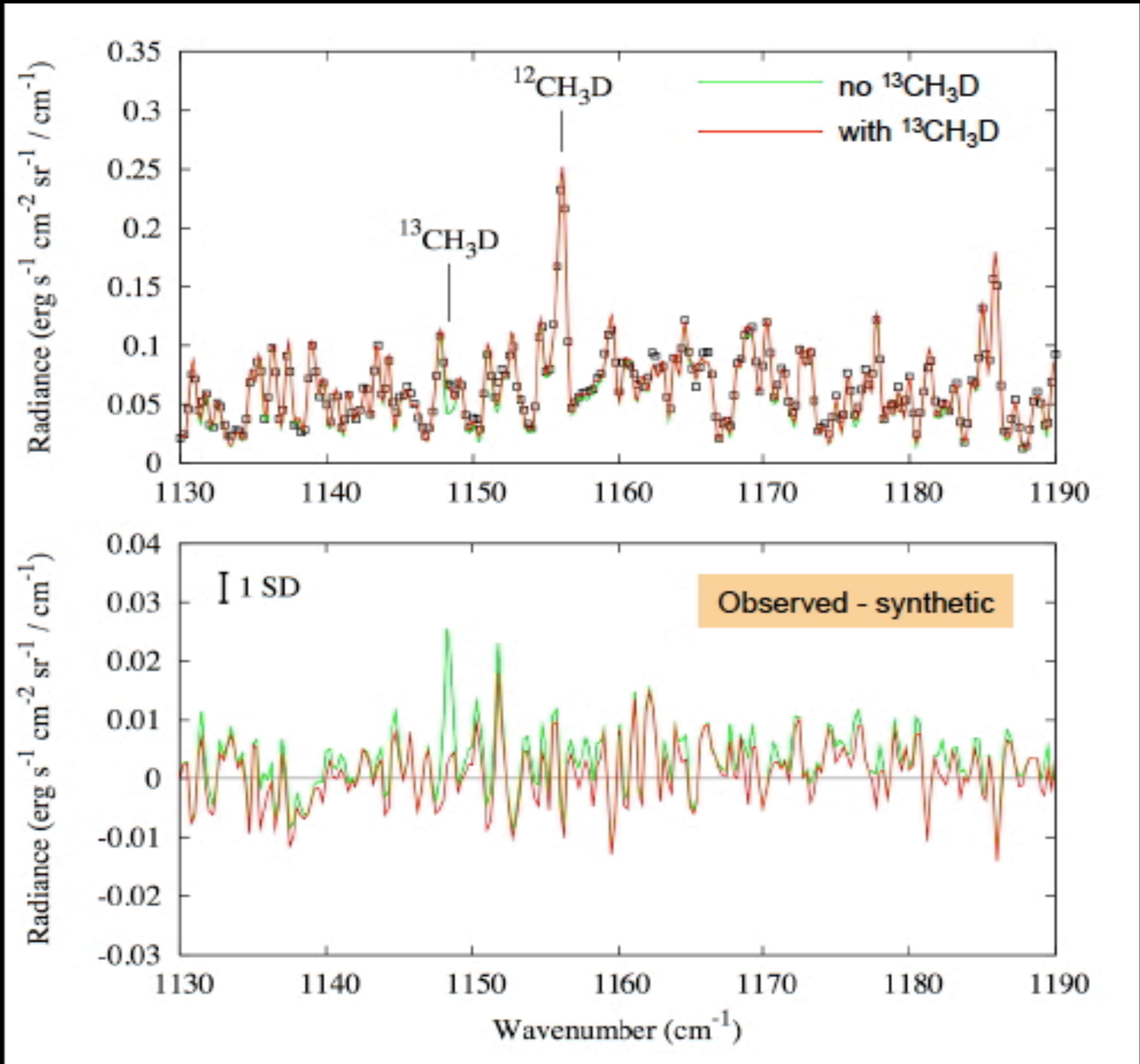
New detections
- Isotopic Ratios



Coustenis et al., 2007

Bézard et al., 2007

Detection of $^{13}CH_3D$ (ν_6) on Titan

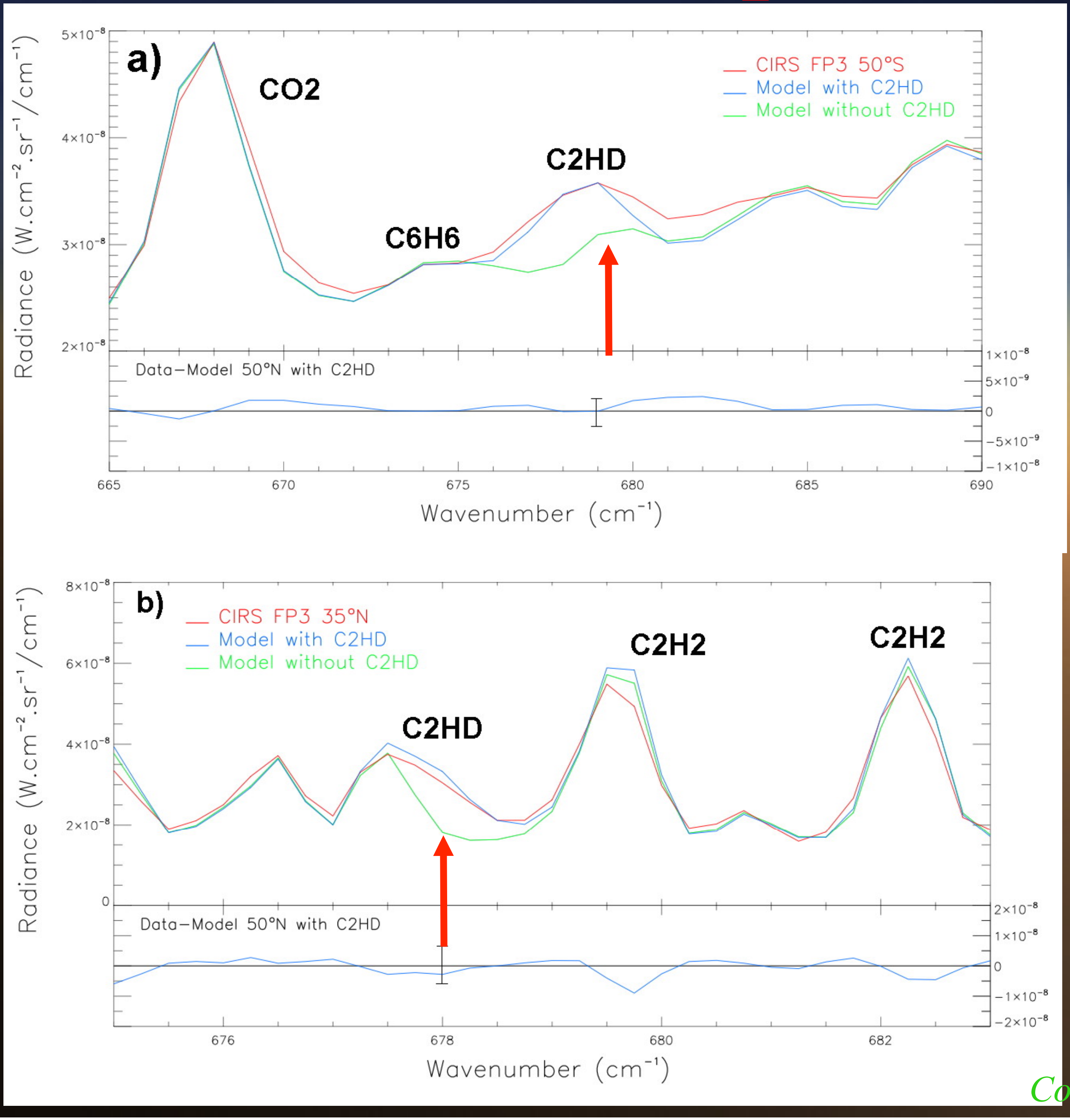


The intensity of the ν_6 band of $^{13}CH_3D$ was not measured

The ν_7 and ν_{20} propane bands exist in this region but are not analyzed due to lack of a line-by-line database only band model

Bezard *et al.* (2007)

Detection of C_2HD

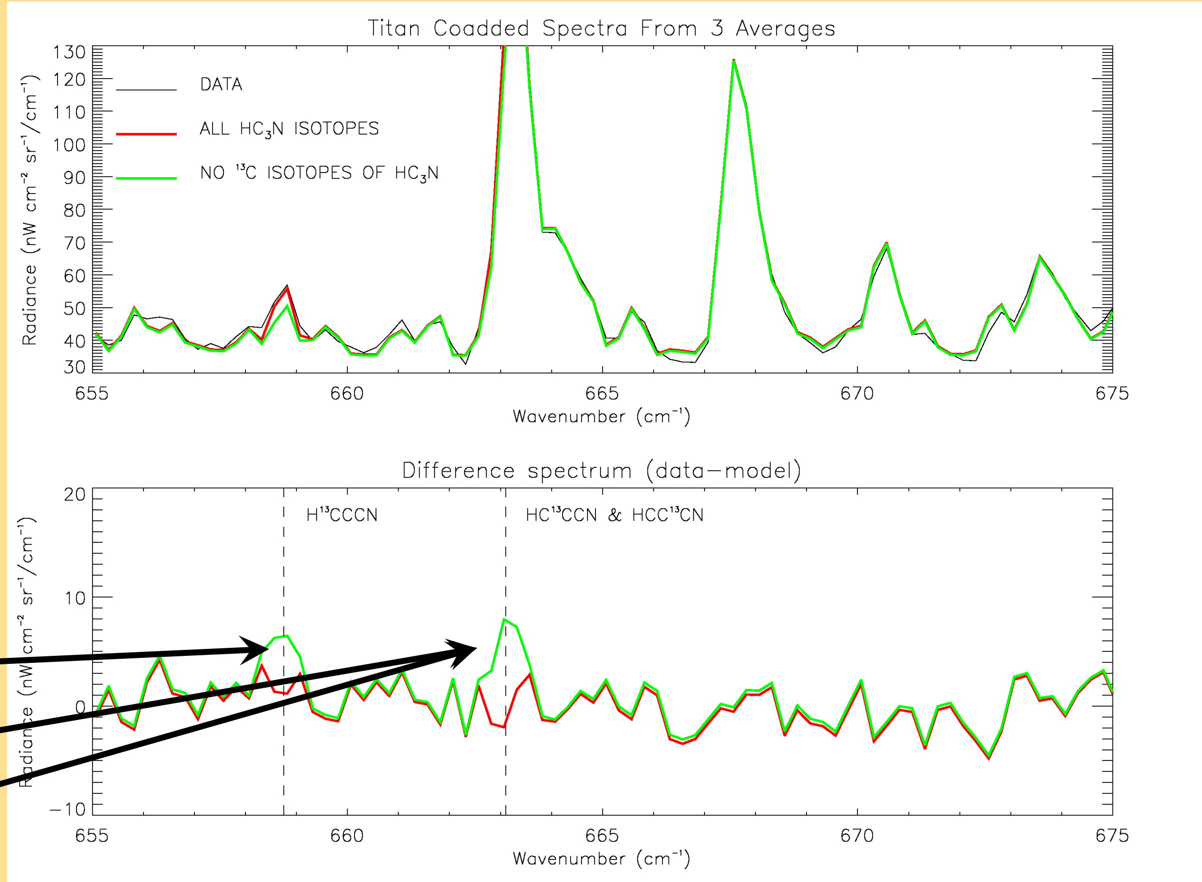


Coustenis et al., 2008

^{13}C in HC_3N: H-C≡C-C≡N

- Cyanoacetylene formed by substitution of -CN (from HCN) into C_2H_2 and C_2H_4.
- HC_3N has a strong ν_5 band @ 663.4 cm^{-1} due to bending of CH.
- Replace $^{12}C \rightarrow ^{13}C$ changes frequency:
  - $H^{13}CCCN$ = 658.7 cm^{-1}
  - $HC^{13}CCN$ = 663.1 cm^{-1}
  - $HCC^{13}CN$ = 663.1 cm^{-1}

(Jolly et al. JMS, 242, 46-54, 2007)

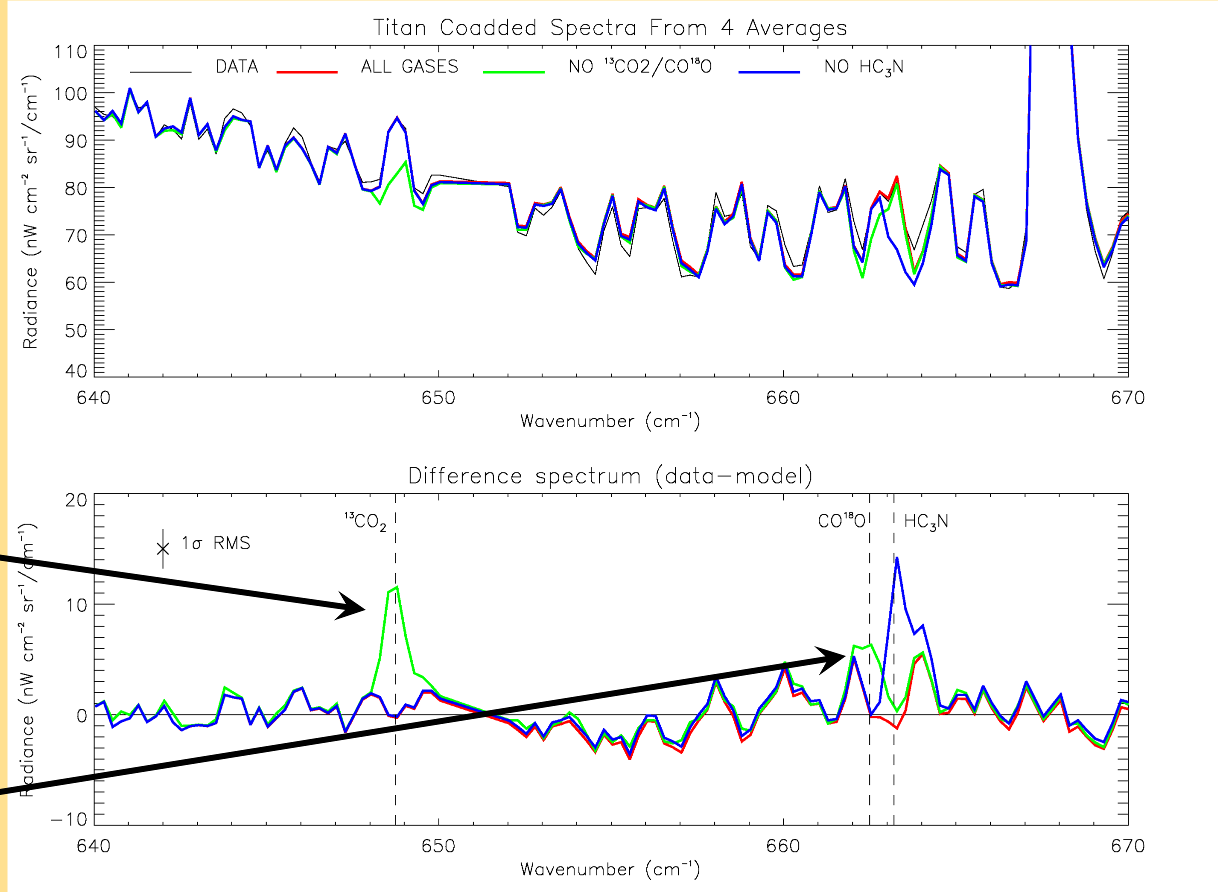


Modeling implies $^{12}C/^{13}C$ ~ 78 ± 12, in line with Huygens GCMS (82.3 ± 1). *Potential* to discriminate between C from HCN and C_2H_2.

Jennings et al., 2008, ApJL

Isotopes of CO_2

- CO_2 has been mapped via ν_2 band @ 667 cm^{-1}.
- Stratospheric abundance ~ 10^{-8}.
- Recently we have detected the isotopic emission of $^{13}CO_2$ @ 648.5 cm^{-1} (6-σ detection).
- … and *probably* the $C^{18}O^{16}O$ emission at 662.5 cm^{-1} (3-σ detection, σ = NESR only).



Retrieved isotopic ratios are $^{12}C/^{13}C$ ~ 84 ± 17, in line with Huygens GCMS (82.3 ± 1), and $^{16}O/^{18}O$ ~ 346 ± 110, perhaps 1.5x enriched versus terra.

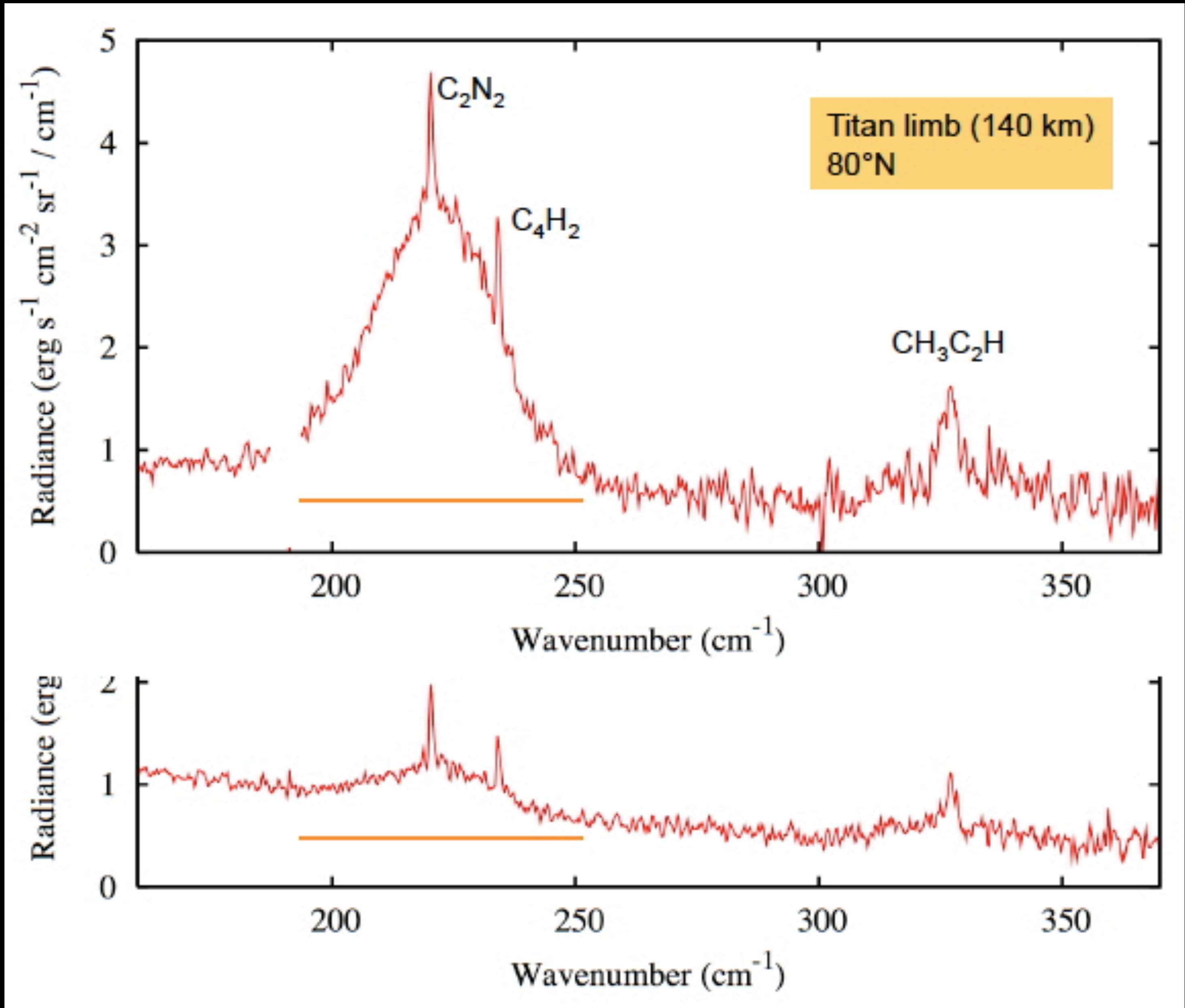
Nixon et al., 2008, ApJL

Summary of CIRS isotopic detections

	SINGLE ISOTOPES				*DOUBLE ISOTOPES*	
	D	**13C**	**15N**	**18O**	**13C2**	**D13C**
Hydrocarbons						
CH_4	D/H ~ 1.2E-4 (Coustenis 07)	12C/13C ~ 77 (Nixon 08)				D/H ~ 1.3E-4 12C/13C~ 82 (Bezard 07)
C_2H_2	D/H ~ 1.8E-4 (Coustenis 08)	12C/13C ~ 85 (Nixon 08)			POSSIBLE	
C_2H_4		POSSIBLE				
C_2H_6	POSSIBLE	12C/13C ~ 90 (Nixon 08)				
C_3H_4, C_4H_2		POSSIBLE				
Nitriles						
HCN		12C/13C ~ 75 (Vinatier 07)	14N/15N ~ 56 (Vinatier 07)			
HC_3N		Y- H13CCCN Y- HC13CCN Y- HCC13CN (Jennings in	UNLIKELY DUE TO SPECTRAL RESOLUTION			
Other						
CO_2		12C/13C ~ 84 (Nixon subm)		16O/18O~346* (Nixon subm)		

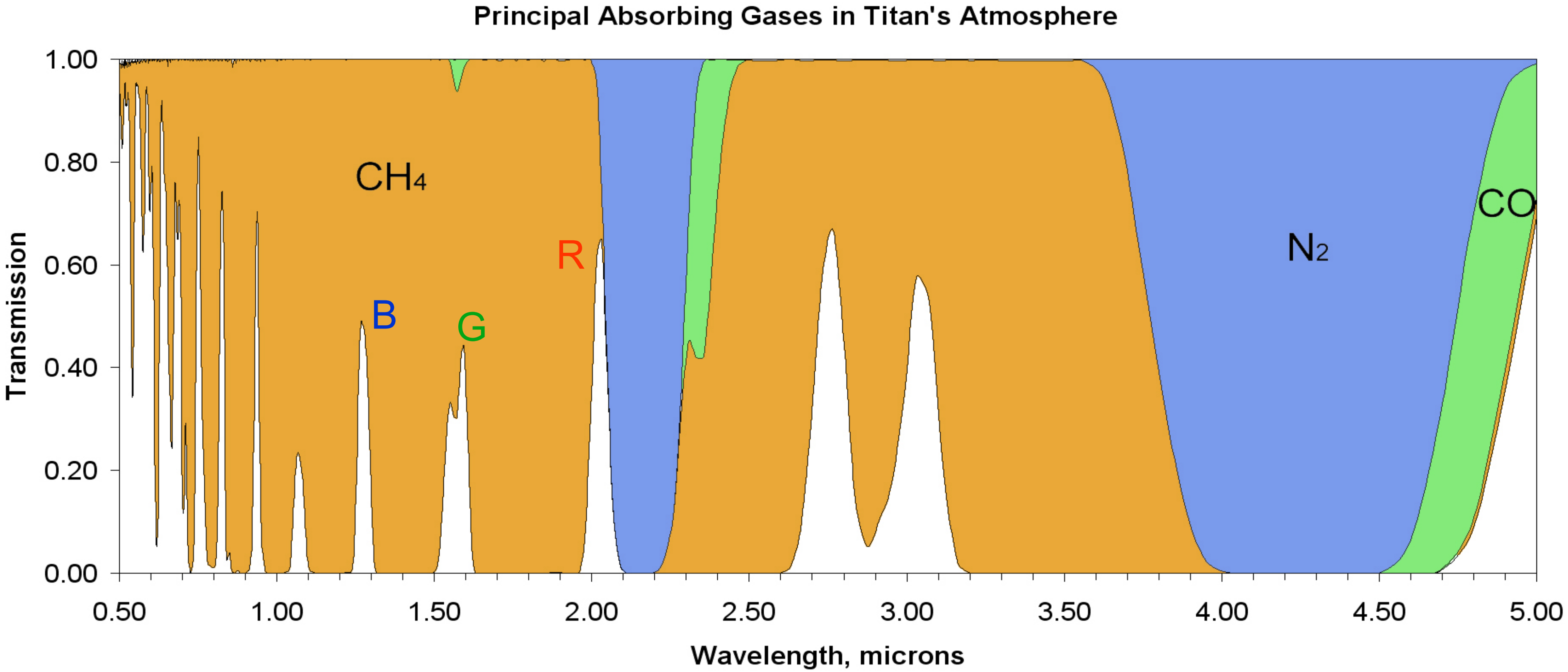
*Tentative

Unidentified features



Flasar *et al.* (2005)

The near IR spectrum of Titan



Detected and searched-for molecules on Titan

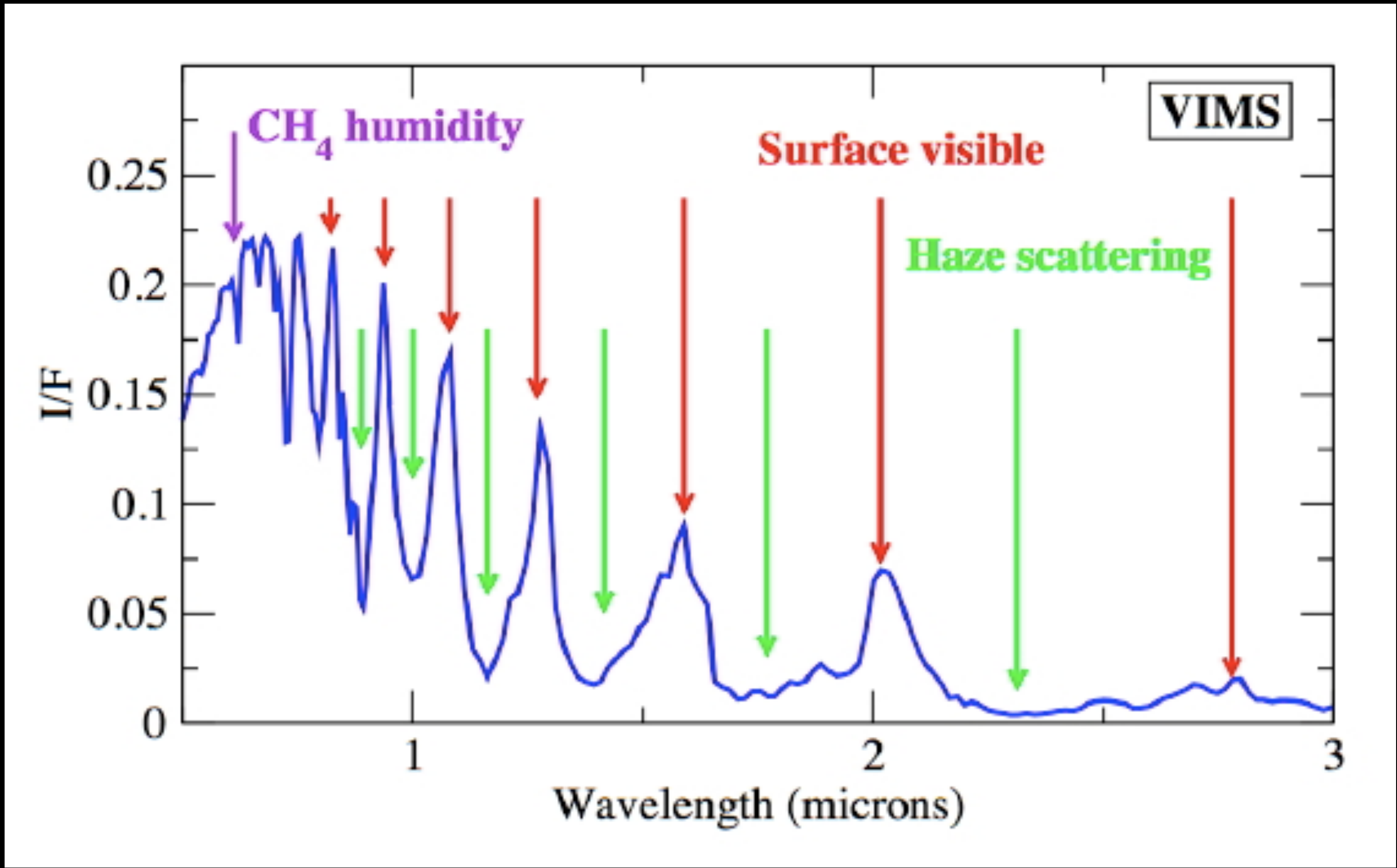
Species	IUPAC name	Common name	Molar mass (g mol^{-1})^b
C_2H_4	ethene	ethylene	28.0532
C_2H_2	ethyne	acetylene	26.0373
CH_3C_2H	propyne	methyl-acetylene	40.0639
C_4H_2	1,3-butadiyne	diacetylene	50.0587
C_6H_6	cyclohexatriene	benzene	78.1118
HCN	formonitrile	cyanide	27.0254
CH_2NH	methyleneimine	-	29.0413
CH_3CN	ethanenitrile	acetonitrile	41.0520
C_2H_3CN	2-propenenitrile	acrylonitrile	53.0627
HC_3N	2-propynenitrile	cyanoacetylene	51.0468
C_2N_2	ethanedinitrile	cyanogen	52.0349
C_4N_2	2-butynedinitrile	dicyanoacetylene	76.0563

Constituent	First detection/ range/Means	Ref. of first detection
Major		
Molecular nitrogen, N_2	Voyager Radio occultation; UV	1,2
Nitrogen, N	Voyager, 1134 Å multiplet	2
Methane, CH_4	Ground-based, UV and IR : 6190&7250 Å, 1.1&7.7 μm	3,4,5
	Ionosphere with Cassini/INMS	6
Monodeuterated methane, CH_3D	Ground-based at 1.65 and 8.6 μm	7,8
Hydrogen , H	V1, 1216 Å	2
Hydrogen, H_2	Ground-based, 3-0 S(1)	4
	Ionosphere, Cassini/INMS	6
Argon, (Ar^{36}, Ar^{40})	Cassini-Huygens/GCMS	9
Minor		
Ethane, C_2H_6	Ground-based, 822 cm^{-1}	10,11
Acetylene, C_2H_2	Ground-based, 729 cm^{-1}	7,12
	Ionosphere, Cassini/INMS	6
Monodeuterated acetylene, C_2HD	Cassini/CIRS, 678 cm^{-1}	13
Propane, C_3H_8	V1/IRIS, 748 cm^{-1}	5,14
Ethylene, C_2H_4	Ground-based, 950 cm^{-1}	7
Methylacetylene, CH_3C_2H	V1/IRIS, 328, 633 cm^{-1}	5,14
Diacetylene, C_4H_2	V1/IRIS, 220, 628 cm^{-1}	15
Benzene, C_6H_6	ISO and Cassini/CIRS, 674 c m^{-1} Huygens/GCMS	9,13,16
Hydrogen cyanide, HCN	V1/IRIS, 712 cm^{-1}	5
Cyanoacetylene, HC_3N	V1/IRIS, 500, 663 cm^{-1}	15
Cyanogen, C_2N_2	V1/IRIS, 233 cm^{-1}	15
Dicyanogen, C_4N_2	V1/IRIS, solid form at 474 cm^{-1}	17
Acetonitrile, CH_3CN	220.7 GHz multiplet	18
Carbon monoxide, CO	Ground-based, mm, submm, microwave, infrared	19
Carbon dioxide, CO_2	V1, 667 cm^{-1}	20
Water, H_2O	ISO/SWS, 237, 243 cm^{-1}	21
Ammonia, NH_3, C_2H_3CN, C_2H_5CN, CH_2NH	Suggested indirectly by modelling Cassini/INMS ionospheric data	22

[1]Lindal et al. (1983); [2]Broadfoot et al. (1981a); [3]Kuiper (1944); [4]Trafton (1972); [5]Hanel et al. (1981); [6]Waite et al. (2005); [7]Gillett (1975); [8]Lutz et al. (1981); [9]Niemann et al. (2005); [10]Gillett et al. (1973); [11]Danielson et al. (1973); [12]Caldwell et al. (1977); [13]Coustenis et al. (2007); [14]Maguire et al. (1981); [15]Kunde et al. (1981); [16]Coustenis et al. (2003); [17]Samuelson et al. (1997); [18]Bézard et al. (1993); [19]Lutz et al. (1983); [20]Samuelson et al. (1983); [21]Coustenis et al. (1998); [22]Vuitton et al. (2006).

Table from Coustenis & Taylor 2008, WSP.

Titan: near-IR bands of methane



* About 3 km-amagat of CH_4 in the atmosphere
* Inhomogeneous path

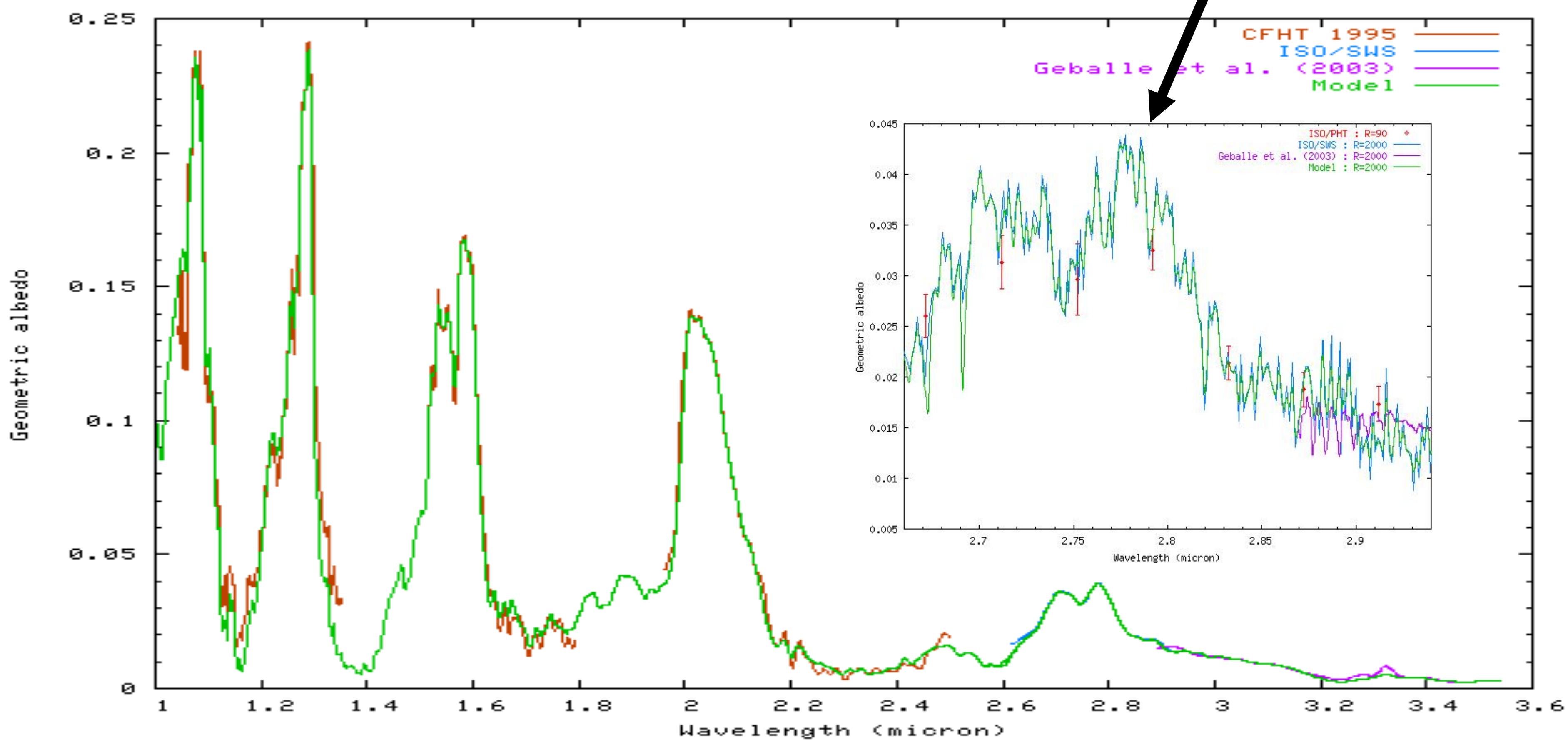
- T= 94 K; p= 1,5 bar at the surface
- T = 70-180 K; p= 100-0,1 mbar in the stratosphere

Brown *et al.* (2005)

Full spectrum of Titan in the near-IR: 1-5 µm: Modelling for the surface composition

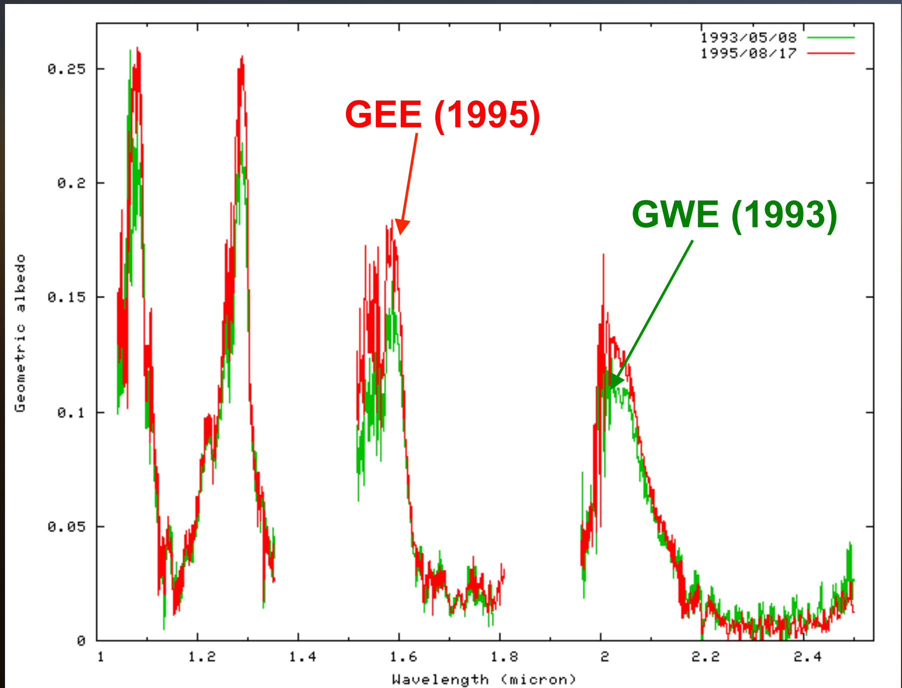
CFHT/FTS, VLT/ISAAC et ISO:
(Coustenis et al., 1995; Negrao, Coustenis et al., 2006, 2007)

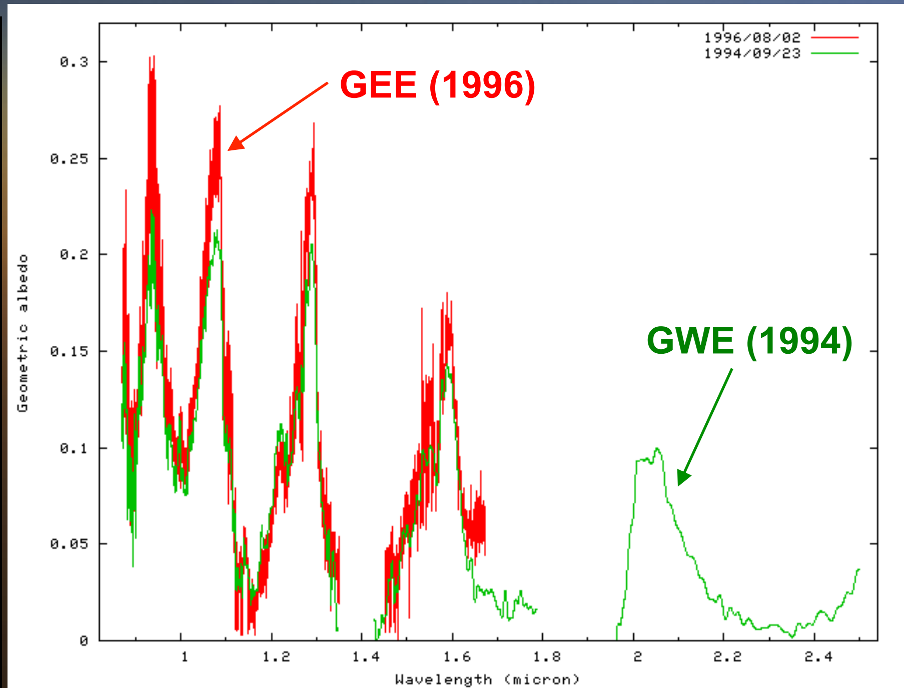
First spectrum of Titan in the 3-micron region
(Coustenis et al., 2006)



CFHT/FTS data

We have observed Titan in a series of campaigns from 1991 to 1996 with the Fourier Transform Spectrometer on the CFH Telescope. The 1991-1993 data were previously analyzed in Coustenis et al. (1995). We present here also three new datasets from the 1994, 1995 and 1996 observations, with additional information from the 0.94 micron methane window on Titan.





Date: 1993/08/05
LCM: 253° (GWE)
Range: 1 to 2.5 μm
Resolution: 5-8.5 cm^{-1}
CH_4 windows: 1.08, 1.28, 1.58, 2.0 μm

Date: 1995/08/17
LCM: 67° (GEE)
Range: 1 to 2.5 μm
Resolution: 5-8.5 cm^{-1}
CH_4 windows: 1.08, 1.28, 1.58, 2.0 μm

Date: 1994/09/23
LCM: 233° (GWE)
Range: 0.9 to 2.5 μm
Resolution: 25 cm^{-1}
CH_4 windows: 0.94, 1.08, 1.28, 1.58, 2.0 μm

Date: 1996/08/02
LCM: 60° (GEE)
Range: 0.9 to 1.7 μm
Resolution: 3 cm^{-1}
CH_4 windows: 0.94, 1.08, 1.28, 1.58 μm

The atmospheric model

We used in this work the Rannou et al. (2003) radiative and transfer code to analyse this data. This is un updated version of Mckay et al. (1989) code. The update concerns mainly the fractal description of the aerosols.

It is a 1D plane parallel model with 70 atmospheric layers, from 0 to 700 km, with a length of about 9.4 km. The model considers inputs on

- the aerosol formation
- the haze production rate (0.805×10^{-13} Kg m^{-2} s^{-1})
- the haze production pressure (1.5 Pa)
- the aerosol charging rate (20 e^{-} μm^{-1})
- the eddy diffusion coefficient (0)

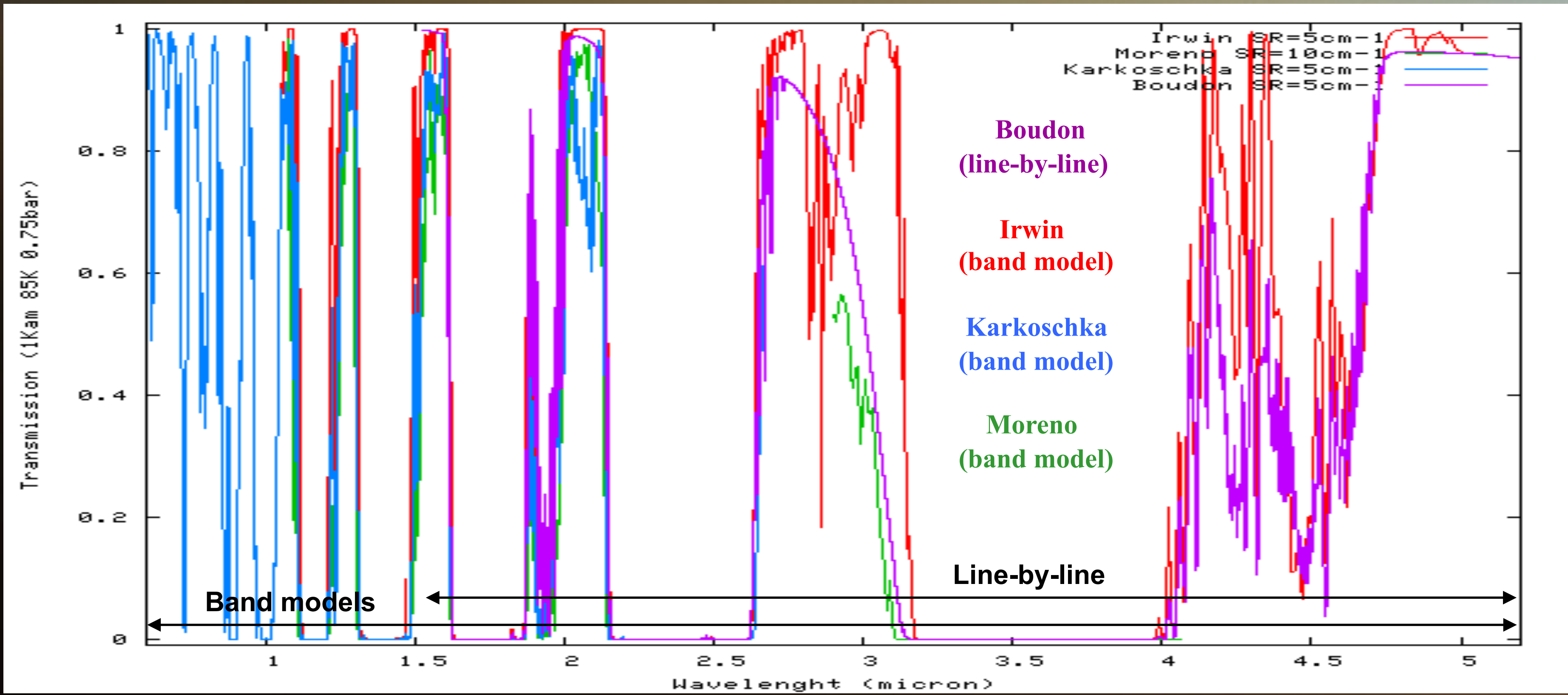
For the radiative transfer calculation inputs also include the aerosol imaginary refractive index, the methane vertical profile, the methane absorption coefficients and the ground reflectivity.

The methane mixing ratio (as a function of altitude) is defined first at the surface. It remains constant up to the saturation point, then following the saturation curve until the tropopause and remains constant above that level.

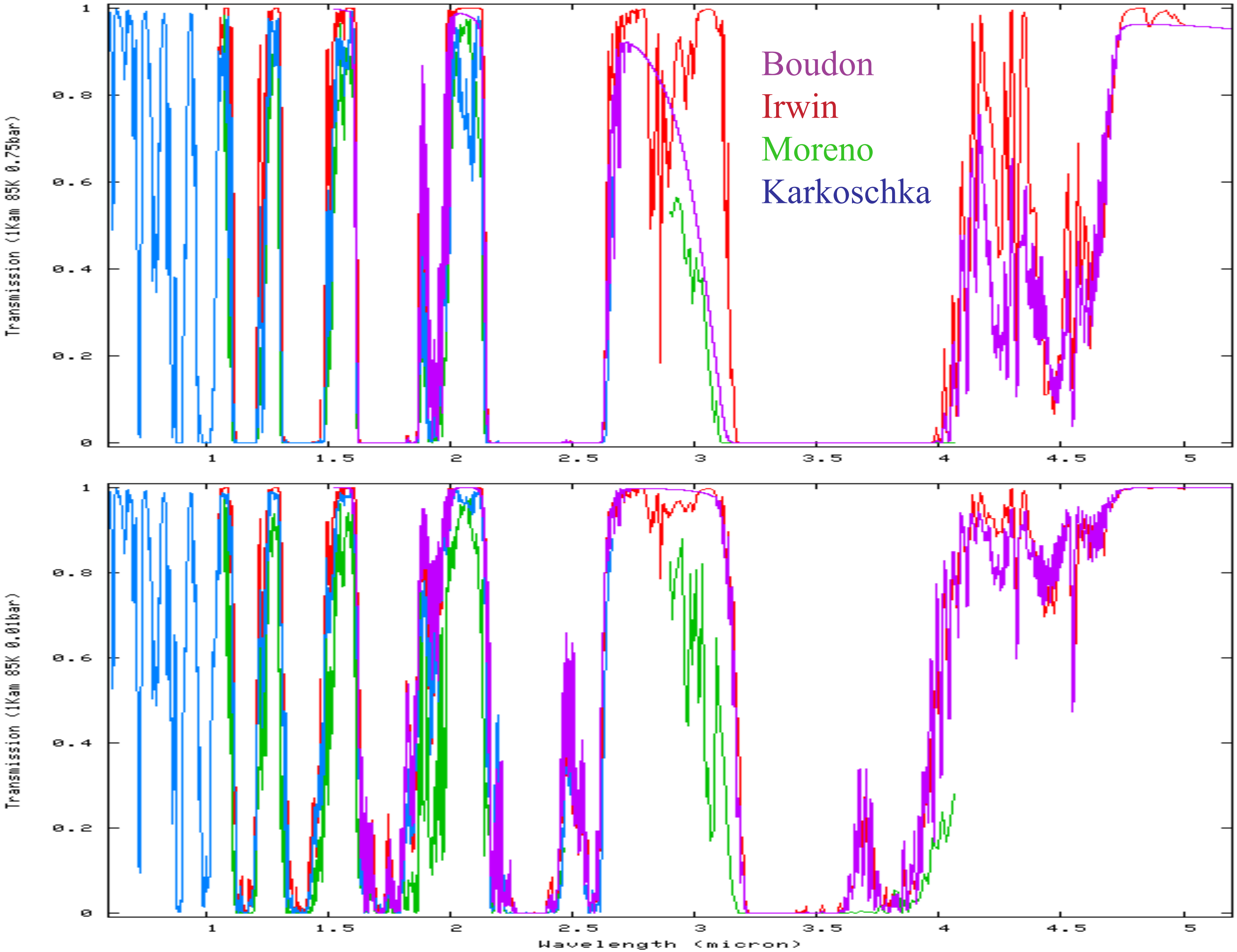
We fixed the surface methane mixing ratio at 5%, according to recent results from the DISR experiment onboard the Huygens probe (Tomasko et al., 2005), yielding a stratospheric mixing ratio of 1.78% which, although higher than the CIRS results, is still within the error bars presented in Flasar et al. (2005).

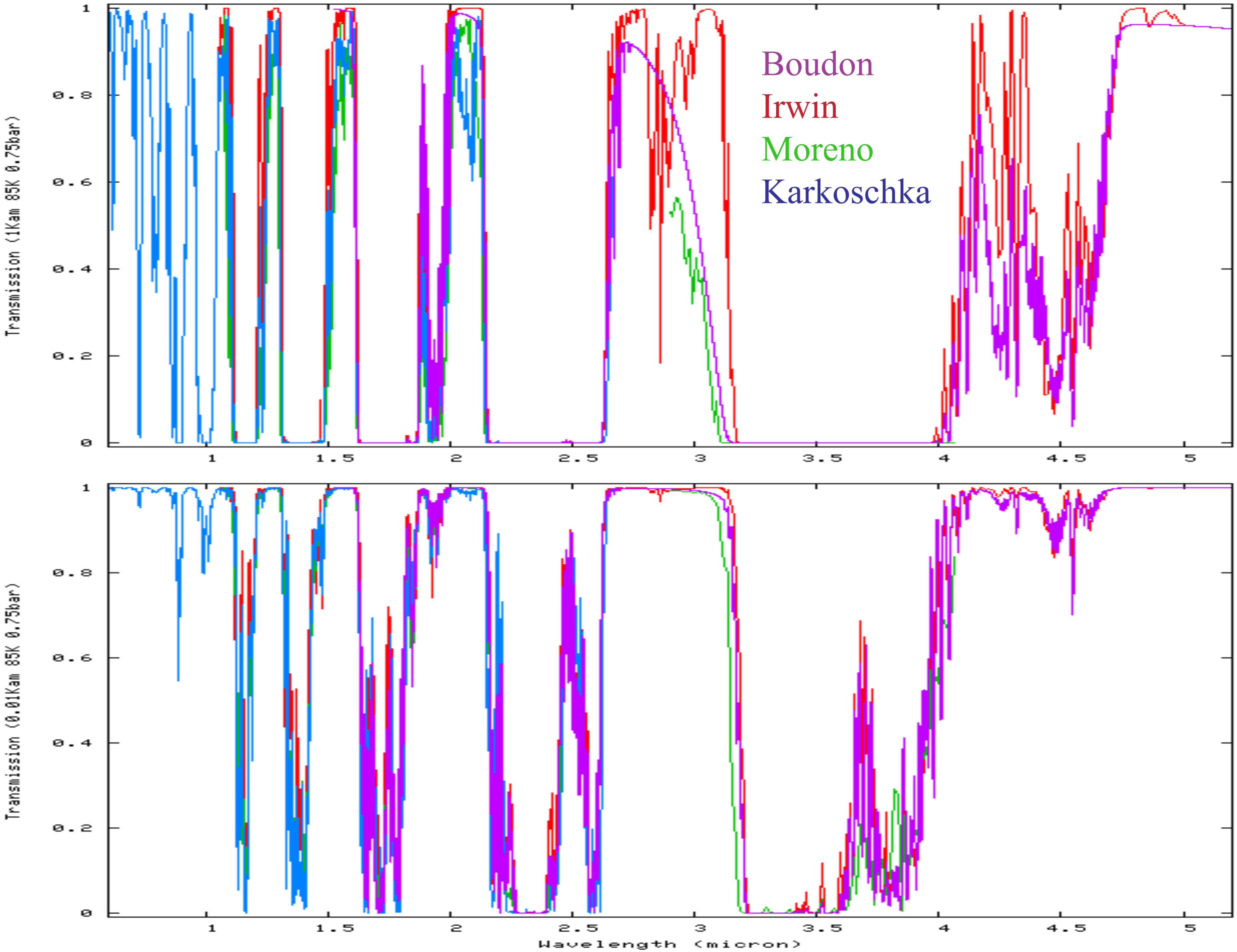
Methane absorption coefficients

In this work we compare methane absorption coefficients from line-by-line calculations by Boudon et al. (2006) with coefficients from band models by Irwin et al. (2006), E. Karkoschka (private communication for λ < 1.05 micron and Karkoschka (1998) for λ > 1.05 micron) and R. Moreno (updated from Coustenis et al. (1995)). These coefficients are plotted below, calculated for one condition of pressure and temperature.

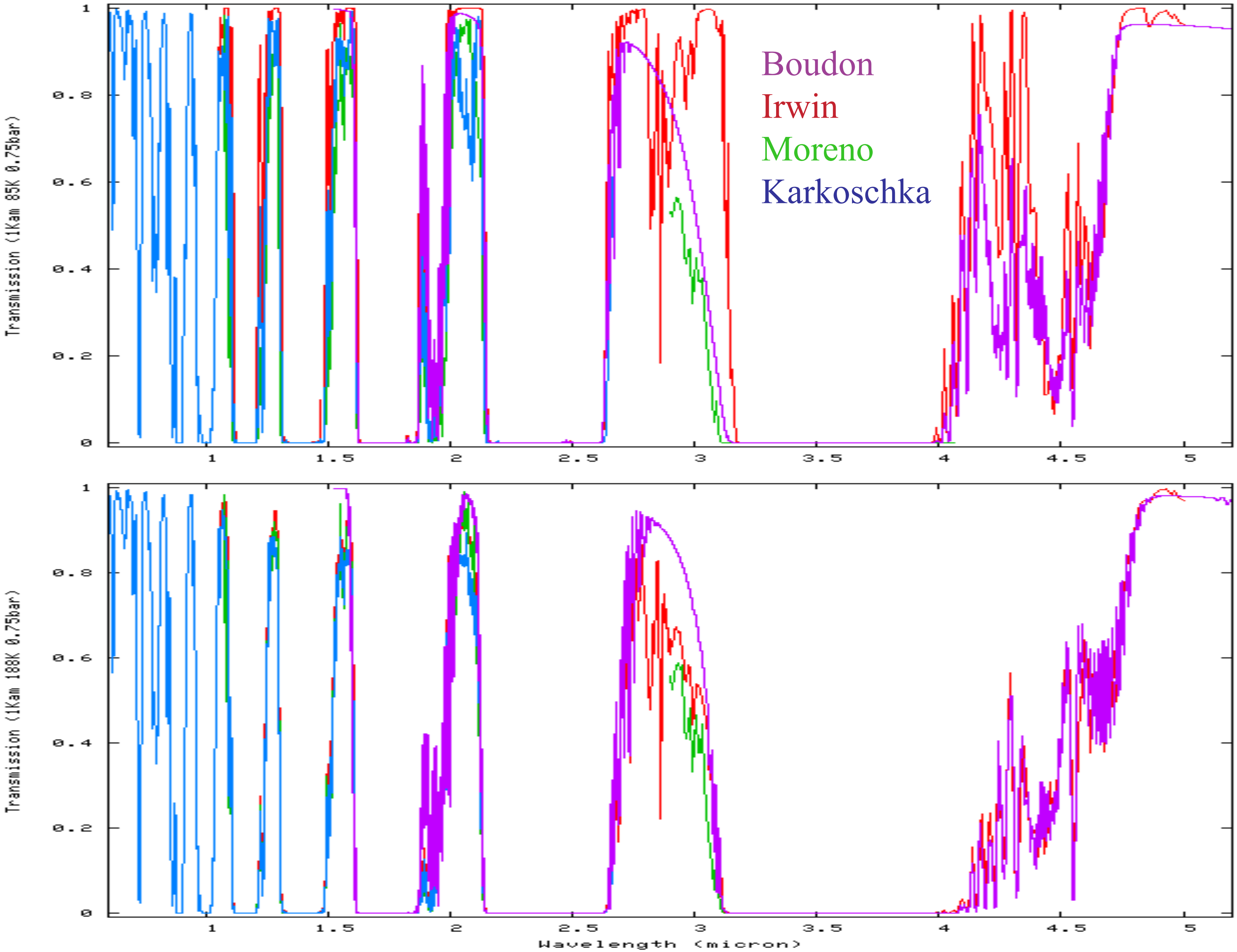


Path-lenght: 1 km.am ; **Temperature:** 85 K ; **Pressure:** 750 mbar


Boudon
Irwin
Moreno
Karkoschka
Transmission (1Kam 85K 0.75bar)
Transmission (1Kam 85K 0.01bar)
Wavelength (micron)



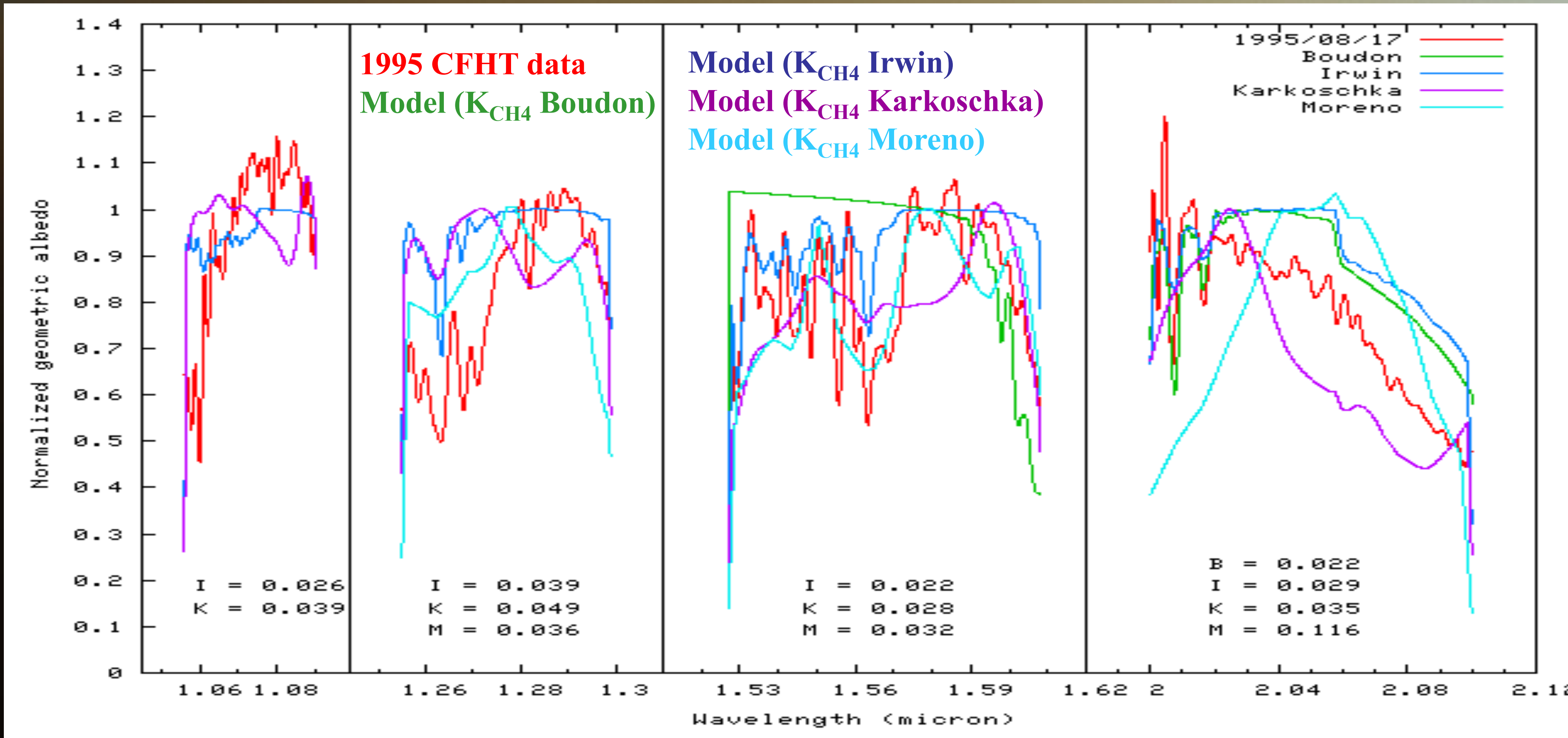
Boudon
Irwin
Moreno
Karkoschka
Transmission (1Kam 85K 0.75bar)
Transmission (0.01Kam 85K 0.75bar)
Wavelength (micron)



Boudon
Irwin
Moreno
Karkoschka
Transmission (1Kam 85K 0.75bar)
Transmission (1Kam 188K 0.75bar)
Wavelength (micron)

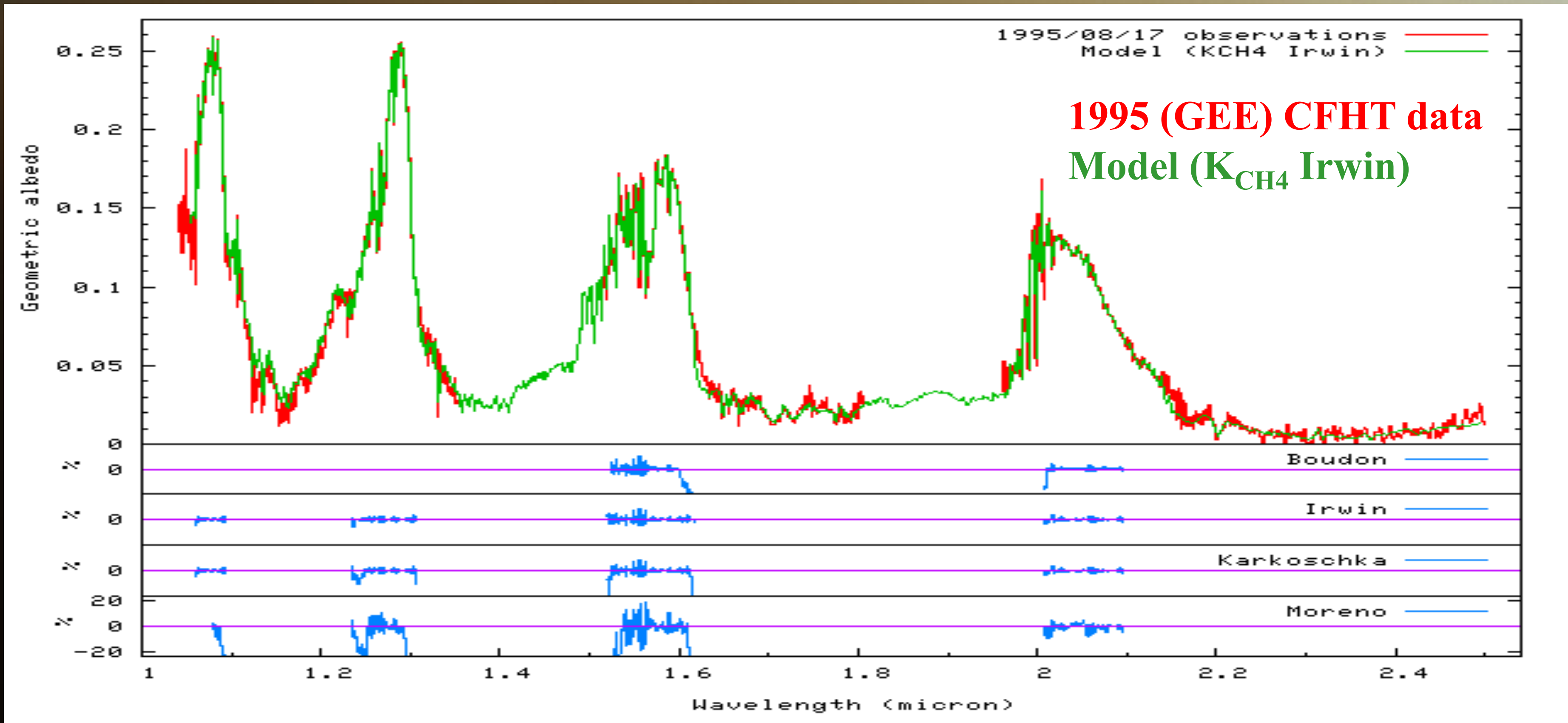
Fit of the CFHT data (with a constant surface albedo)

We calculated the geometric albedo (using a constant surface albedo) in the different methane windows, and then normalized the geometric albedo value at the center of each methane window. This was done both for the observations (the figure below shows the 1995 data as an example) and for the model, for each set of methane coefficients. The χ^2 factor was calculated for each set of coefficients. Line-by-line calculations by Boudon et al. (2006) and Irwin et al. (2006) band model seem to yield the best results.



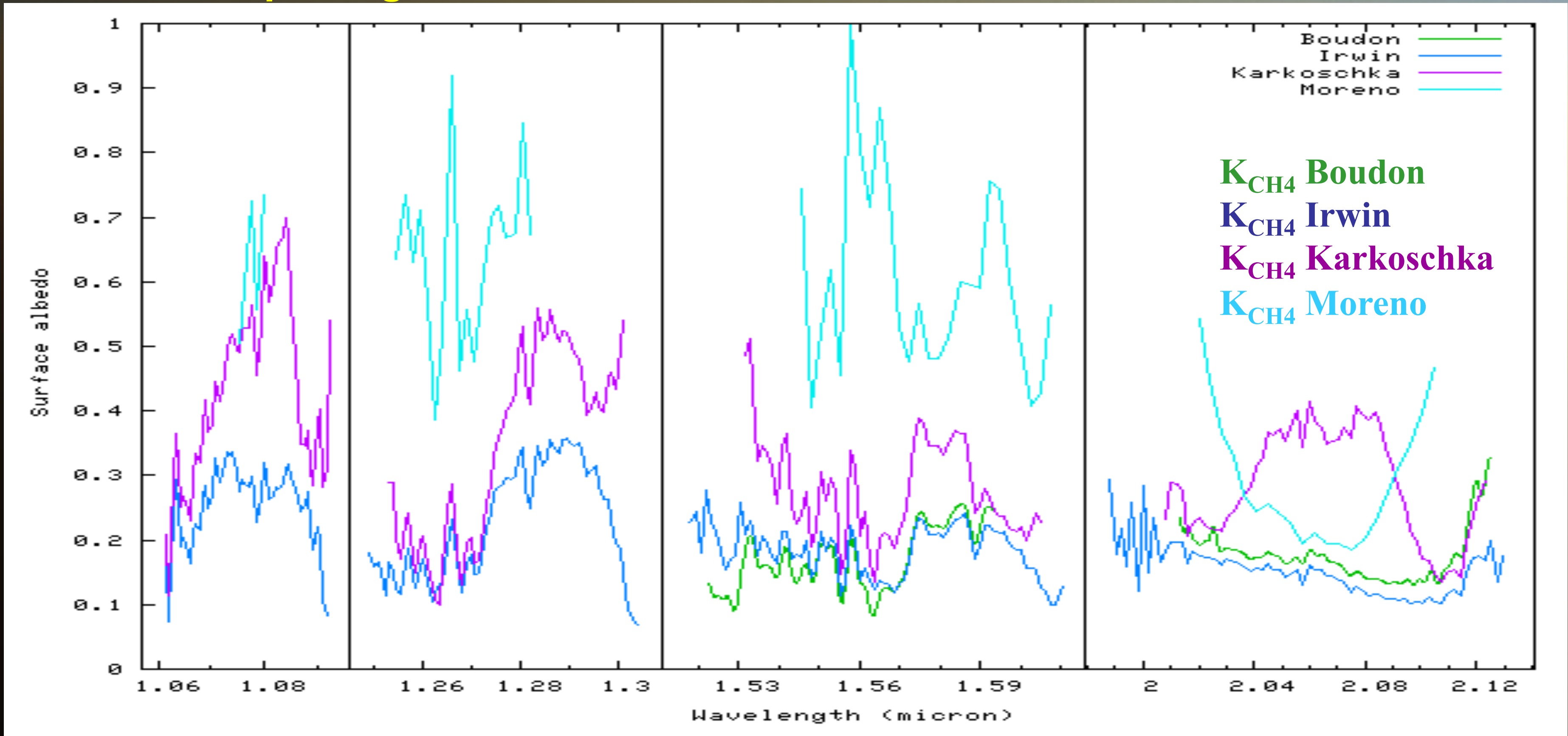
Fit of the CFHT data (with a variable surface albedo)

The next step in the comparison of the methane coefficient datasets is the study of their influence on the retrieved surface albedo. For this a fit of each dataset from 1993 to 1996 was performed, using the four sets of methane coefficients at our disposal. The figure below shows an example for the 1995 observations using the Irwin et al. (2006) coefficients. We furthermore show in the same figure four panels indicating the remaining differences between the model and the data in the methane windows.



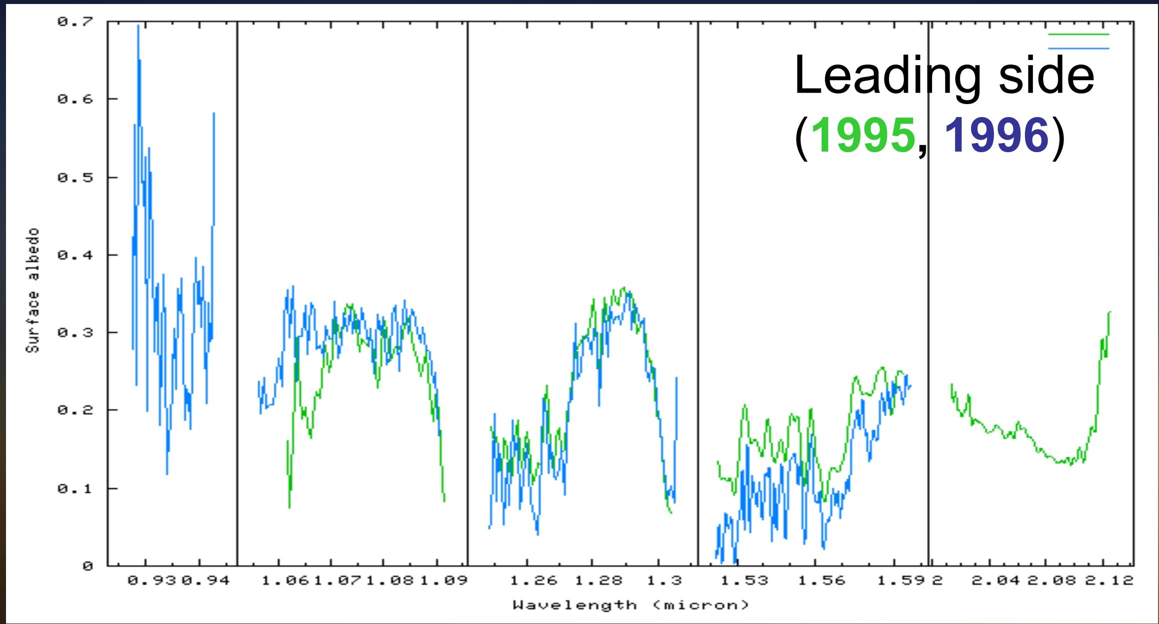
Surface albedo (1995, GEE)

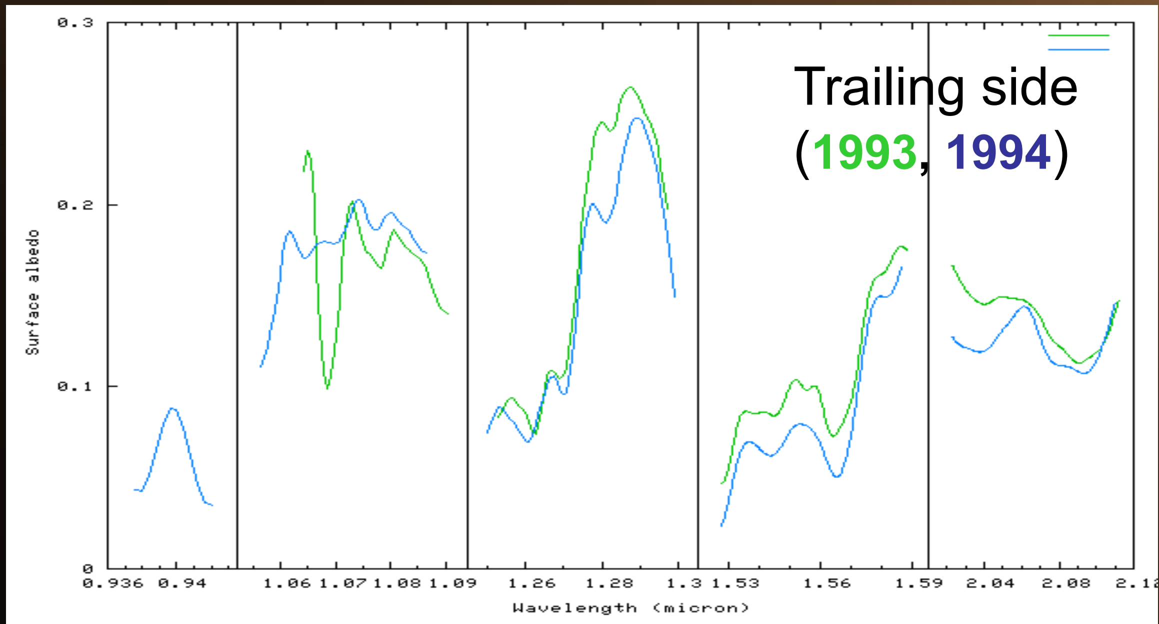
The figure below serves the purpose of showing the large influence of the methane absorption coefficients in the retrieval of the surface albedo. The Karkoschka and Moreno datasets produce the highest surface albedos. Boudon and Irwin coefficients yield quite similar surface albedos for both the dark and the bright sides of Titan at 1.6 and 2.0 micron. These dramatical differences explain, at least in part, the reasons why various investigators have been reporting such different surface albedo values.



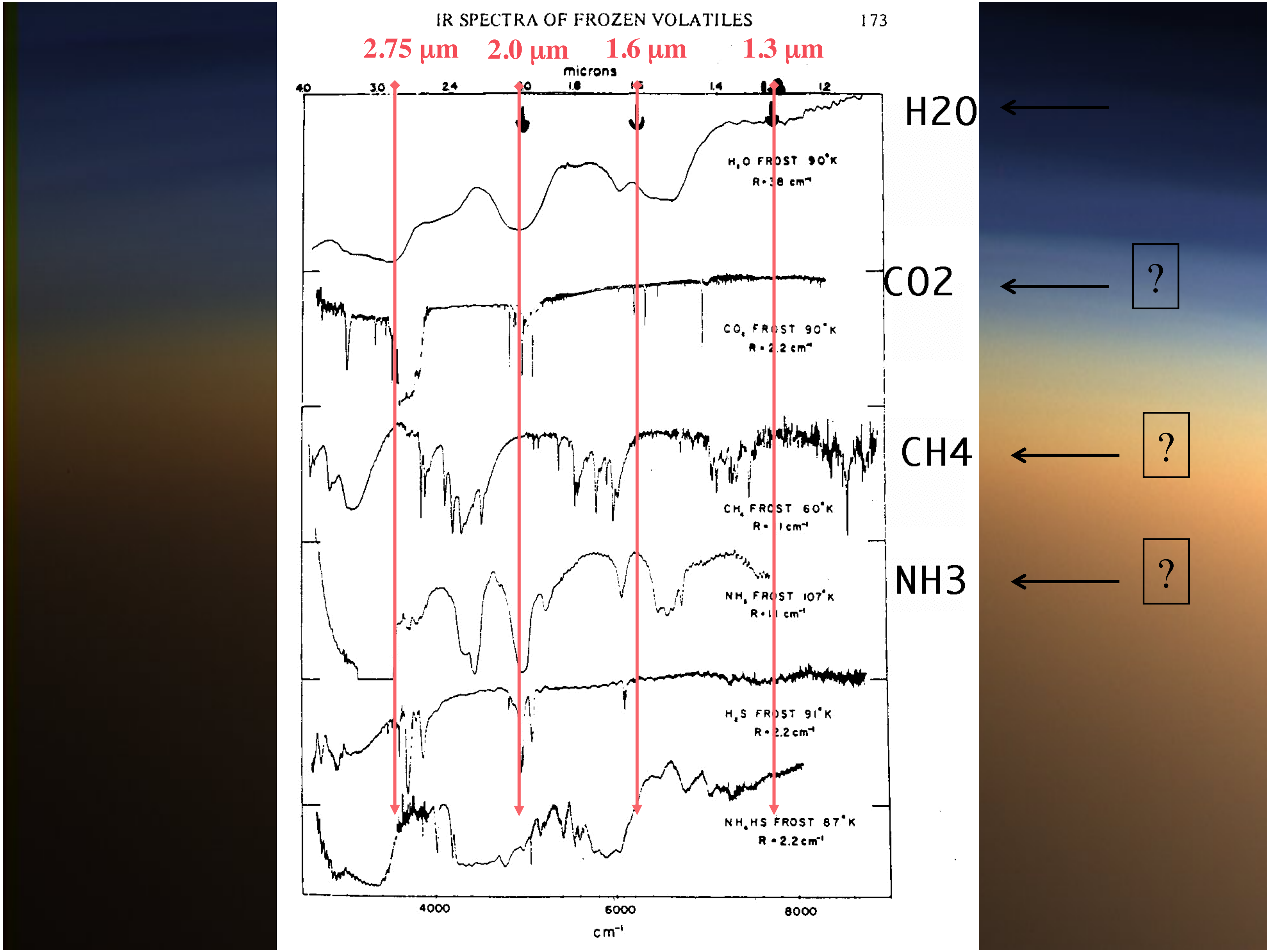
Negrão *et al.* (2006a)

Surface albedo



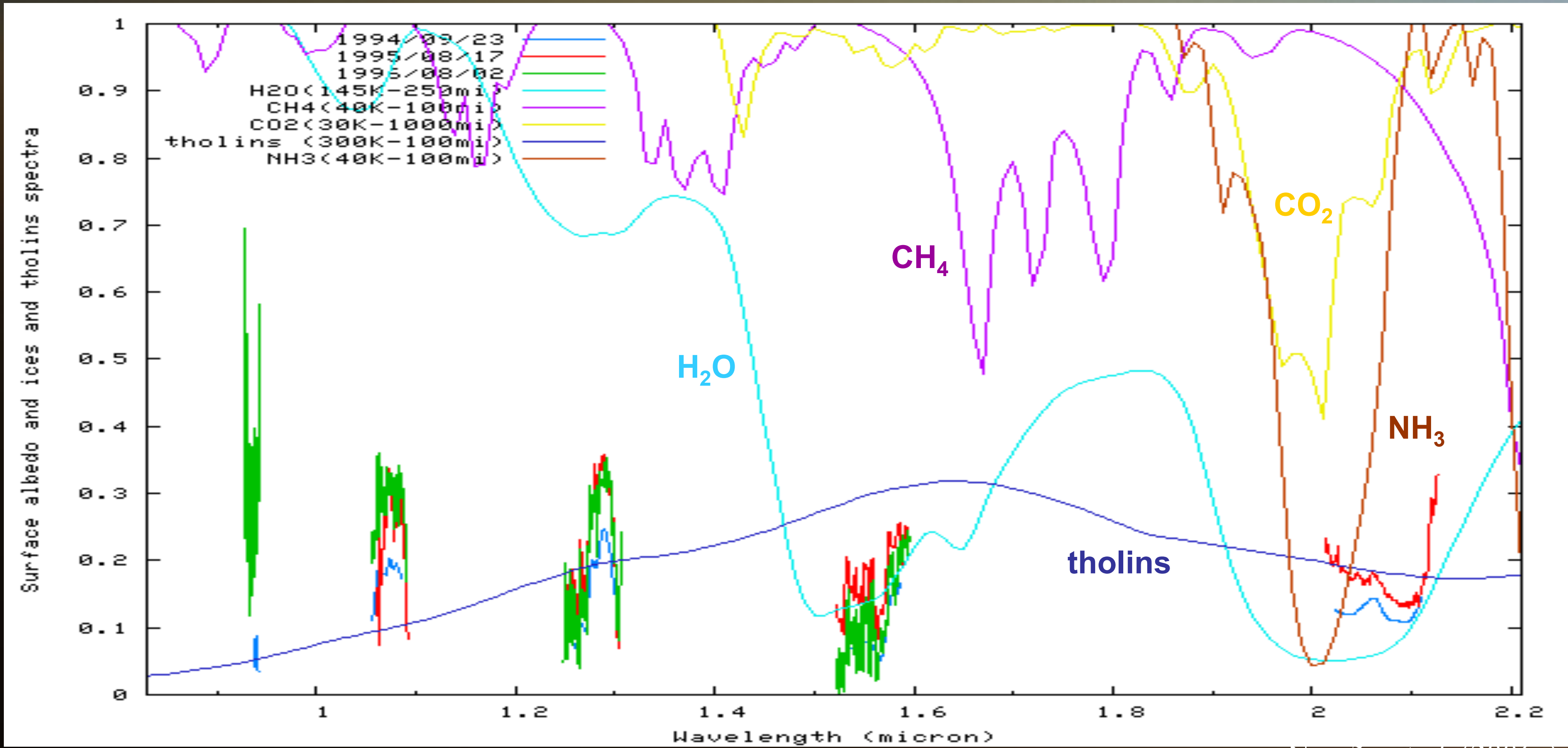


Surface albedos derived for Titan's bright and dark side. The values from the Aug. 17, 1995 dataset are quite compatible with those from the Aug. 2, 1996 observations. Similarly, for the trailing side: the Aug. 5, 1993 data are quite compatible with those inferred from the Sept. 23, 1994 dataset. Given the uncertainties, the leading hemisphere appears signicantly brighter than the trailing hemisphere. The differences of the extreme surface albedo from 233 LCM to 67 LCM are : 340%, 57%, 40%, 44% and 50% at 0.94, 1.08, 1.28, 1.6 and 2.0 microns.


IR SPECTRA OF FROZEN VOLATILES
173
2.75 μm
2.0 μm
1.6 μm
1.3 μm
microns
40
3.0
2.4
1.8
1.4
12
H2O
H2O FROST 90°K
CO2
CO2 FROST 90°K
?
CH4
CH4 FROST 60°K
?
NH3
NH3 FROST 107°K
?
H2S FROST 91°K
NH4HS FROST 87°K
R = 2.2 cm-1
4000
6000
8000
cm-1

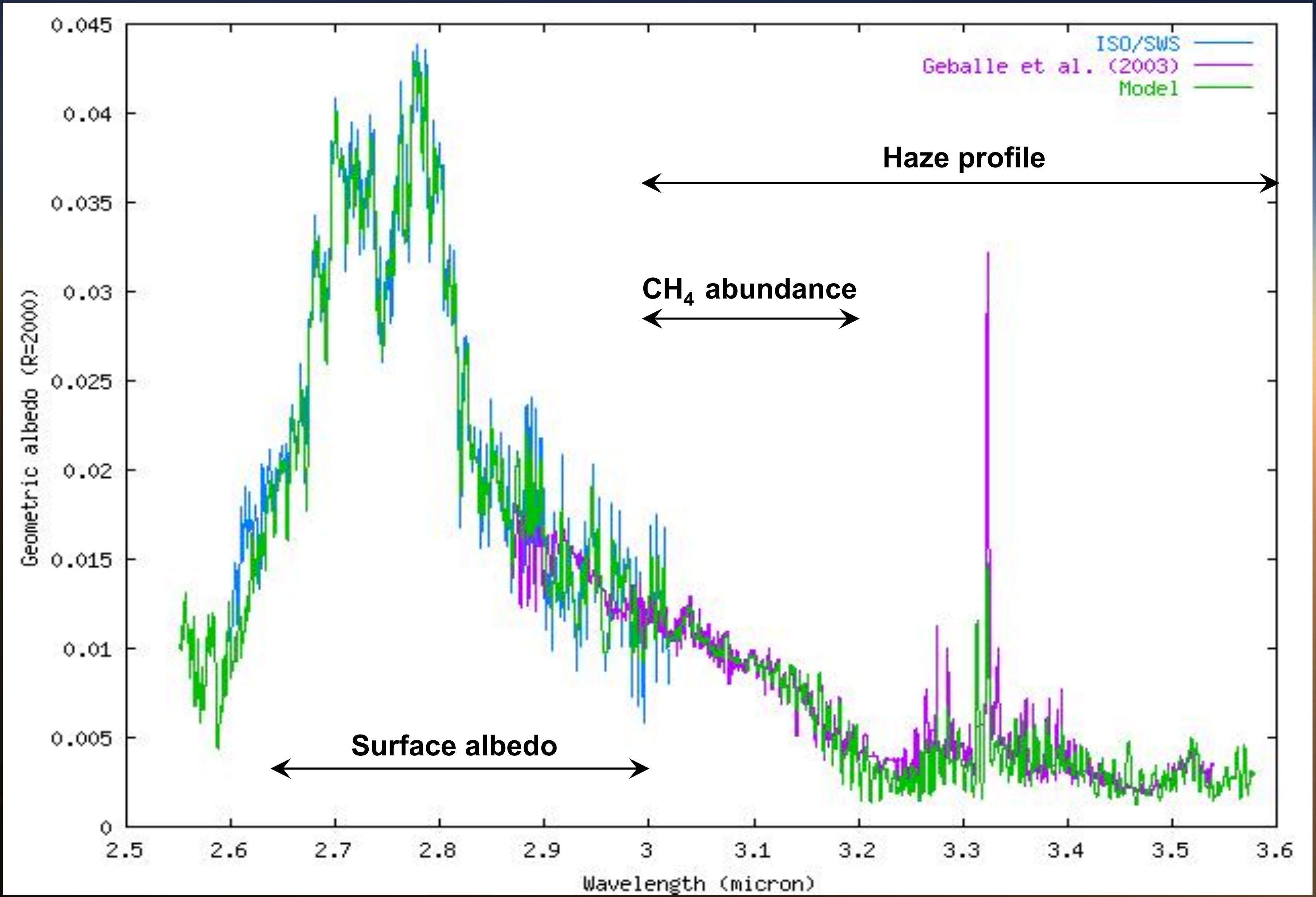
Comparison with the ices

This figure shows the comparison between the retrieved surface albedo, for both the dark and bright side, and the spectra of tholins (Coll et al., 1999), H2O ice (Grundy and Schmitt, 1998), CH4 ice (Grundy et al., 2002), CO2 ice (Quirico and Schmitt, 1997) and NH3 ice (Schmitt et al., 1998). Water ice could explain the form of the surface albedo at longer wavelengths but a darker component (tholins?) is necessary to fit the albedo at shorter wavelenghts.



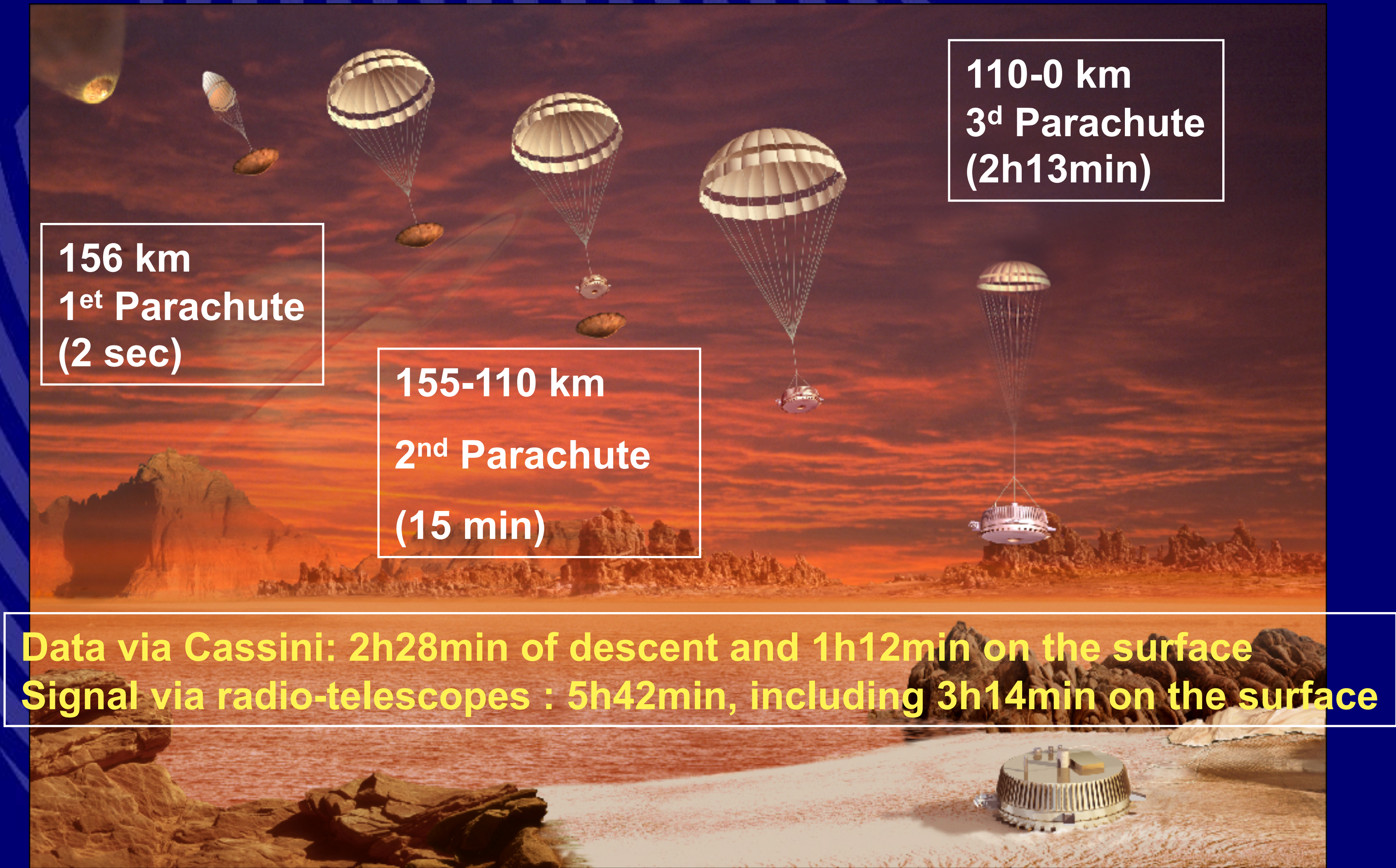
Negrão *et al.* (2006a)

⇨ ISO/SWS and Keck II fit



Coustenis *et al.* (2006)

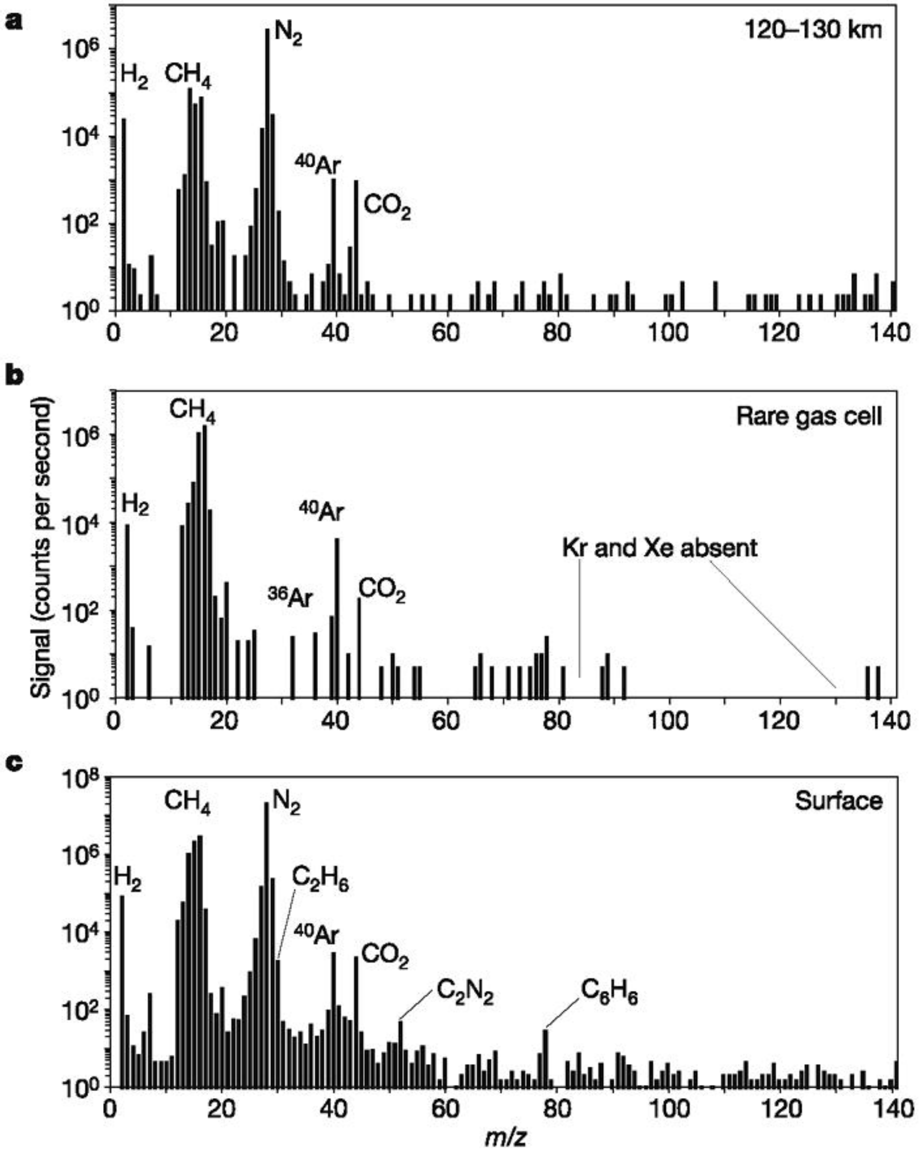
Huygens Descent and Landing Overview



esa

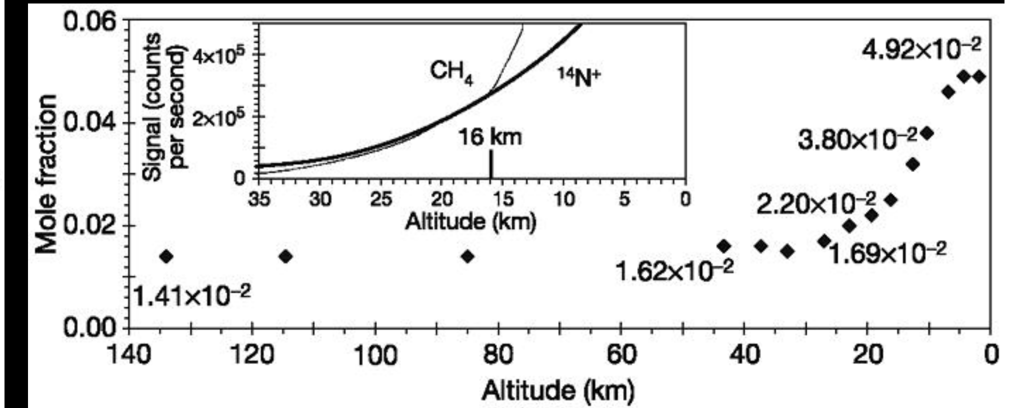
Observations with Huygens GCMS

(Niemann et al., Nature, 438, 779-784, 2005)



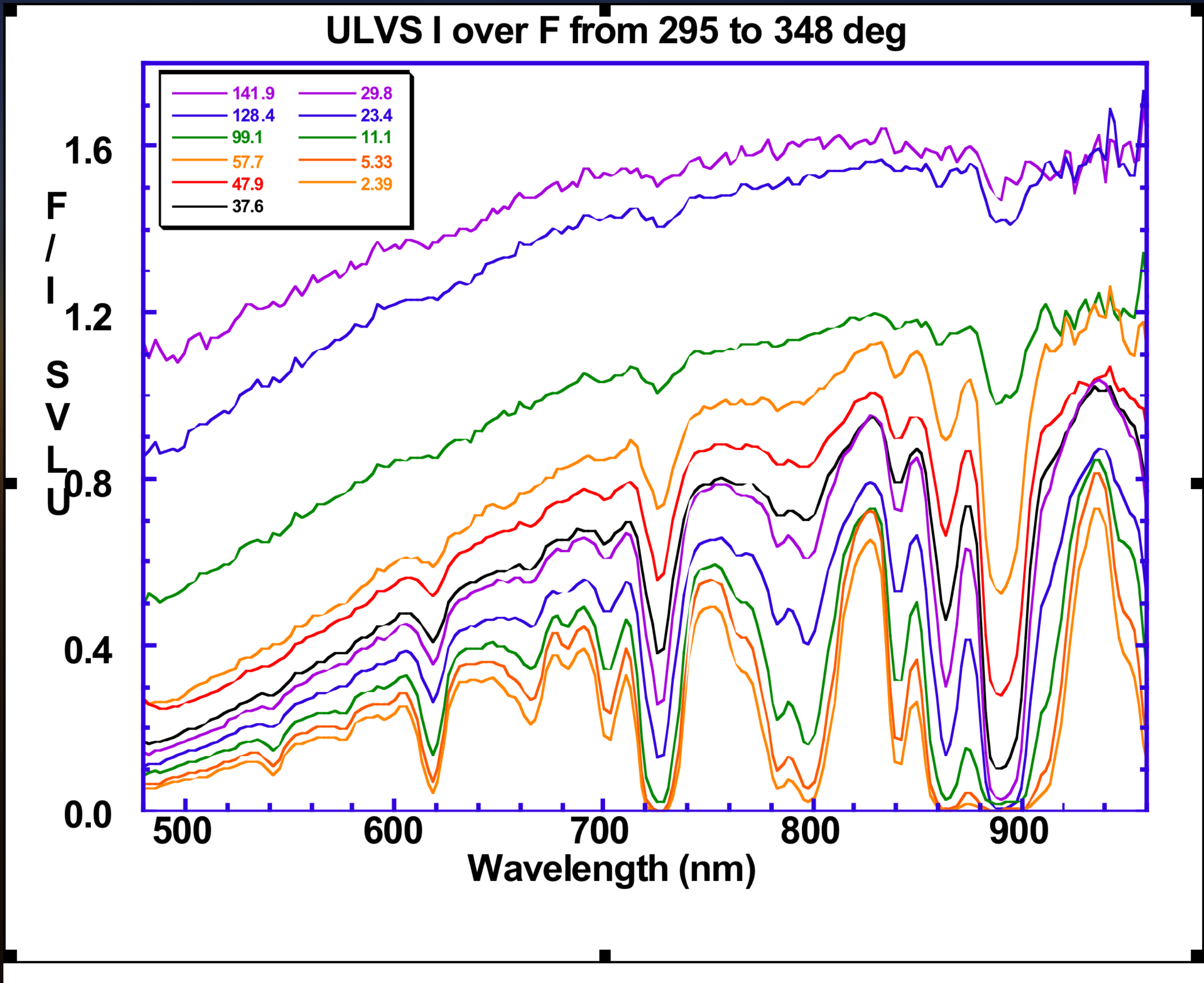
Detection of various organic compounds in the atmosphere and on the surface:

Ethane, acetylene, cyanogen, benzene, carbon dioxide, Argon.



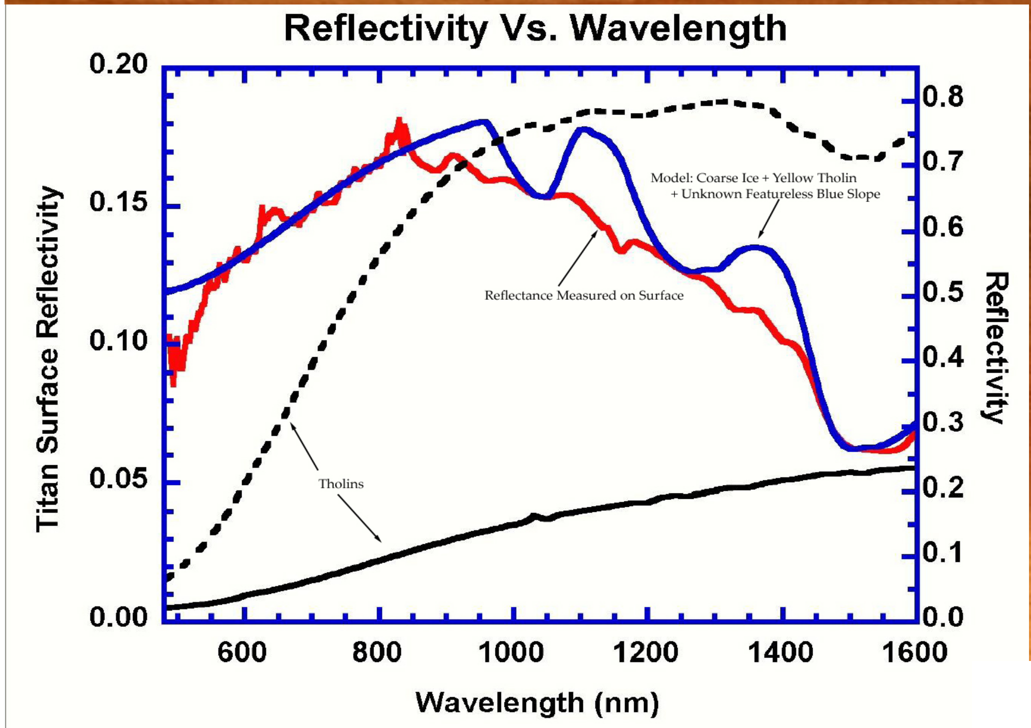
Vertical profile of methane in Titan's lower atmosphere

Aerosols and methane bands on Titan from Huygens DISR



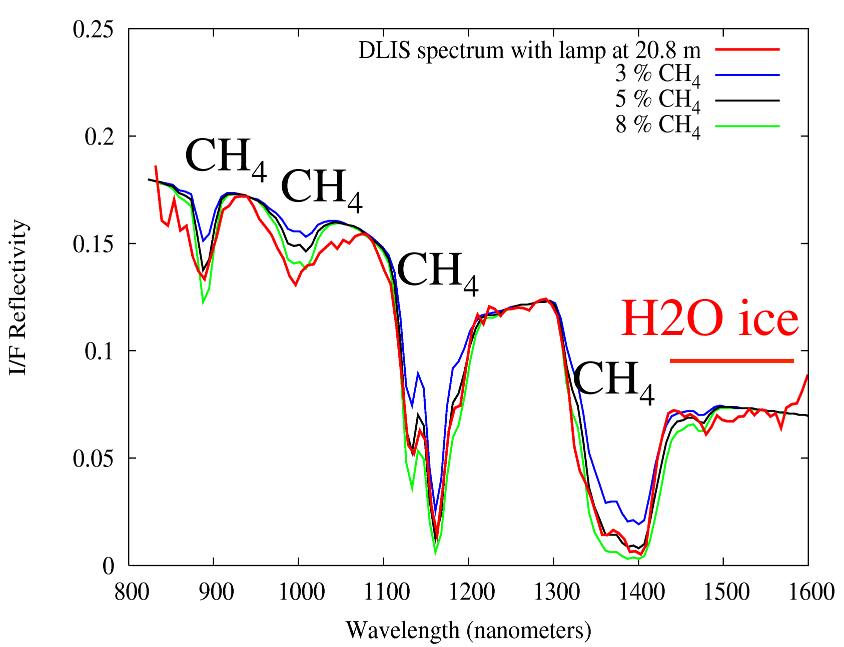
Tomasko *et al.* (2008)

➢Fit of the DISR data: 0.8-1.6 micron



No data available for the CH_4 absorption at λ< 1.6 micron (theoretical or experimental)

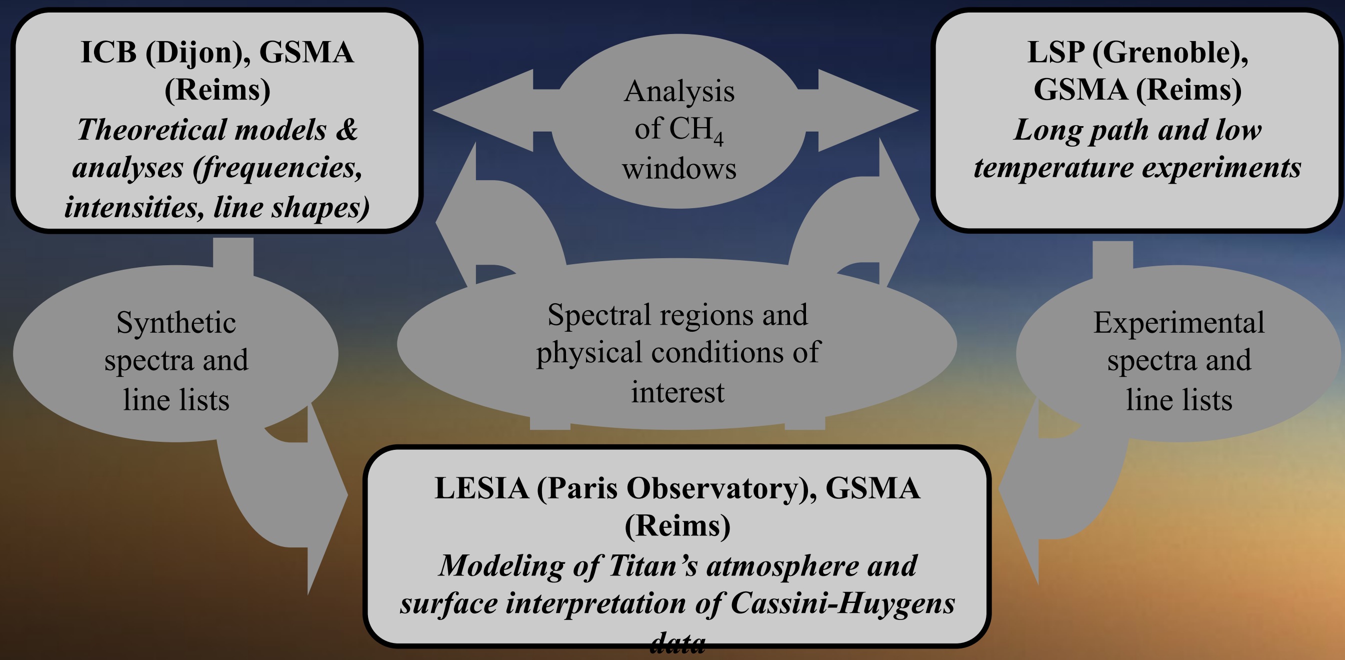
Jacquemart et al., 2008



Surface reflectivity measured by DISR (in red) *(Tomasko et al., 2005)*

- **Methane : about 5% at the surface**
- **Surface :**
  - **Dark material**
  - **absorption by water ice + ?**

ANR CH4@Titan : Coustenis et al. 01/01/2009-31/12/2012



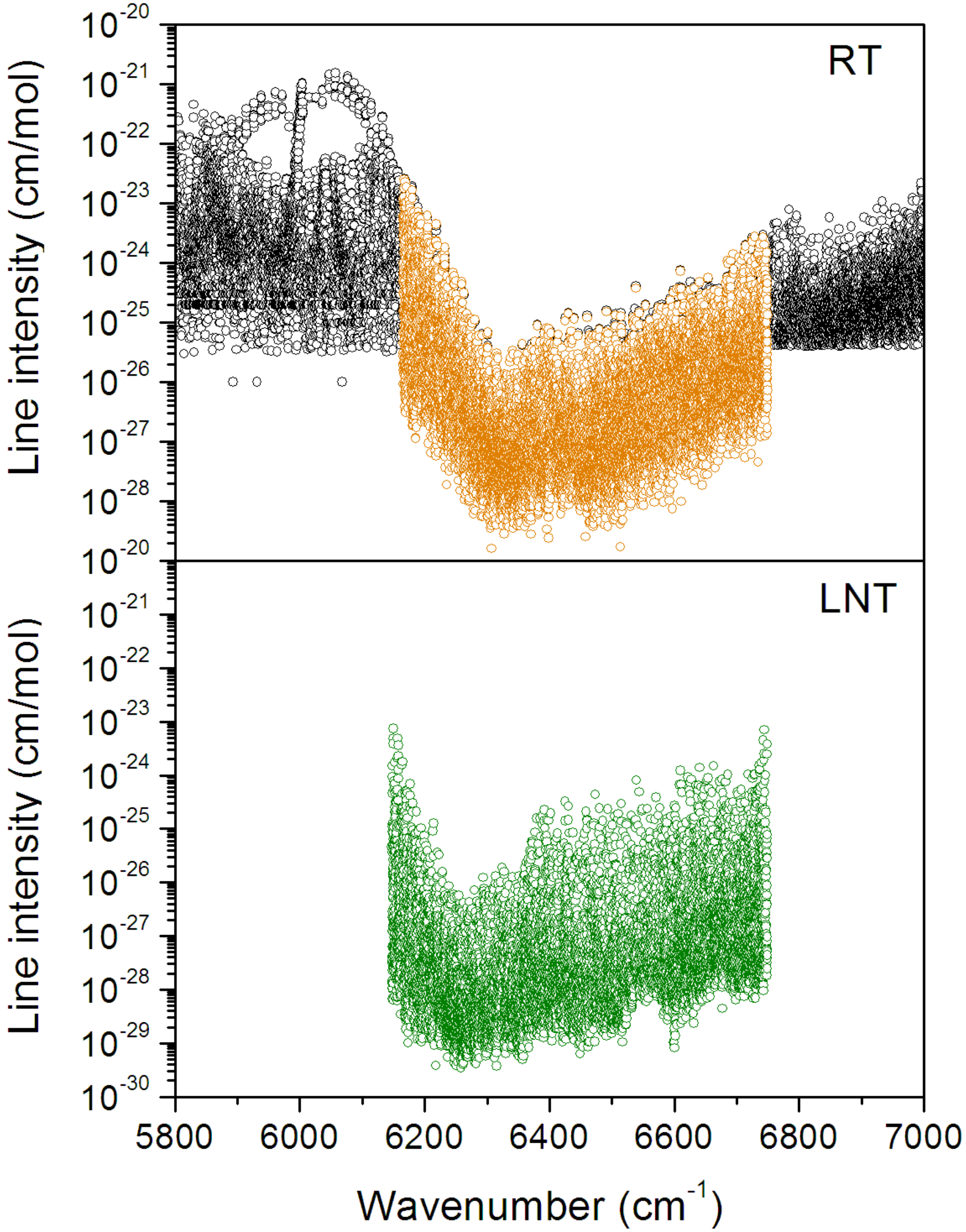
Partenaire	Organisme gestionnaire des crédits	Responsable scientifique
Partenaire 1	CNRS DELEGATION REGIONALE ILE DE FRANCE OUEST ET NORD	Mme Coustenis Athéna
Partenaire 2	CNRS DELEGATION REGIONALE CENTRE EST	M. Boudon Vincent
Partenaire 3	CNRS DELEGATION REGIONALE ALPES	M. Campargue Alain
Partenaire 4	UNIVERSITE CHAMPAGNE-ARDENNE REIMS	M. Tyuterev Vladimir
TOTAL		

Obs Paris-Meudon

Univ. Bourgogne, Dijon

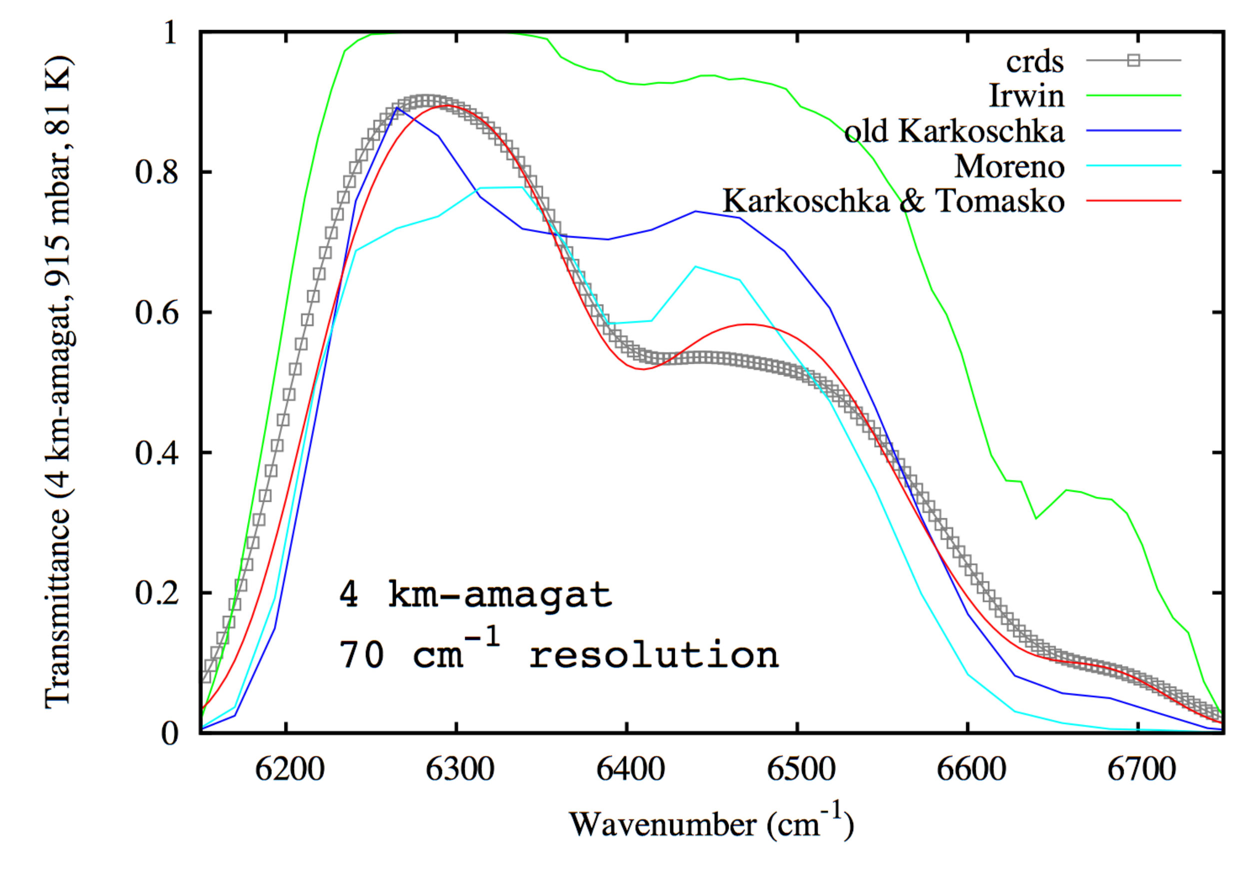
LSP, Grenoble

GSMA, Univ. Reims



RT
LNT
Line intensity (cm/mol)
Line intensity (cm/mol)
Wavenumber (cm-1)
5800
6000
6200
6400
6600
6800
7000

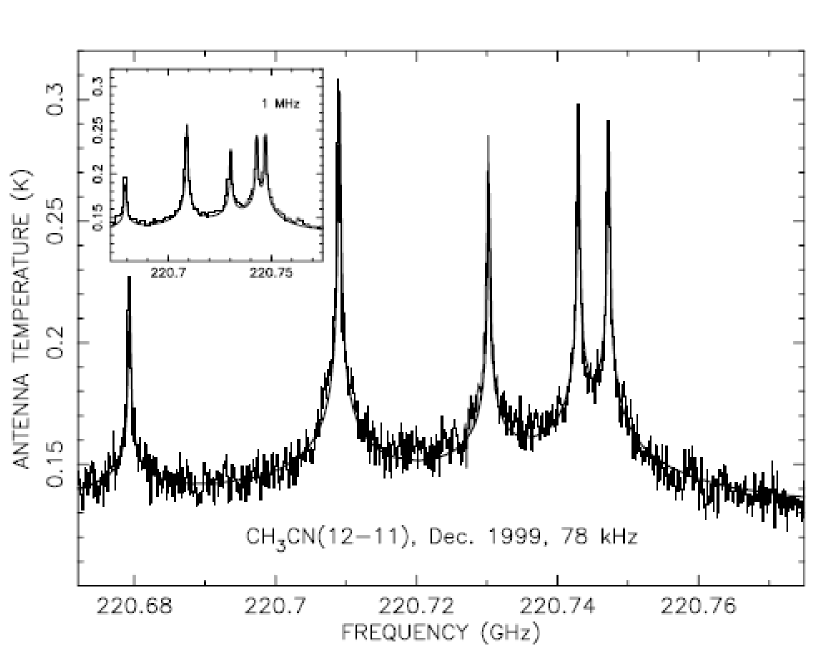
Comparison with band models and DISR data inferences



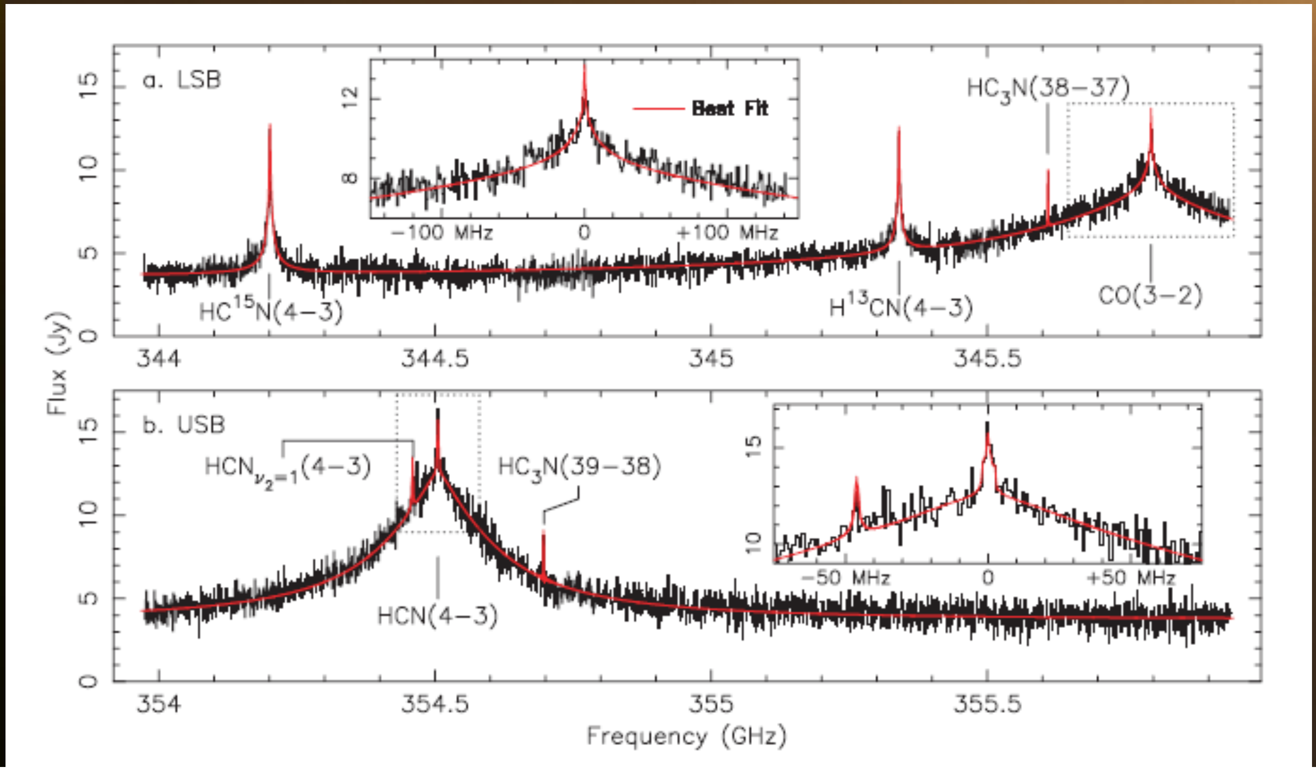
- Comparison with different band models used in analysis of Titan spectra (VIMS, DISR)

- Irwin et al. (2006): not enough absorption
- Good agreement with Karkoschka & Tomasko's (2009) model based on lab and DISR data

Nitriles on Titan at (sub)mm wavelengths



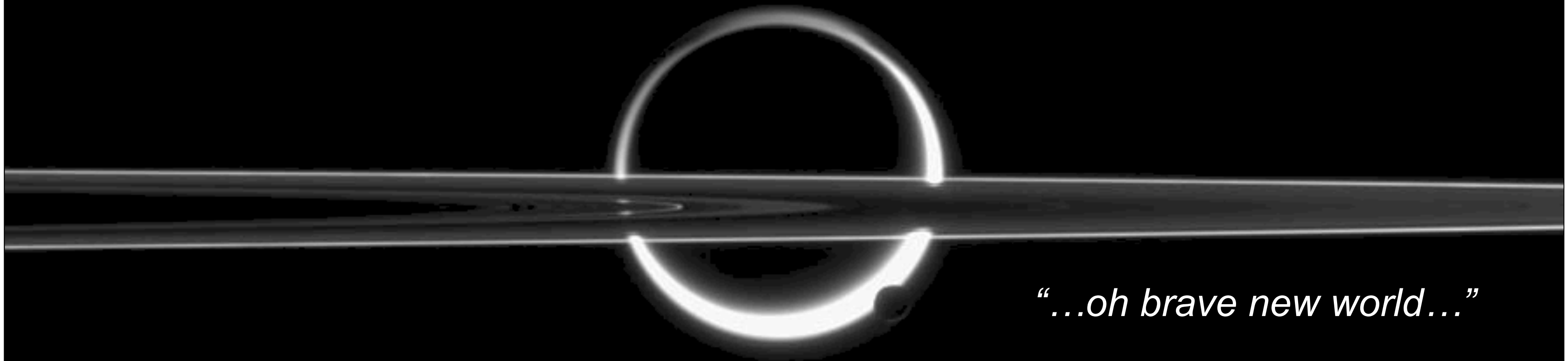
IRAM, Marten et al. 2002



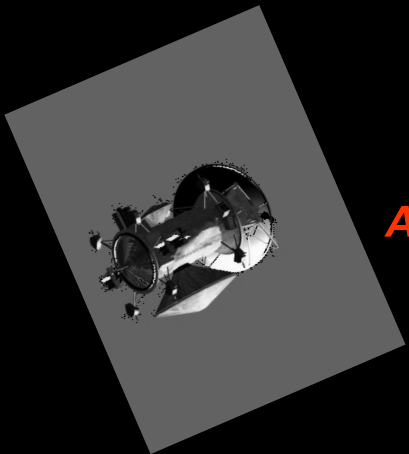
***SMA** (8 x 6m diameter interferometer, located near summit of Mauna Kea, HI),*
Gurwell 2004

TSSM

Titan Saturn System Mission



"…oh brave new world…"



A 2008 TSSM ESA-NASA-JPL study

A. Coustenis, J. Lunine, D. Matson, J-P. Lebreton, K. Reh, Ch. Erd

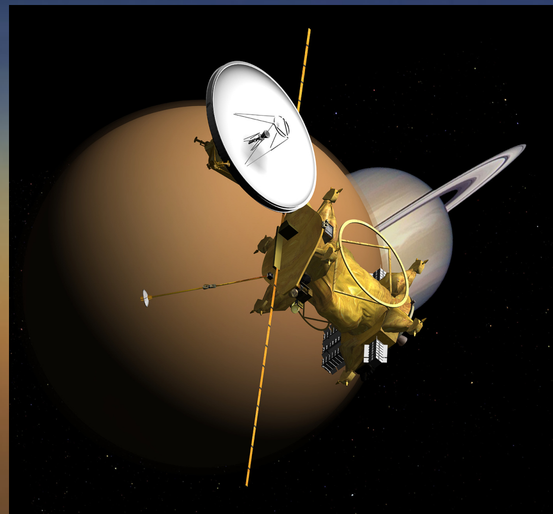
and the Joint Science Definition Team

Science

TSSM mission architecture

Combining

- the orbiter (first of Saturn, with Enceladus flybys, then dedicated to Titan), with
- a hot-air balloon/montgolfière, and
- a North-pole lake-landing probe

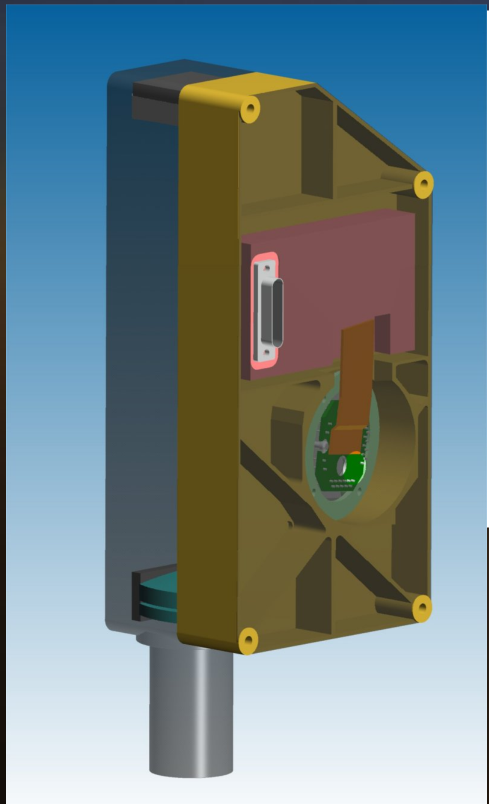


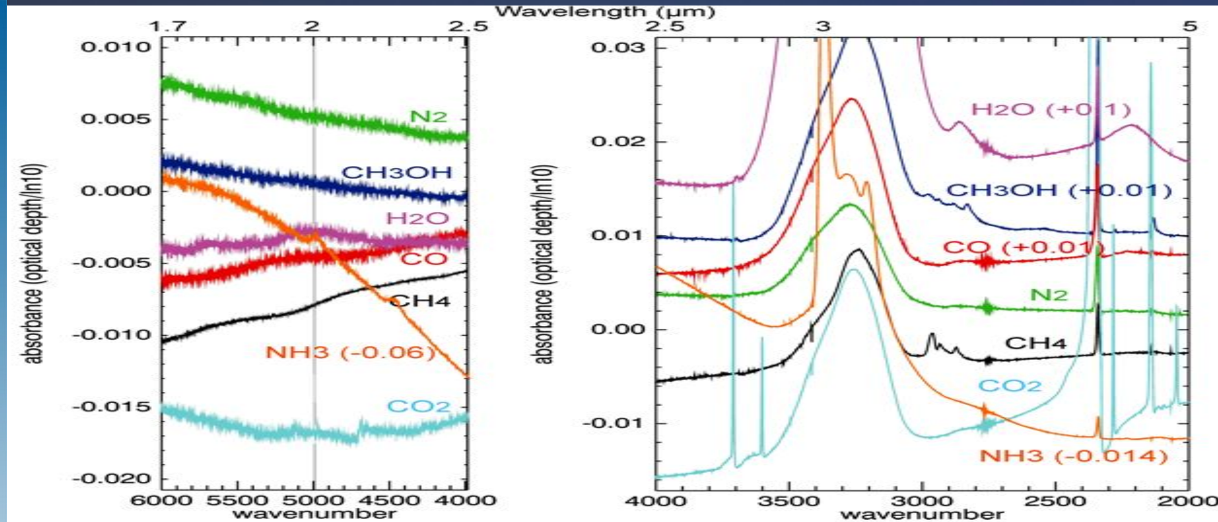
Dedicated Titan orbiter will also be used for relay

A hot-air balloon (Titan montgolfière) will float at 10 km above the surface around the equator for at least 6 months (T=83K, wind speed=1-2 m/s) with altitude control

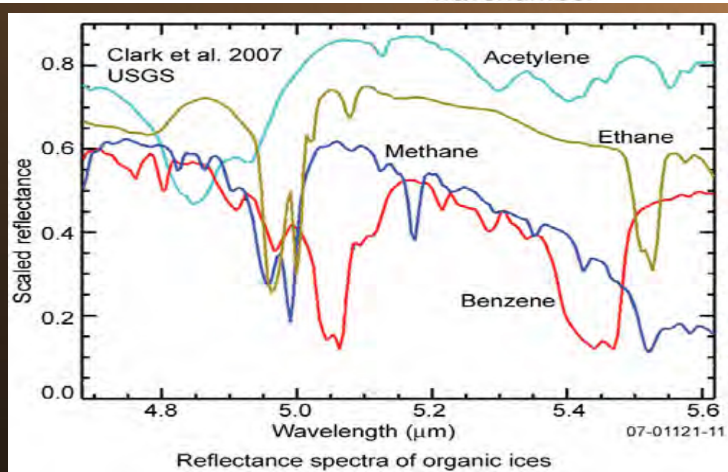
A short-lived (9 hrs) probe/ lander with chemical analysis package will land in a northern lake (Kraken Mare)

Instrument requirement for composition





Near-IR-spectrometer (BIS)
Wavelength range:
near-IR (1-5.6 μ)



BIS will inherit from VIHI (Visible and IR Hyperspectral Imager) on BepiColombo

Future investigations in the thermal IR with TSSM

- TSSM/ Thermal IR spectrometer (TIRS):

will work in 7-333 micron (30-1500 cm^{-1})

  - Try to ascertain whether interspecies variations in $^{12}C/^{13}C$ are real.
  - Search for new species (CH_3CN, C_3H_6, CH_2CHCH_2…) & isotopes ($HC_3{}^{15}N$, $^{13}C_2H_2$…)
- Community:
  - Need line data for many bands of propane.
  - Need more accurate line data for most isotopic species.

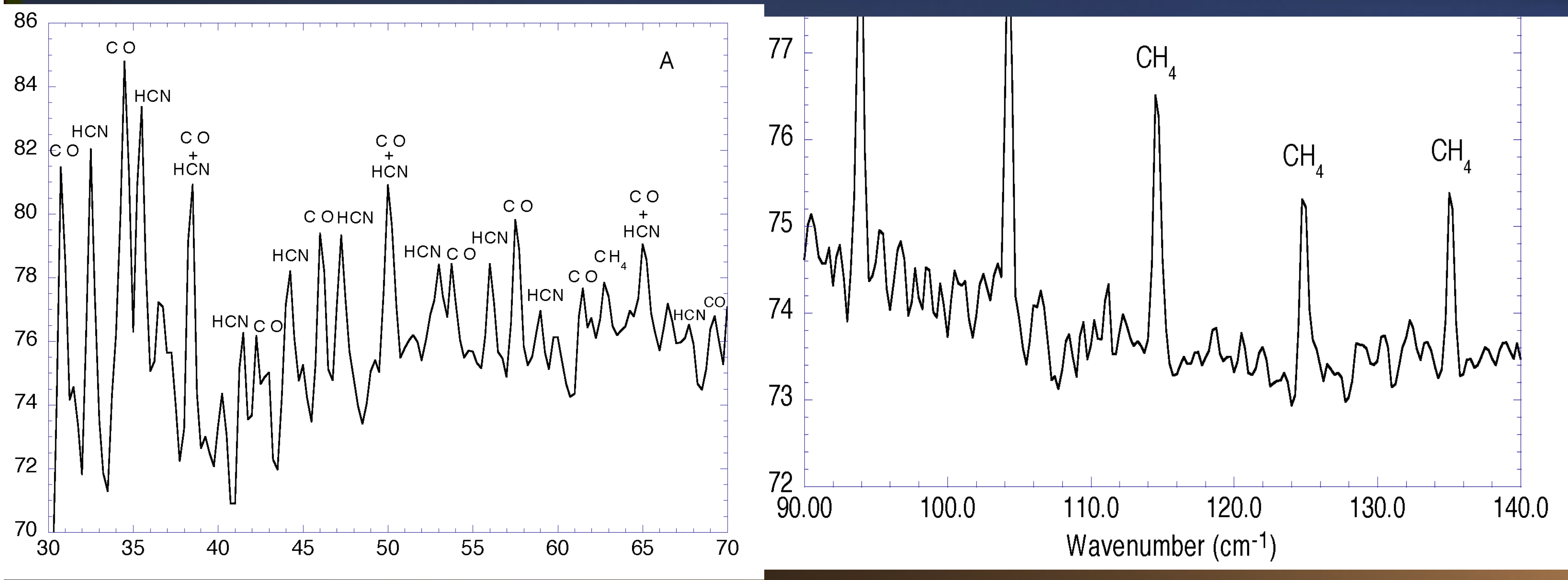
The case for a submillimeter sounder (SMS) on the TSSM Titan Orbiter

E. Lellouch, S. Vinatier, P. Hartogh,
G. Beaudin, R. Moreno, A. Coustenis et al.

Main science goals

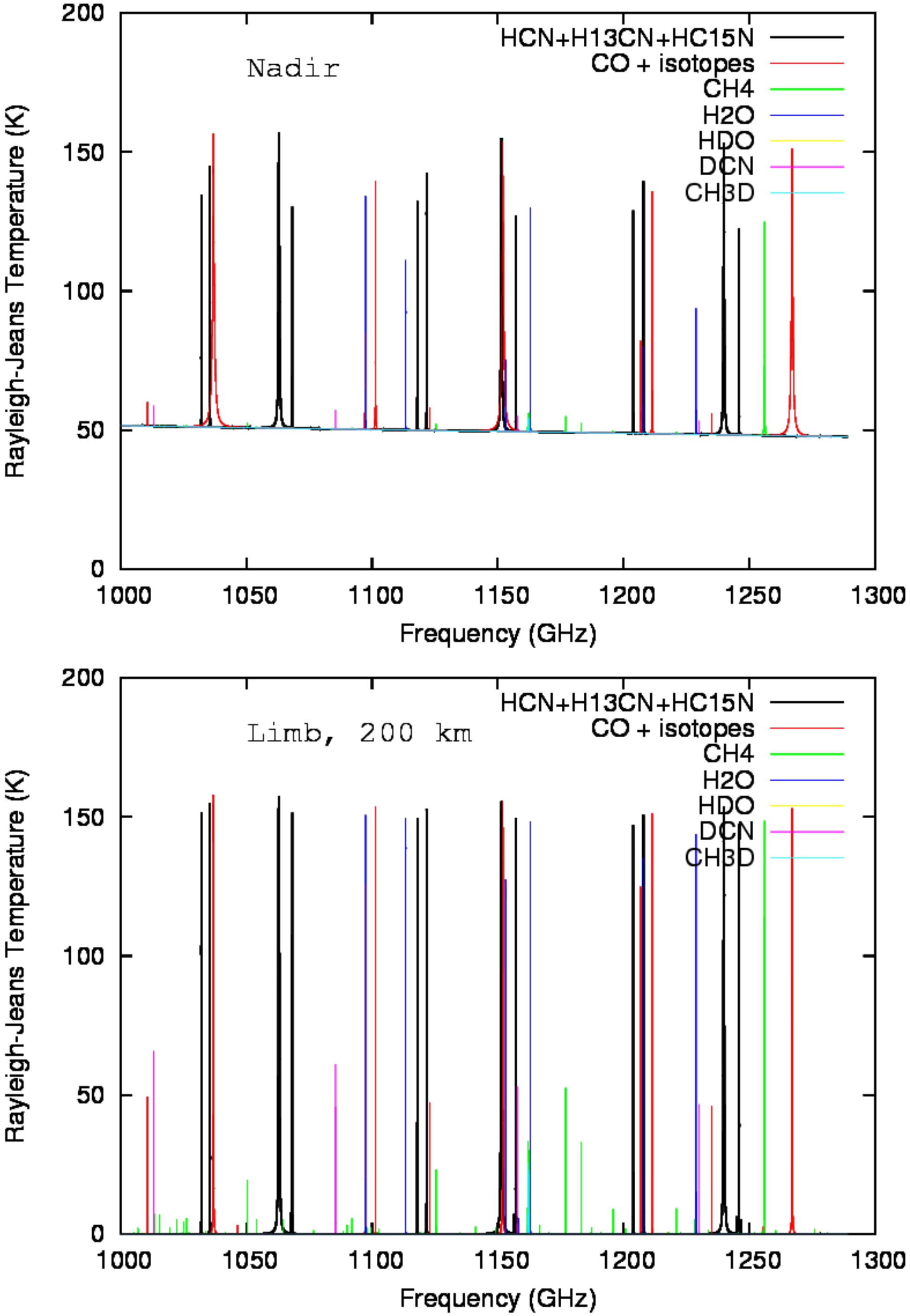
- Determine the 3-D field of temperature, wind, and composition in the stratosphere, mesosphere and lower thermosphere of Titan
- (Enceladus science goals: composition, density, temperature and dynamics of gas plume, but models need to be done)

Titan's submillimetre spectrum seen by Cassini / CIRS (R=0.5 cm^{-1})



Flasar et al. 2004

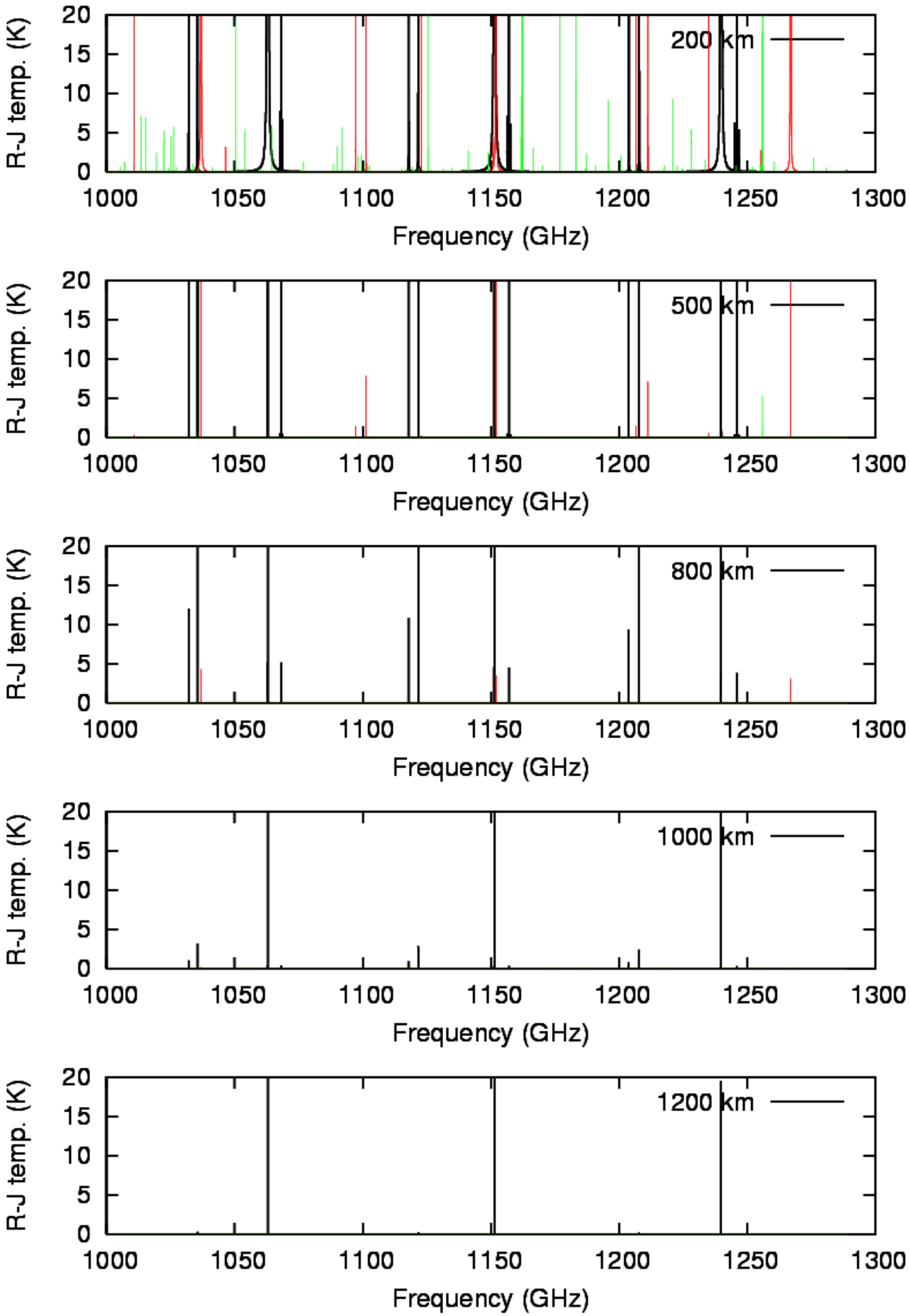
Titan's expected spectrum at 1.0-1.3 THz



Detection limit :

Typically 1.5 K in 1mn

0.2 K in 1 hr



Titan's expected spectrum at 1.0-1.3 THz

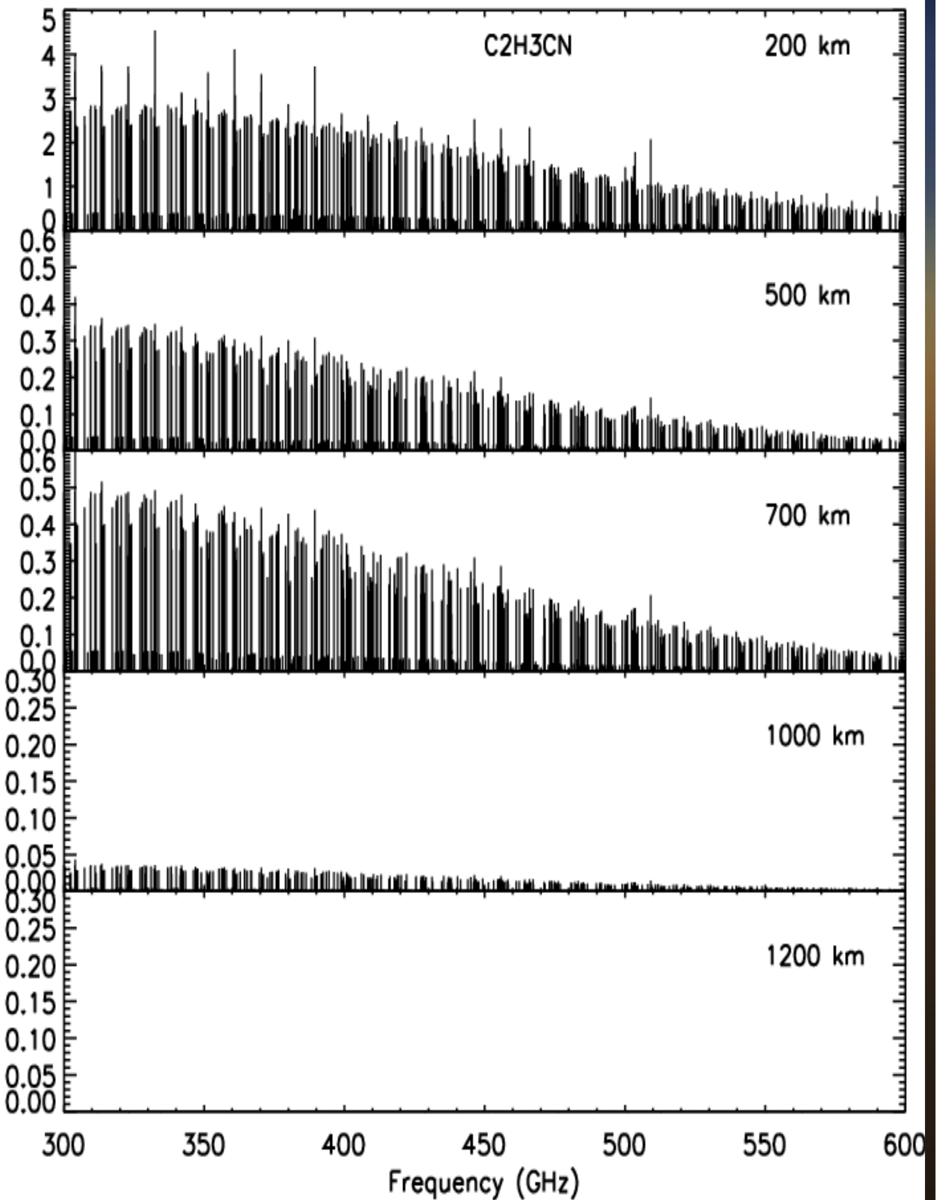
HCN CO CH4

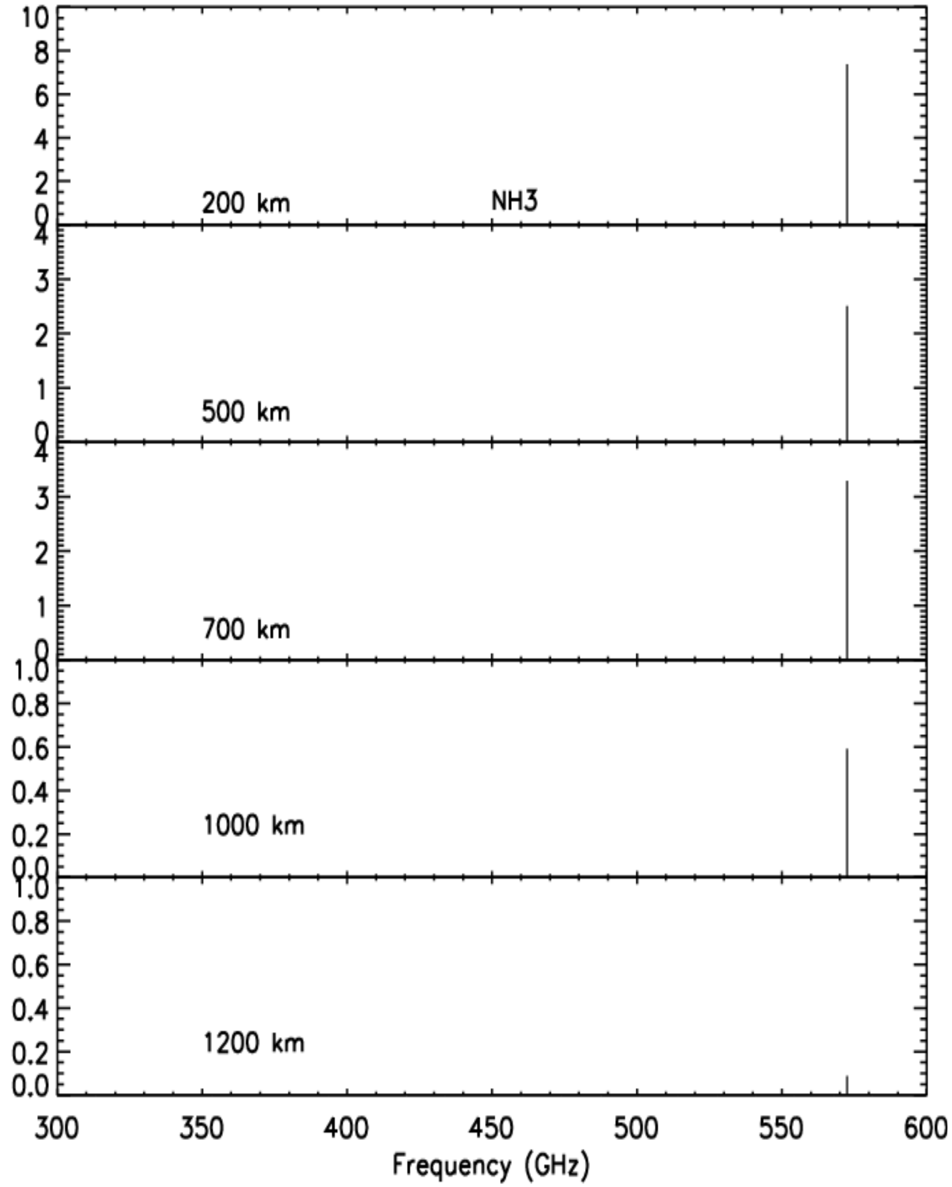
THERMAL SOUNDING:

- From CH_4 (uniform) : up to ~500 km
- From CO (almost certainly uniform) ; no homopause uncertainty problem: up to ~800 km
- From HCN (not uniform vertically nor spatially, but feasible through multiple lines incl. isotopes, cf. CO on Venus) : up to ~1200 km

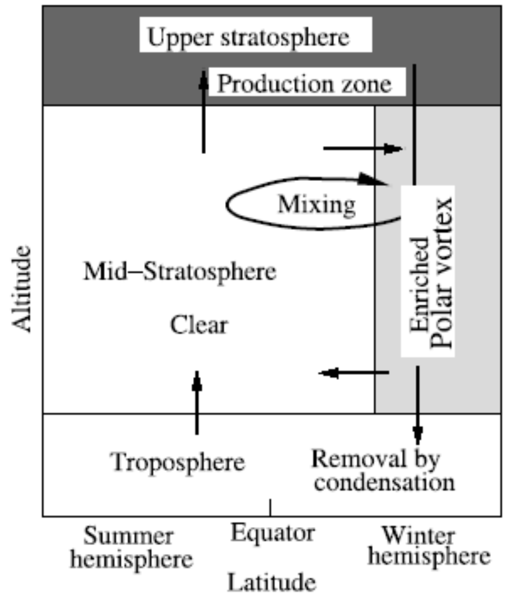
Advantage: *LTE is not a major issue like in IR*

Detectability of C2H3CN and NH3 (models P. Lavvas)





Agnostospheric chemistry



- *Study chemistry-dynamics couplings*:

Obtain 3-D (i.e. altitude-latitude-local time) distribution of known minor stratospheric species and relation to wind field

- *Study chemical complexity*:

Search for and map « INMS species » at deeper (<900 km) levels: heavy nitriles (HC5N, C2H3CN…, NH_3 , CH_2NH, CH3CCH…): calculations show that many species can be detected. More species (HC5N, etc…) TBD

→ **Make the link between thermospheric and stratospheric chemistry**

- *Study some specific problems*:
  - Origin of oxygen (H_2O, CO)
  - Isotope ratios
    - D/H in HCN and H_2O vs. in CH_4

Titan chemistry from synergy of submm with thermal IR

	Thermal IR	Submm
Temperature sounding	CH_4 and N_2 0-550 km	CH_4, CO, HCN ~100 – 1200 km
Winds	Thermal winds (zonal)	Direct winds (zonal +meridional) (and thermal winds)
Composition	Hydrocarbons Nitriles (light) CO_2 Condensates, isotopes	Nitriles, some hydrocarbons (CH3CCH, CH2NH…) CO, H_2O, NH3 Rare isotopic species

Some conclusions and thoughts for further developments

Titan

organics that remain to be seen

Some organics, as yet unobserved on Titan in the thermal IR, but potentially observable with CIRS and their deduced upper limits in Titan's atmosphere from previous observations.

	Strongest signatures		Upper limit of mean mixing ratio in Titan's stratosphere	
Studied compounds	Frequency (cm^{-1})	Band strength at 300 K (cm^{-2} atm^{-1})	using Voyager IRIS spectra	using ISO disk-average data
Hydrocarbons				
CH_2CCH_2	356	65	5×10^{-9}[a]	2×10^{-9}[b]
	845	407		
C_4H_4	629	288	7×10^{-10}[c]	
C_6H_2	622	428	4.4×10^{-10}[d]	
C_8H_2	621.5	496	4×10^{-10}[e]	
Nitriles				
CH_3CN	362[1]	4.4		
CH_2CHCN	230	10	8.4×10^{-8}[g]	$<5 \times 10^{-10}$[b]
	954	100		
CH_3CH_2CN	207	15	2.5×10^{-7}[a]	$< 1 \times 10^{-10}$[b]
	1075	37		
$CH_3CH_2CH_2CN$	728/742	3.5	5×10^{-7}[a]	
$(CH_3)_2CHCN$	538	3.3	2×10^{-7}[a]	
ΔCN	726	19	1.5×10^{-7}[a]	
	818	34		
CH_3CCCN	338	100	1.0×10^{-8}[a]	
	499	91		
$CH_3CHCHCN$	728	230	2.5×10^{-7}[a]	$< 5 \times 10^{-10}$[b]
CH_2CHCH_2CN	557	64	4×10^{-8}[h]	$< 5 \times 10^{-10}$[b]
	942	110		
$CH_2C(CH_3)CN$	535	33	7.5×10^{-8}[h]	$<5 \times 10^{-10}$[b]
	928	130		
C_4N_2	614	34.4	5.6×10^{-9}[i]	
NCCHCHCN (trans)	947	178	1×10^{-8}[j]	
Other N organics				
CH_3NC	526	8.8	1.3×10^{-9}[k]	
CH_2N_2	419	144	5.0×10^{-9}[k]	
CH_3N_3	250	9	5.4×10^{-9}[k]	

Flasar et al., 2004

What do we need to interpret our observations

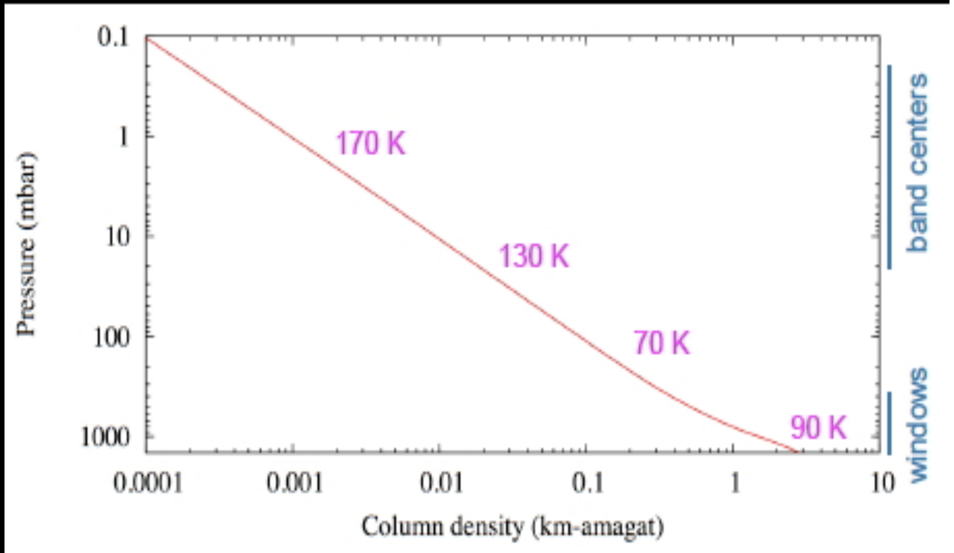
For molecules known to be present

- Line positions for all bands, including hot bands
- Absolute band strength
- Data for most abundant isotopes

➢ Then data for molecules to be searched

➢ All this in the right conditions of p,T and in N2 and H2-He

Spectroscopic needs



Laboratory measurements

-Long pathlength (e.g. CRDS)

- p-T range covering Titan's atmosphere

Spectroscopic analyses

- Tetradecade (1,6-1,9 µm) : still incomplete
- Isodecade (1,3-1,5 µm) : almost no analysis
- Higher polyades (<1,28 µm) : no analysis

Studies of far wings of CH_4 broadened in N_2

- Laboratory measurements and modeling
- The far wing of ν_3 could be a significant source of opacity in the 2.75 µm window
- Only available measurements are for CH_4 broadened by H_2 (Hartmann et al. 2000)