Titan Huygens Conference
ESTEC, 13-17 April 2004

Titan's atmosphere and surface from imaging and spectroscopy in the past decade

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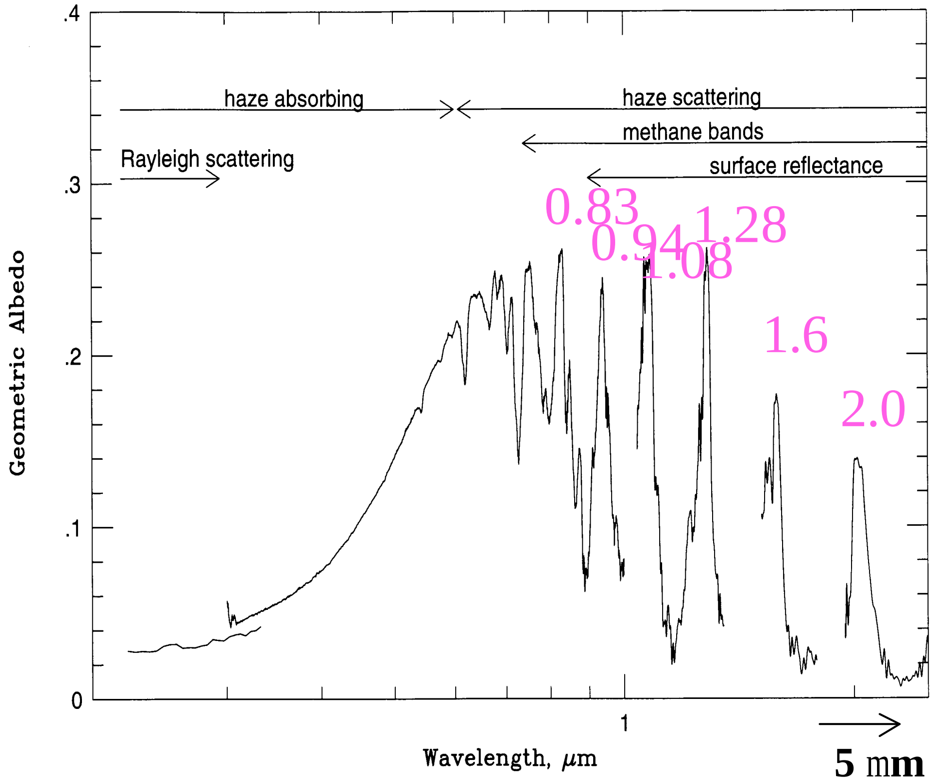
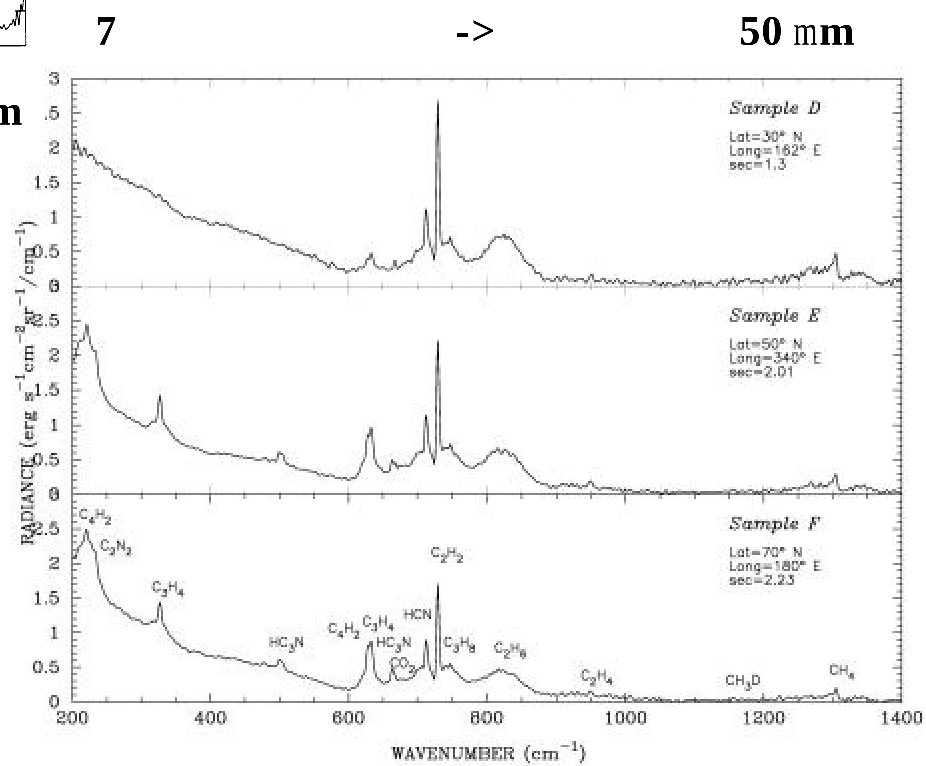
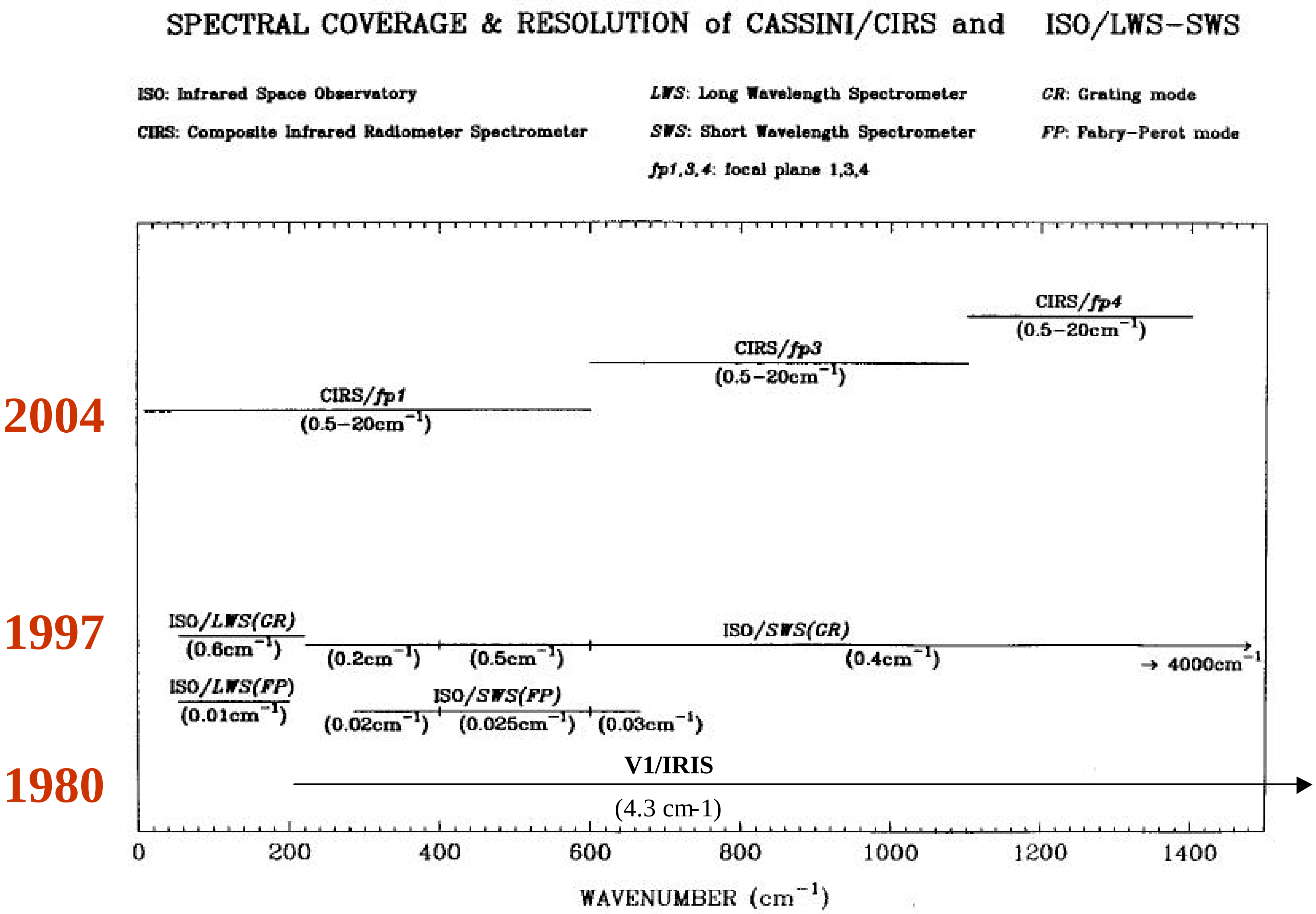


Titan’s UV and near-IR spectrum mainly through ground-based measurements (CFHT, UKIRT, IRTF, Keck, VLT, etc), with the exception of HST and ISO from space.

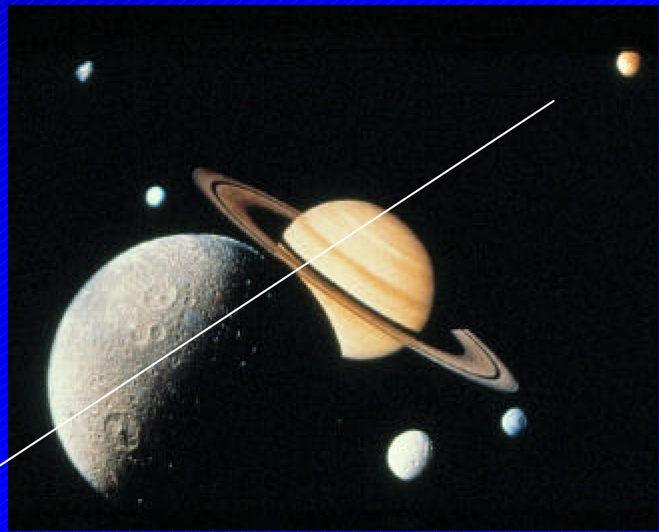


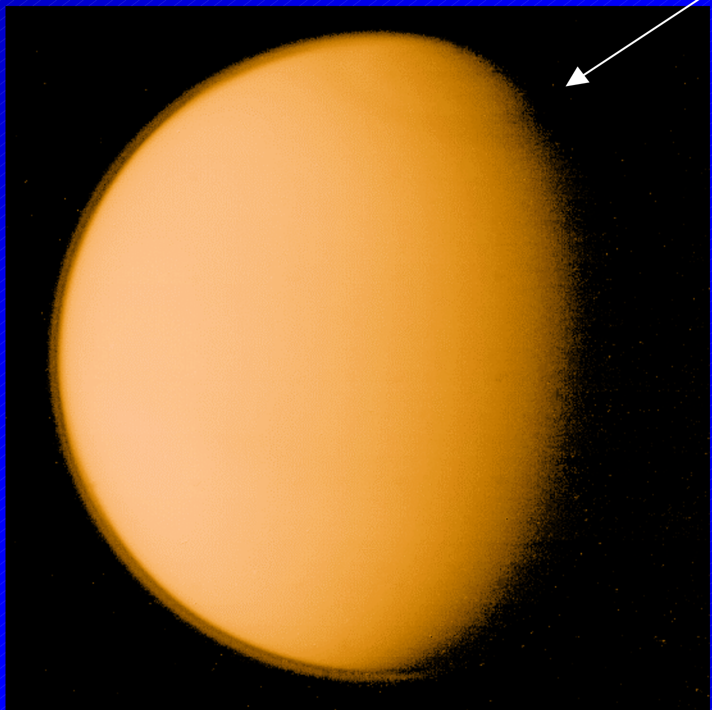
Titan’s far-IR spectrum mainly through space observations since 1980: Voyager, ISO and Cassini in the future. (Parts thereof were observed from the ground e.g. by Gillett long before that and also since then).

Titan's mid-IR space observations



Titan, the shy giant





Titan is the second largest satellite in our Solar System and lies hidden beneath a thick shroud of haze which has prevented until recently a direct detection of its surface. Its atmosphere is mainly composed of N_2, CH_4 and H_2. Numerous organics were detected, during the Voyager flyby in 1980.

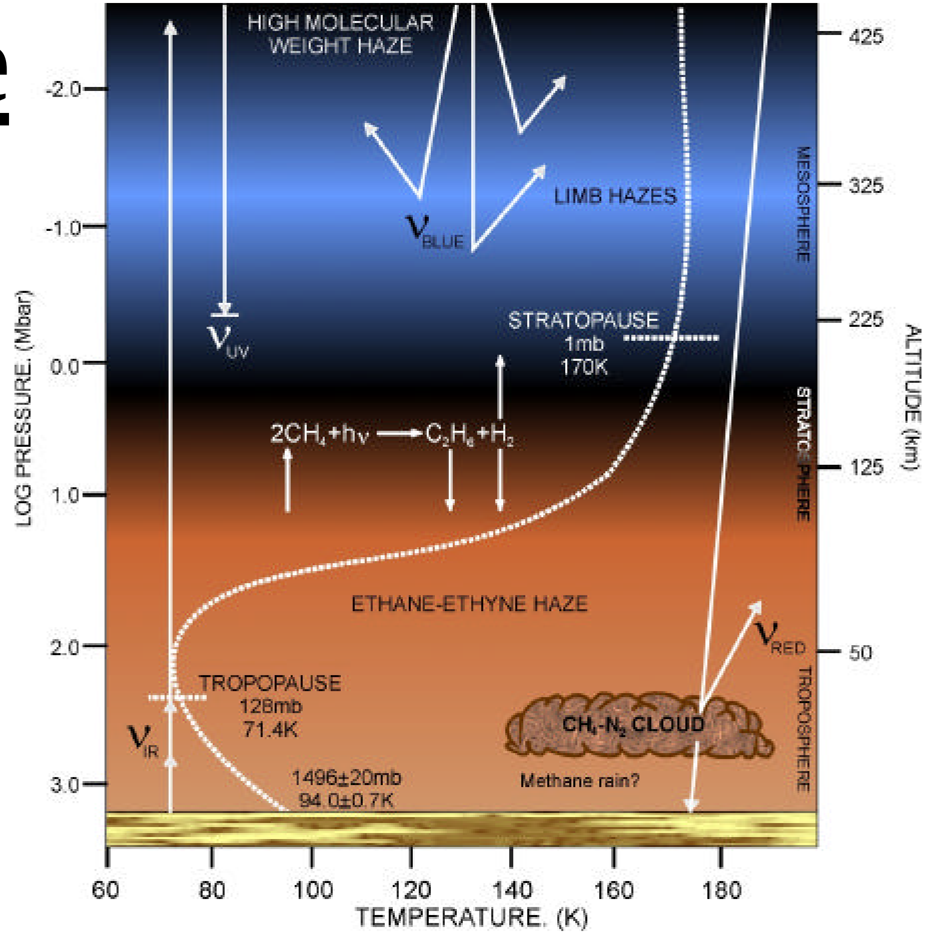
Surface Radius	2575 km	
Mass	1.35×10^{23} kg ($=0.022 \times$ Earth)	
Mean Density	1880 kg m^{-3}	
Distance from Saturn from Sun	1.23×10^{9}m ($=20$ Saturn radii) 9.546 AU	
Orbital Period around Sun	15.95 days 29.5 years	
Obliquity	26.7°	
Surface Temperature	94 K	
Surface Pressure	1.44 bar	
Composition (mole fractions):		
Nitrogen	N_2	90–97%
Argon	Ar	0–6%
Methane	CH_4	0.5–4%
Hydrogen	H_2	0.2%
Ethane	C_2H_6	1×10^{-5}
Acetylene	C_2H_2	2×10^{-6}
Propane	C_3H_8	5×10^{-7}
Ethylene	C_2H_4	1×10^{-7}
Diacetylene	C_4H_2	1×10^{-9}
Hydrogen Cyanide	HCN	1×10^{-7}
Carbon Monoxide	CO	$\sim 10^{-5}$
Carbon Dioxide	CO_2	1×10^{-8}
Water	H_2O	8×10^{-9}

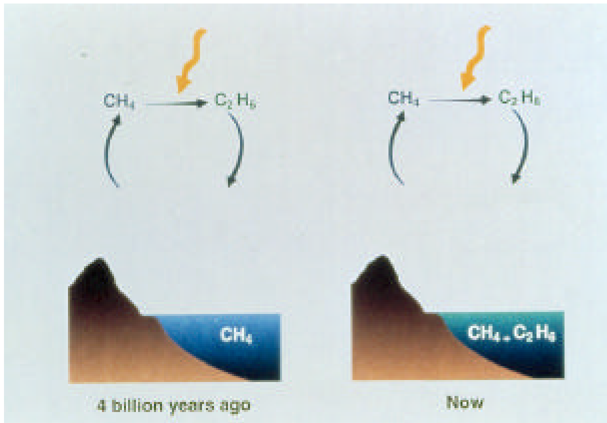
Informations obtained by Voyager 1 (IRIS):

- N2 is the major component
- CH4 & other hydrocarbons
- H2
- nitriles
- Little oxygen: CO, CO2

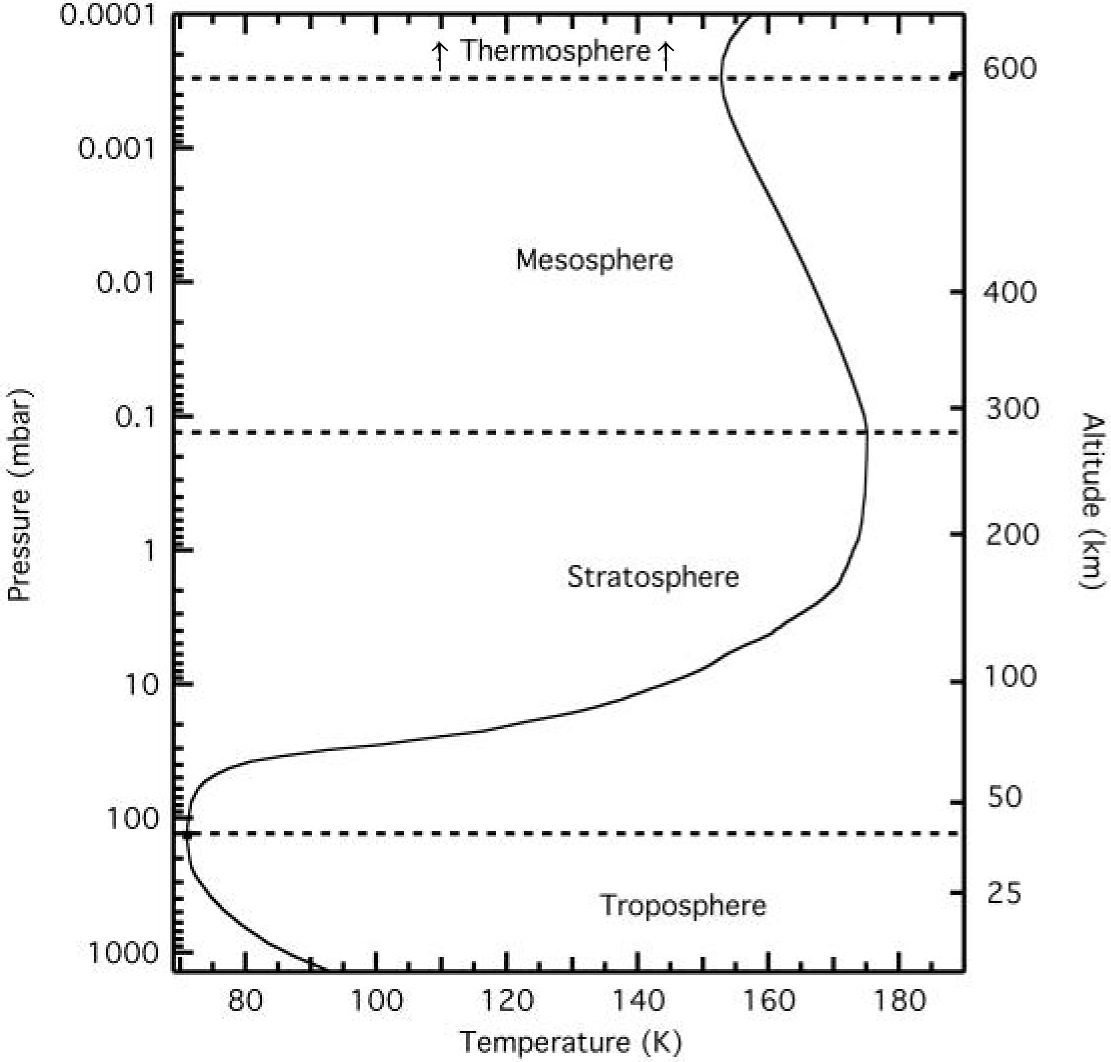
Interest for pre-biotic chemistry

Titan's atmosphere



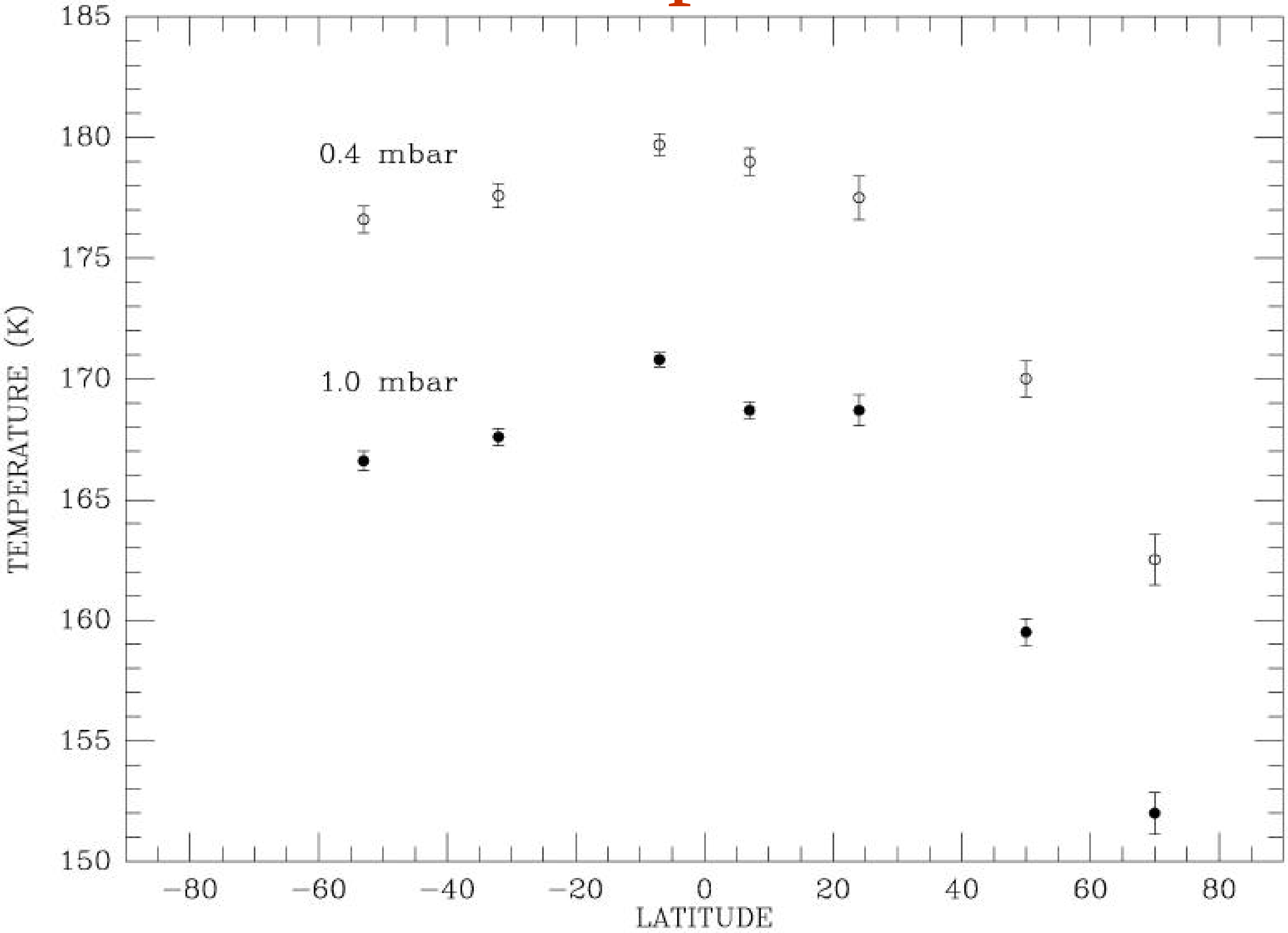


See Poster
by Lavvas et al.

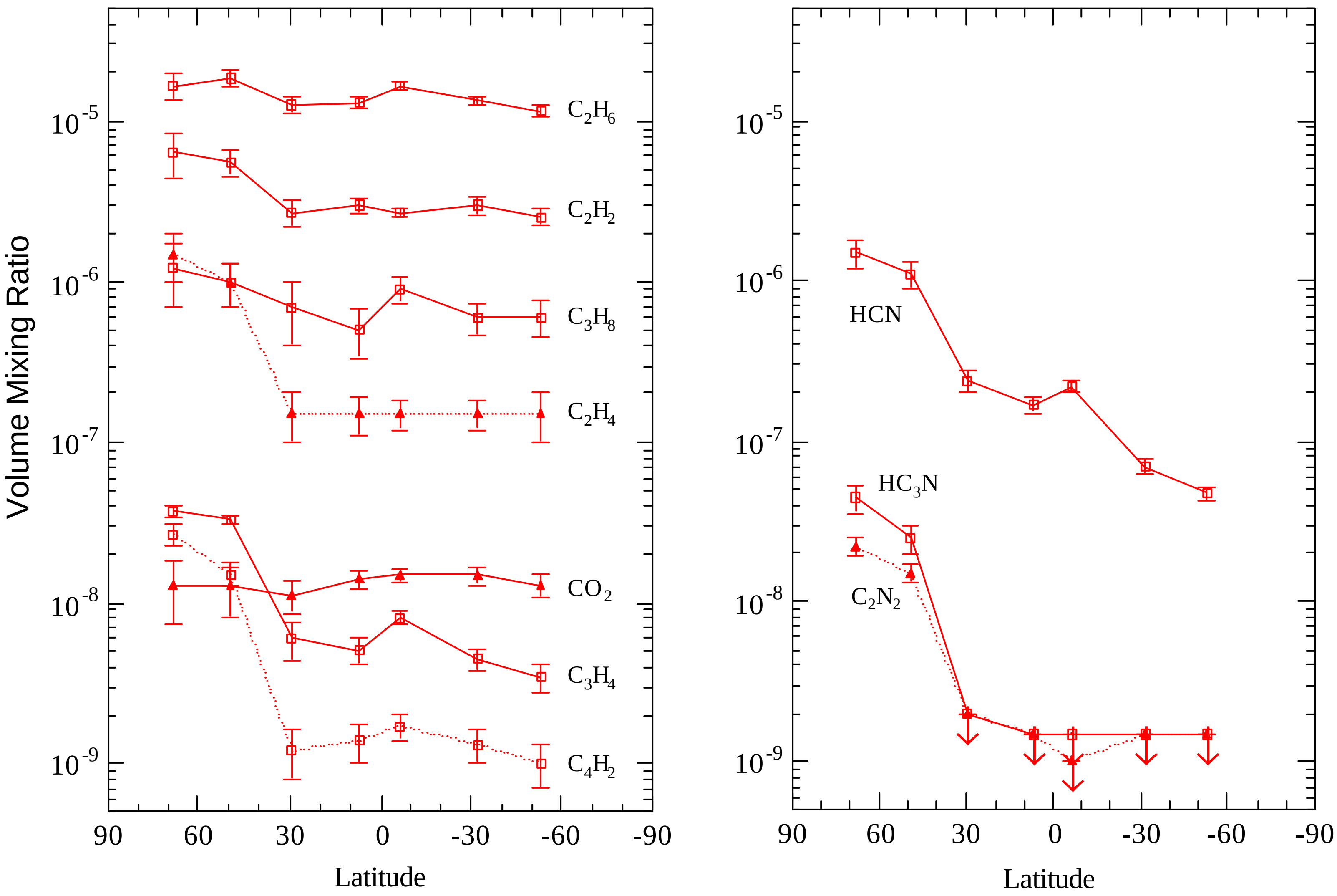


↑ Thermosphere ↑
Mesosphere
Stratosphere
Troposphere
0.0001
0.001
0.01
0.1
1
10
100
1000
Pressure (mbar)
80
100
120
140
160
180
Temperature (K)
600
400
300
200
100
50
25
Altitude (km)

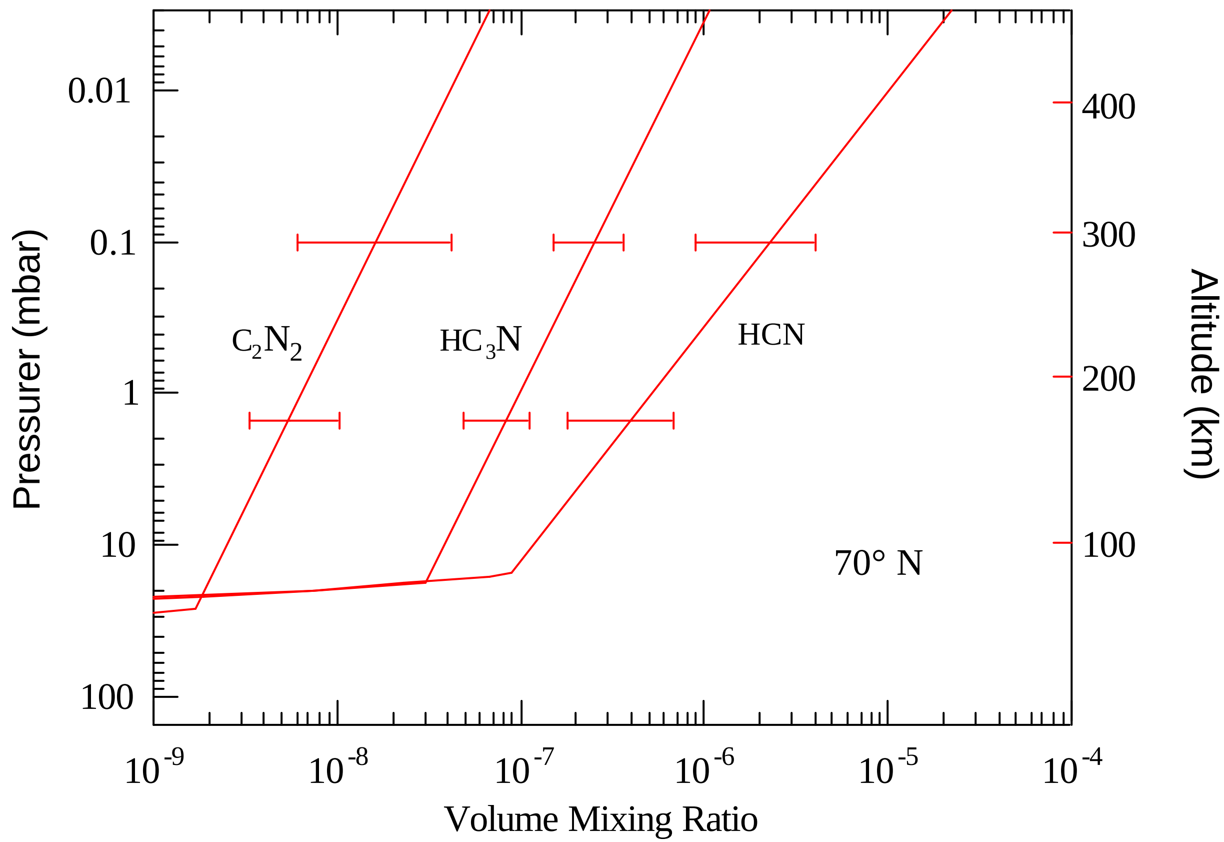
Titan's temperature field



Coustenis & Bézard (1995)



Coustenis & Bézard (1995)



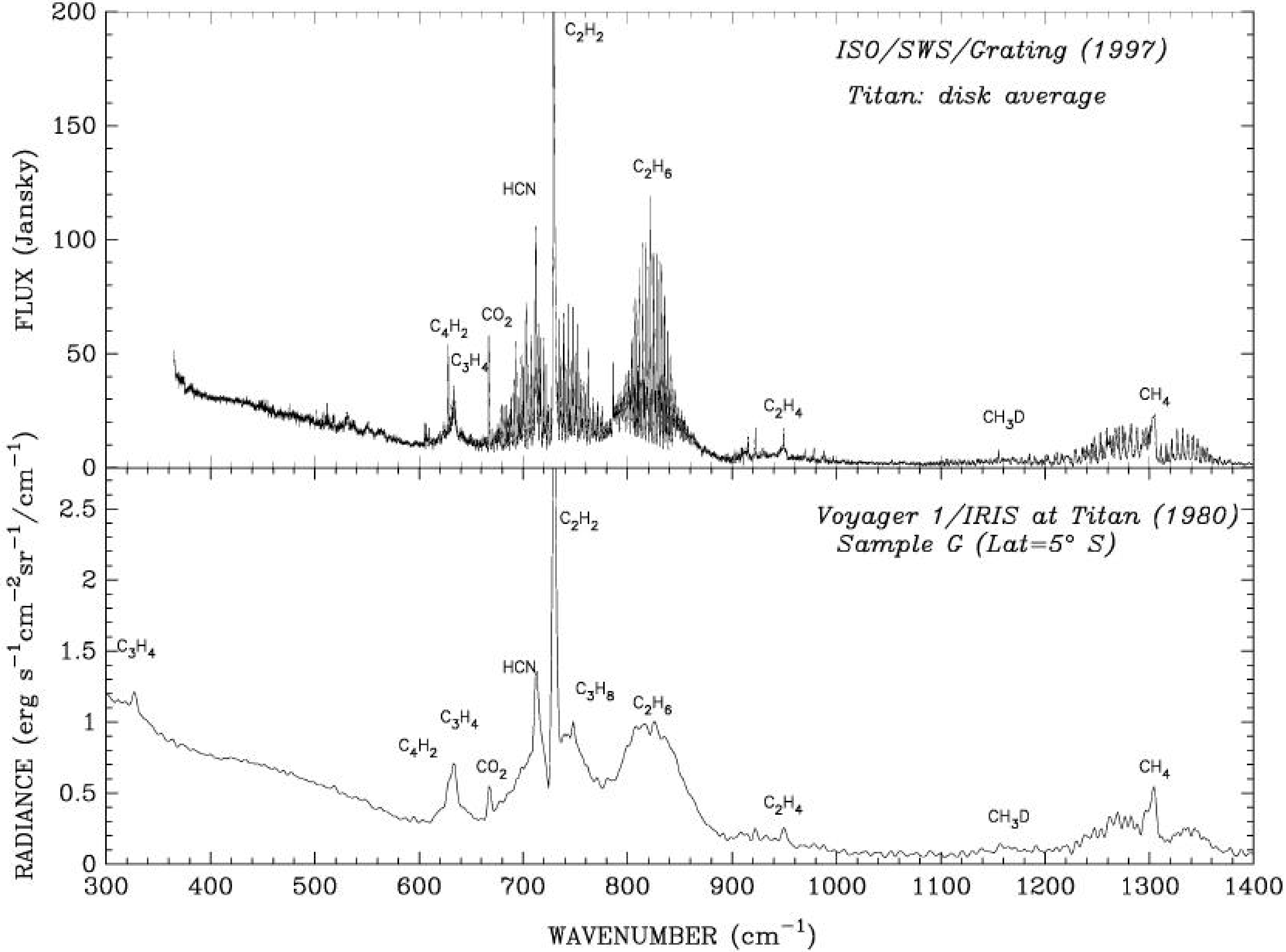
Voyager IRIS: Coustenis *et al.* (1991)

The Infrared Space Observatory

- ISO is an Earth-orbit infrared observatory
  (November 1995 - April 1998, duration of 28 months)
- The He-cooled telescope diameter is 60 cm.
- ISO operates in the 2 - 200 micron spectral range
  using 4 instruments:
  - 2 spectrometers (SWS and LWS)
    - SWS: **2.5 - 45 mm**
    - LWS: **45 - 200 mm**
  - 1 photometer (ISOPHOT)
    - PHT-S: **2.5-5 & 6-12 mm**
  - 1 camera (ISOCAM)

  in two different modes:
  - a Grating mode (R=1500 - 3000)
  - a Fabry - Pérot mode (R=10000 - 20000)

ISO/SWS vs V1/IRIS

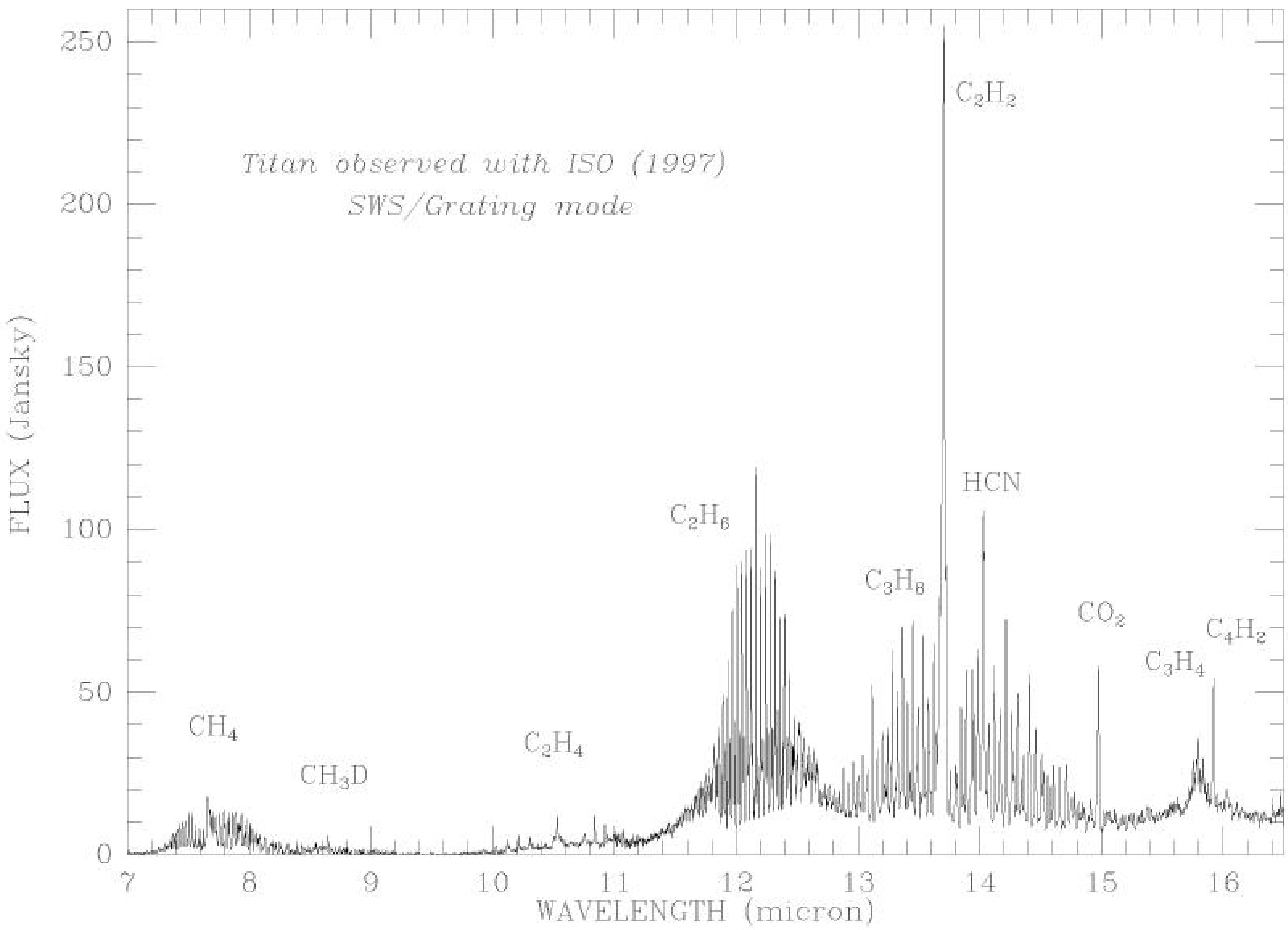


The Titan ISO data are high-resolution disk-averages

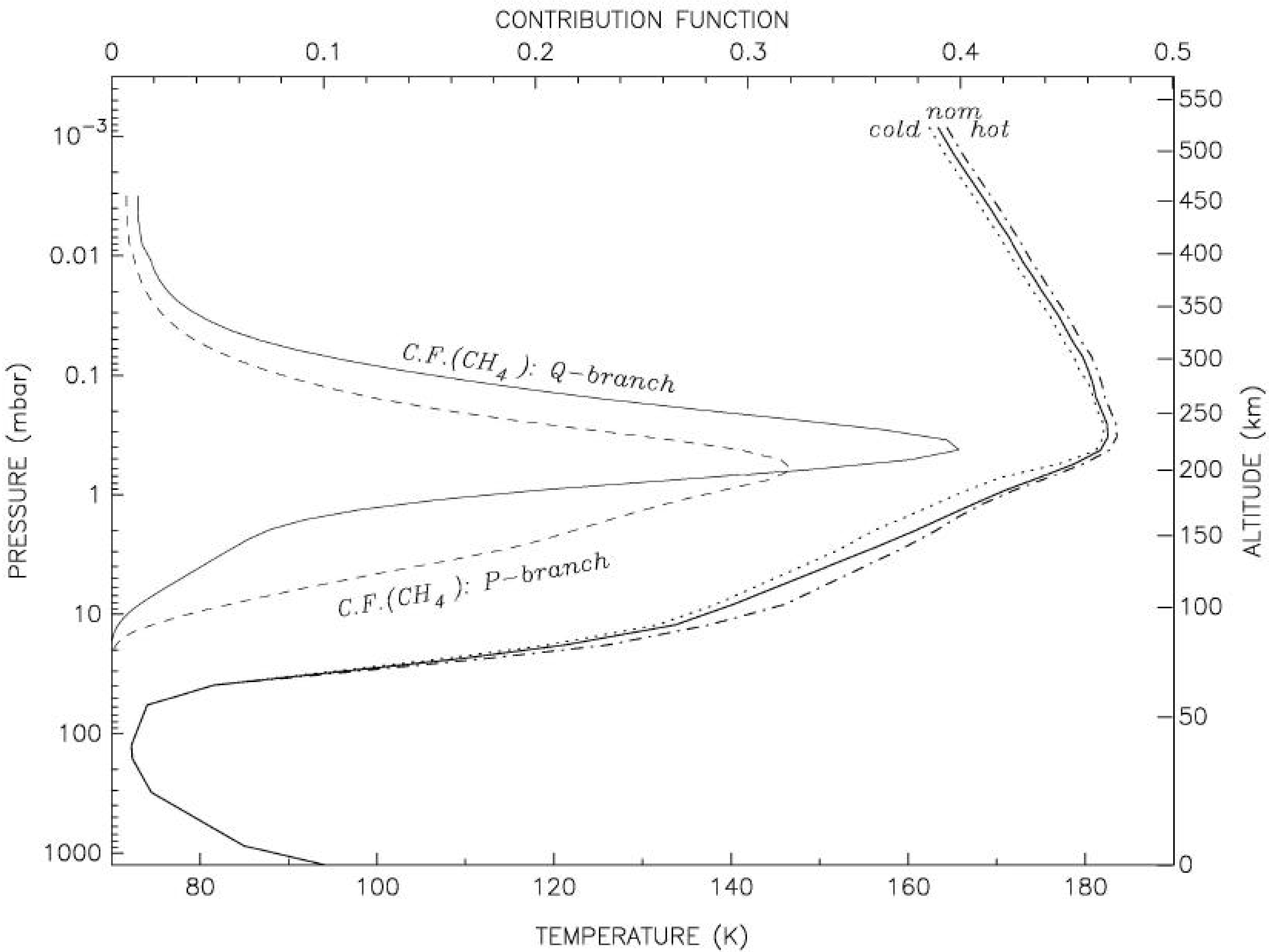
- acquired on January 10
- and December 27 1997

With all the instruments

- Compared to Voyager/IRIS the thermal infrared spectra afford 10 times higher resolution
- The usable SWS range covered is from 7-17 micron
- The 7.7 μm (1304 cm^{-1}) CH_4 band gives the T profile
- Then, through the radiative transfer equation, the best fit of the observed emission in the rest of the spectrum gives the mean molecular abundances

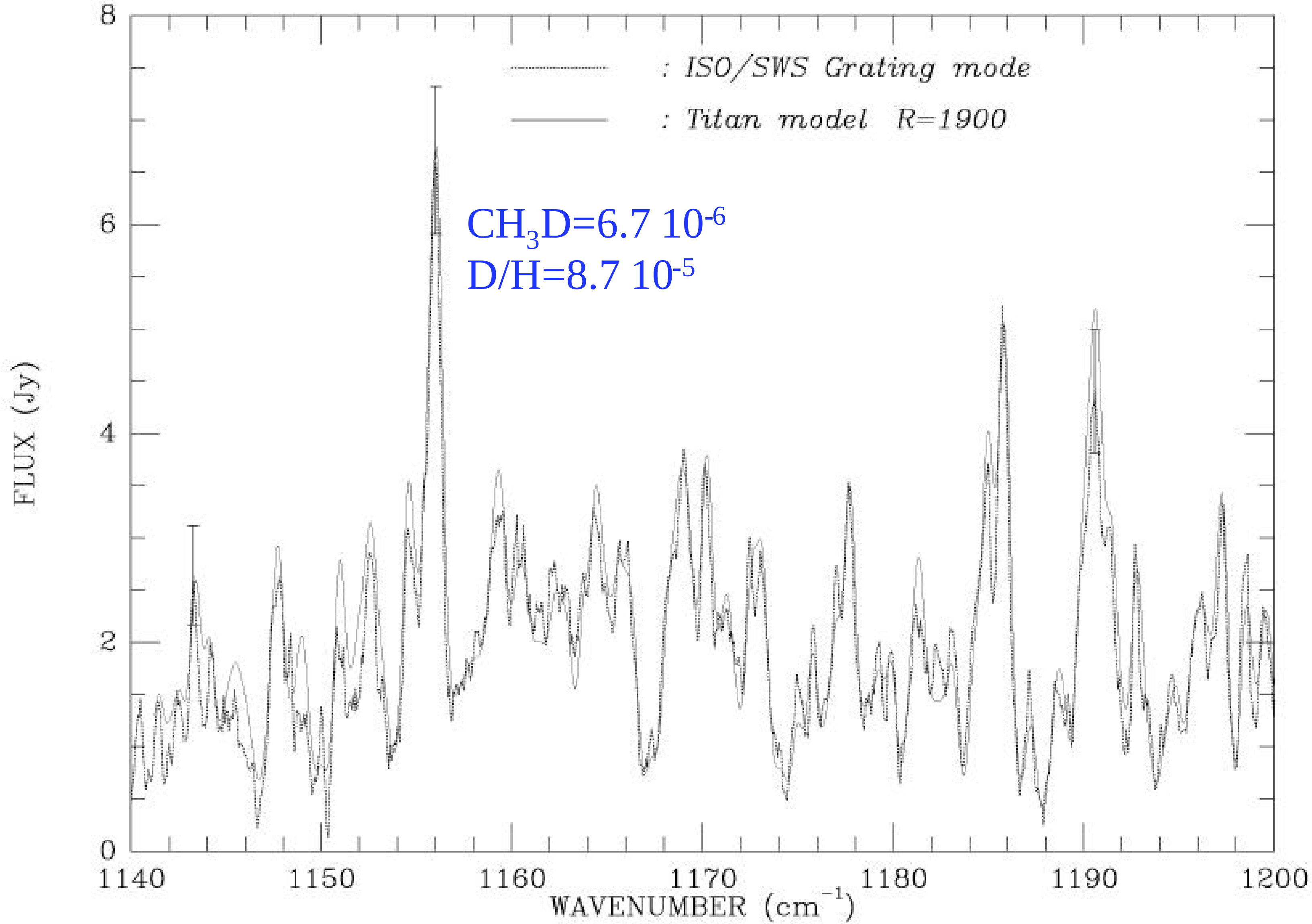


ISO/SWS : Coustenis et al. (2003)



ISO/SWS : Coustenis et al. (2003)

CH_3D and the D/H ratio



ISO/SWS : Coustenis et al. (2003)

Evidence for water vapor on Titan

- **Context:**

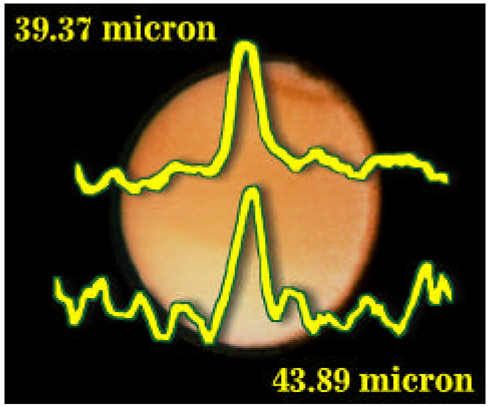
- CO_2 and H_2O have been recently discovered in the stratospheres of the giant planets with ISO (Feuchtgruber et al., 1997).
- Water vapor was expected in Titan's atmosphere since the discovery of CO and CO_2. H_2O is deposited in the upper atmosphere in the form of icy particles. Then:
  - H_2O vaporization & photolysis $\rightarrow$ OH
  - OH + hydrocarbon radicals (CH_3) $\rightarrow$ CO
  - CO + OH $\rightarrow$ CO_2 + H

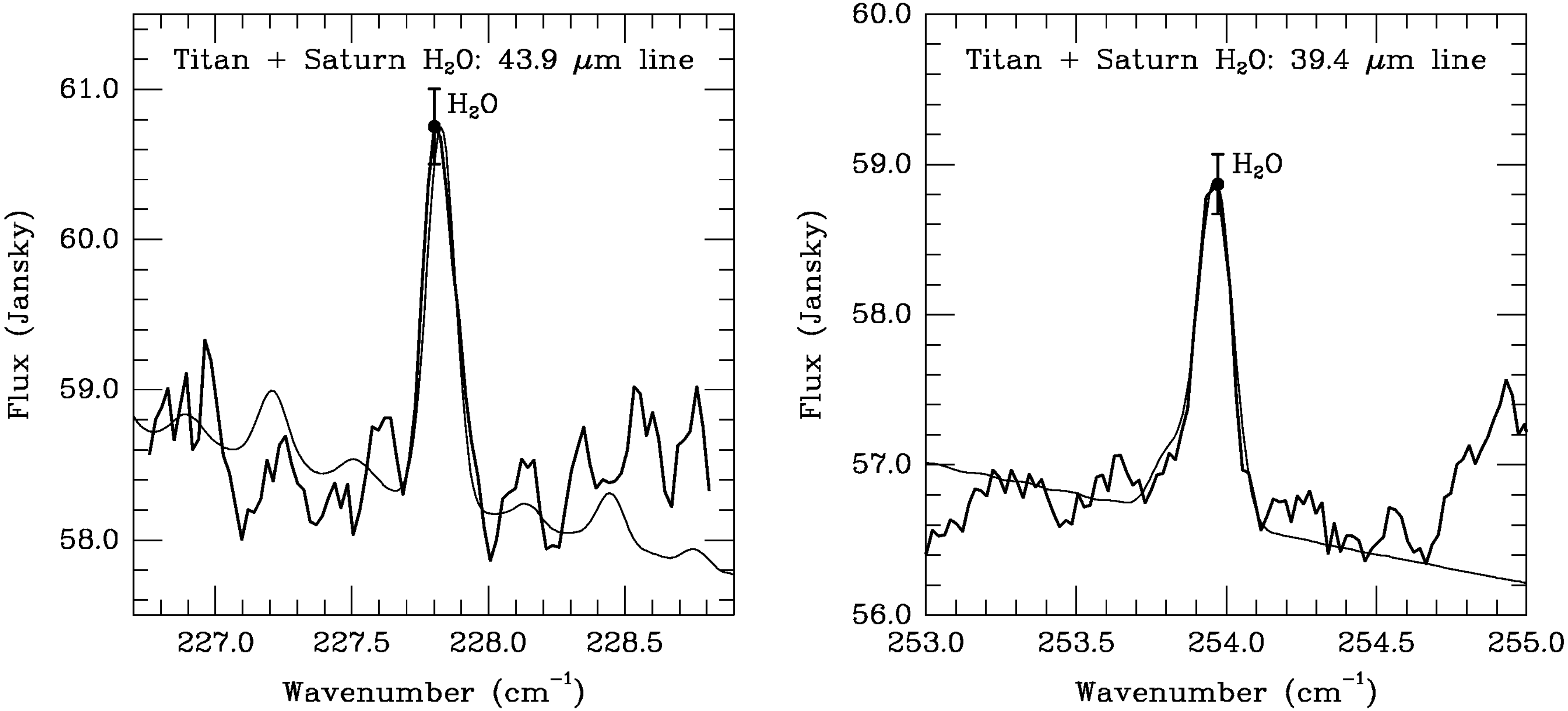
Observations:

We observed Titan in December 1997 during a total of 4.2 hrs integration time with SWS in the grating mode, with resolving power of 1800-2050 (AOT-02).

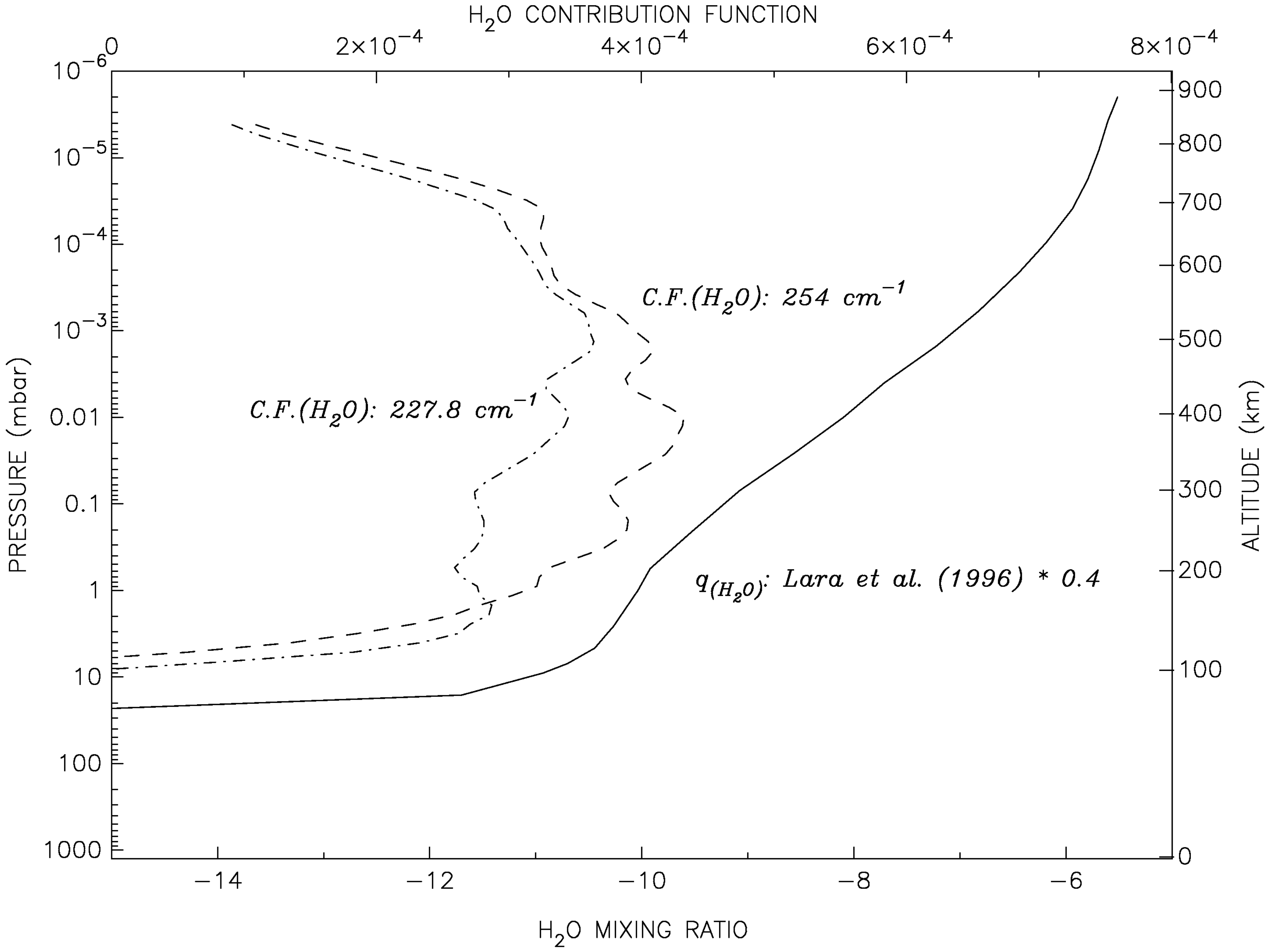
- We found two emission features at locations where pure rotational water lines are expected. After reduction of the data, the lines appear as follows:

Line position		*Cont. level*	*Sat.*	*H_2O Peak flux*	*std dev*	*Det.*
mm	*cm^{-1}*	*Jy*	*Jy*	*Jy*		*Jy*
39.4	254	56.5	0.6	1.6	0.2	8 σ
43.9	227.8	59.5	0.5	2.0	0.25	8 σ





ISO/SWS : Coustenis et al. (1998)



ISO/SWS : Coustenis et al. (1998)

Water vapor abundance and flux

–Synthetic spectra were generated with a radiative transfer model based on T, and other opacity sources from the rest of the ISO/SWS spectrum and compared with the data.

–A constant mixing ratio of $4\ 10^{-10}$ can fit the data.

–Also, a vertical distribution is compatible:

$$\sim 0.4 \times \text{Lara et al. (1996)}$$

–The associated mole fraction at 400 km of altitude is

$$q(H_2O) \sim 8 \times 10^{-9}$$

–The column density is $\sim 2.5 \times 10^{14}$ mol cm^{-2} above the surface.

–The inferred water influx at Titan at 700 km altitude is

$$(0.8 - 2.8) \times 10^{6} \text{ mol cm}^{-2}\text{s}^{-1},$$

–At Saturn: $(1.5\text{-}5) \times 10^{6}$ cm^{-2}s^{-1} (Feuchtgruber et al., 1997).

–Then, H_2O flux (Saturn/Titan) ~ 0.5 - 6.2

H_2O sources:

– We find that H_2O flux on Titan is ~1.6×10^6 mol cm^{-2}s^{-1}, and flux (Saturn/Titan) ~ 0.5 - 6.2

- The H_2O flux is in agreement with Lara & al. (1996) value allowing to fit the observed CO_2 abundance by Voyager and ISO. This agreement holds regardless of CO adopted, because CO_2 is independent of CO at equilibrium (CO equil. lifetime ~10^9 years).

– H_2O influx may have two primary sources:

- Interplanetary dust component in the Solar System: IC

  H_2O influx predicted by the meteroid ablation model in agreement with this work [2×10^6 mol cm^{-2} s^{-1}: English & al., 1996]

  IC (Saturn/Titan) ≈ 7.5 (due to gravitational focussing)

  [marginally in agreement with ISO upper limit of 6.2]

- Local dust component (sputtering and collisions from icy satellites and rings): LC

  LC also in favor of Saturn (due to gravitational energetics and magnetic lines of force)

  But: - Higher velocities of icy particles and sputtering from Iapetus, Hyperion, and Phoebe could bring more water on Titan.

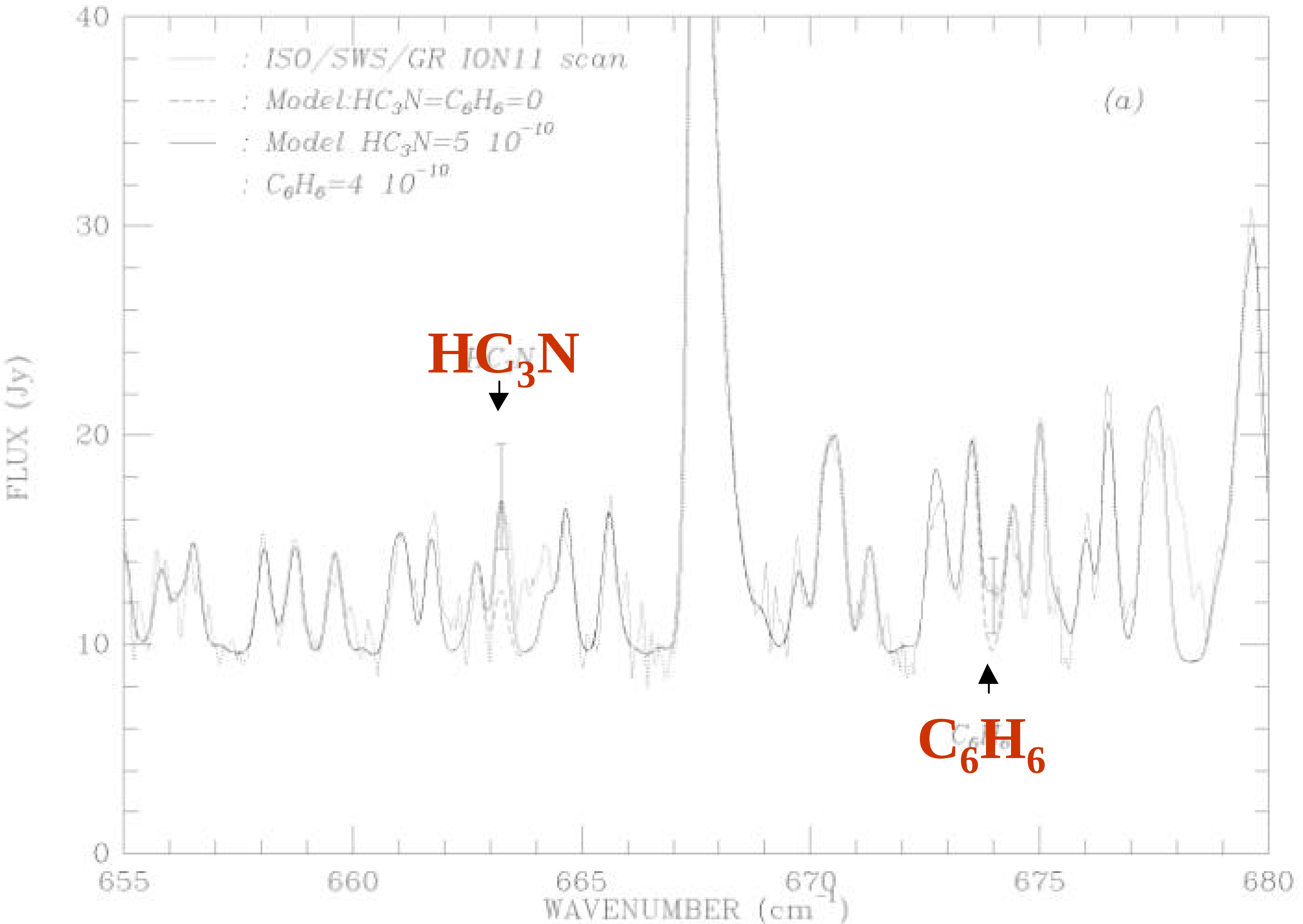
Evidence for benzene on Titan

Context:

– Benzene has been recently discovered in the stratospheres of the giant planets Jupiter and Saturn with ISO (Bézard et al., 2002) but not in Uranus and Neptune. Nothing appeared in the V1/IRIS data at 674 cm^{-1} at the resolution of 4.3 cm^{-1}.

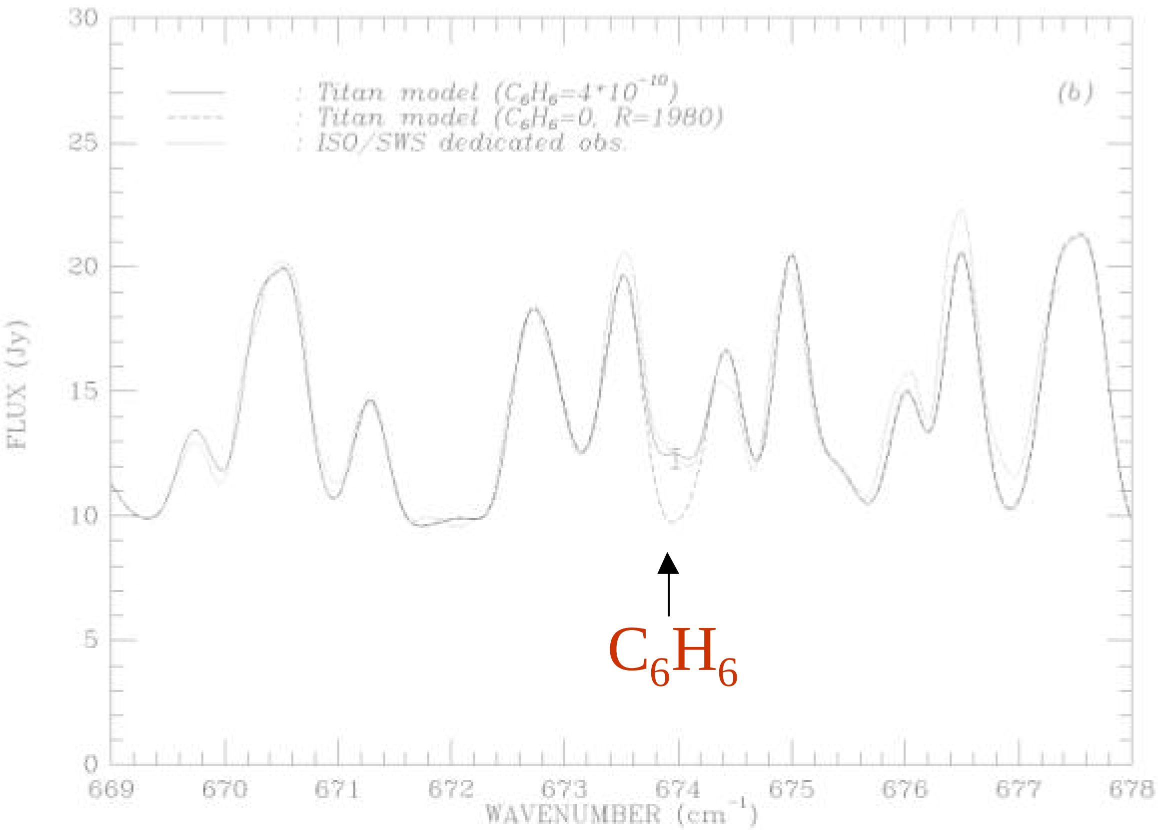
– Benzene was expected in Titan's atmosphere with a formation dominated by propargyl recombination through (Wilson et al., 2002) :

$$2(CH_4 + h\nu \rightarrow {}^1CH_2 + H_2)$$
$$2(C_2H_2 + {}^1CH_2 \rightarrow C_3H_3 + H)$$
$$\underline{C_3H_3 + C_3H_3 \rightarrow [n\text{-}]\ C_6H_6}$$
$$2C_2H_2 + CH_4 \rightarrow C_6H_6 + 2H + H_2$$



We observed Titan in December 1997 during 1 hr of integration time with a resolving power of ~2000 in the 14.76-14.94 µm region (dedicated observation). We then clearly observed HC_3N in emission at mid-latitudes at 663 cm^{-1} and inferred and abundance of about 5±3 10^{-10} relevant to the 9-mbar pressure level.

Benzene on Titan



We found an emission feature at 674 cm^{-1} where the ν_4 band of C_6H_6 occurs. We have found a 3Jy additional flux which can be explained with a benzene emission of about **4±3 10^{-10}** relevant to the 9-mbar region and corresponding to a column density of **2 10^{15} mol cm^{-2}** (Coustenis et al., 2003).

Results

•Molecule	Voyager	ISO	Ratio
•C_2H_2	$3.0\ 10^{-6}$	$3\text{-}5.5\ 10^{-6}\uparrow$ (v.d.)	
•C_2H_4	$1.5\ 10^{-7}$	$1.2\ 10^{-7}$	→
•C_2H_6	$1.5\ 10^{-5}$	$2.0\ 10^{-5}$	→
•C_3H_4	$6.5\ 10^{-9}$	$1.2\ 10^{-8}$	→
•C_3H_8	$7.0\ 10^{-7}$	$2.0\ 10^{-7}$	→
•C_4H2	$1.5\ 10^{-9}$	$2.0\ 10^{-9}$	→
•CH_3D	$1.1\ 10^{-5}$	$6.7\ 10^{-6}$	
•D/H	$1.5\ 10^{-4}$	$8.7\ 10^{-5}$	→
•C_3H_4 (allene)		$<2.0\ 10^{-9}$	
•C_6H_6 (benzene)		$4\ 10^{-10}$	
•HCN	$2.0\ 10^{-7}$	$3.0\ 10^{-7}$	→
•HC_3N	$<1\ 10^{-9}$	$5\ 10^{-10}$	
•C_2N_2	$<1\ 10^{-9}$		
•CO_2	$1.5\ 10^{-8}$	$2.0\ 10^{-8}$	→
•H_2O @ 400 km		$8\ 10^{-9}$	

With respect to a Voyager-inferred modeling of the Titan disk-average, we find that the differences with the Voyager stratospheric abundances are small but the mixing ratios are more precise.

- Coustenis et al., 1993, *Icarus* 102, 240-260 ; Coustenis and Bézard, 1995, *Icarus* 115, 126-140
- Coustenis et al., 2002, *Icarus*, in press. ; Coustenis et al., 1998, *Astron.&Astroph.* 336, L85.

Table 1. Atmospheric composition of Titan

From Flasar et al., 2004

	Gas	Mole fraction				Comments-Ref.
n ts						
	N_2		0.85-0.98			Inferred indirectly *(a)*
	Ar		< 0.07			Inferred indirectly *(b)*
	CH_4		0.005-0.034			In the stratosphere *(b)*
			0.03-0.085			Near the surface (*b, l*)
ı	H_2		0.0011-0.0013			*(b)*
ıstituents		*Equator (c)*	*North Pole (d)*		*Disk-average (e)*	
		0.5-20 mbar	*~ 0.1 mbar*	*~ 1.5 mbar*	*0.5-20 mbar*	
·bons						
e	C_2H_2	2.85×10^{-6}	4.7×10^{-6}	2.3×10^{-6}	5.5×10^{-6}	
	C_2H_4	1.5×10^{-7}		$3.\times10^{-6}$	1.2×10^{-7}	
	C_2H_6	1.5×10^{-5}	1.5×10^{-5}	1.0×10^{-5}	2.0×10^{-5}	
etylene	C_3H_4	6.5×10^{-9}	6.2×10^{-8}	2.0×10^{-8}	1.2×10^{-8}	
	C_3H_8	7.0×10^{-7}		5.0×10^{-7}	2.0×10^{-7}	
ne	C_4H_2	1.5×10^{-9}	4.2×10^{-8}	2.7×10^{-8}	2.0×10^{-9}	
	C_6H_6				4.0×10^{-10}	
terated	CH_3D	1.1×10^{-5}			6.7×10^{-6}	
ı cyanide	HCN	1.95×10^{-7}	2.3×10^{-6}	4.0×10^{-7}	3.0×10^{-7}	
etylene	HC_3N	$\leq1\times10^{-9}$	2.5×10^{-7}	8.4×10^{-8}	5.0×10^{-10}	
ı	C_2N_2	$\leq1\times10^{-9}$	1.6×10^{-8}	5.5×10^{-9}		
ile	CH_3CN				1.5×10^{-9}	At 1 mbar *(f)*
cetylene	C_4N_2		Solid phase			(k)
ompounds						
por	H_2O				8×10^{-9}	At 0.01 mbar *(g)*
ioxide	CO_2	1.45×10^{-8}	$\leq7\times10^{-9}$	$\leq7\times10^{-9}$	2.0×10^{-8}	
onoxide	CO				$(2.2\text{-}4.2)\times10^{-5}$	In the troposphere *(h)*
					$(2\text{-}3.9)\times10^{-5}$ $(0.33\text{-}0.9)\times10^{-5}$	In the lower and in the higher stratosphere *(i)*
					$4\text{-}6\times10^{-5}$	In the higher stratosphere *(j)*

Table 1. Some organics, as yet unobserved on Titan in the thermal IR, but potentially observable with CIRS and their deduced upper limits in TitanÕs atmosphere from previous observations

Studied Compounds	***Strongest signatures***		***Upper limit of mean mixing ratio in Titan's stratosphere***	
	Frequency (cm^{-})	*Bandstrength at 300 K ($cm^{-2}\ atm^{-1}$)*	*using Voyager IRIS spectra*	*using ISO disk-averaged data*
Hydrocarbons				
CH_2CCH_2	356 845	65 407	5×10^{-9} *(a)*	2×10^{-9} *(b)*
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†	4.4		
CH_2CHCN	230 954	10 100	8.4×10^{-8} *(g)*	$< 5\times10^{-10}$ *(b)*
CH_3CH_2CN	207 1075	15 37	2.5×10^{-7} *(a)*	$< 1\times10^{-10}$ *(b)*
$CH_3CH_2CH_2CN$	728/742	3.5	5×10^{-7} *(a)*	
$(CH_3)_2CHCN$	538	3.3	2×10^{-7} *(a)*	
Δ CN	726 818	19 34	1.5×10^{-7} *(a)*	
CH_3CCCN	338 499	100 91	1.0×10^{-8} *(a)*	
$CH_3CHCHCN$	728	230	2.5×10^{-7} *(a)*	$< 5\times10^{-10}$ *(b)*
CH_2CHCH_2CN	557 942	64 110	4×10^{-8} *(h)*	$< 5\times10^{-10}$ *(b)*
$CH_2C(CH_3)CN$	535 928	33 130	7.5×10^{-8} *(h)*	$< 5\times10^{-10}$ *(b)*
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)*	

† Feature not yet observed. CH_3CN detected in millimeter observations (l), with a derived mole fraction 1.5×10^{-9} at 1 mbar.

From Flasar et al., 2004

New species for Cassini?? - not any more !

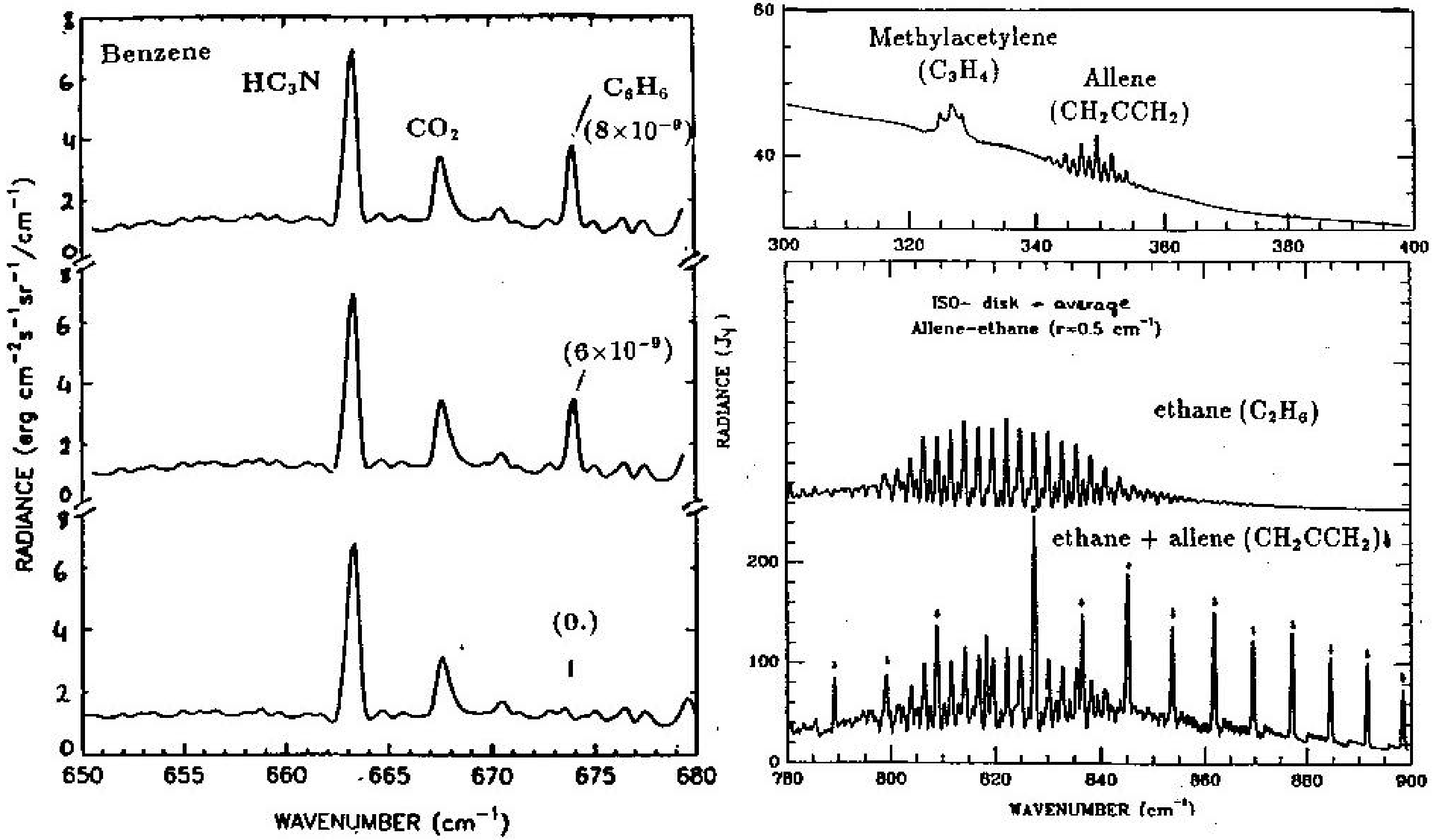
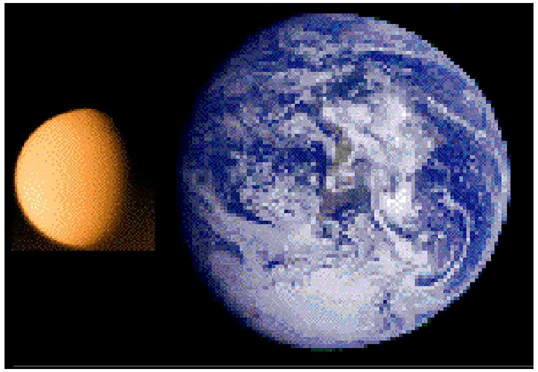


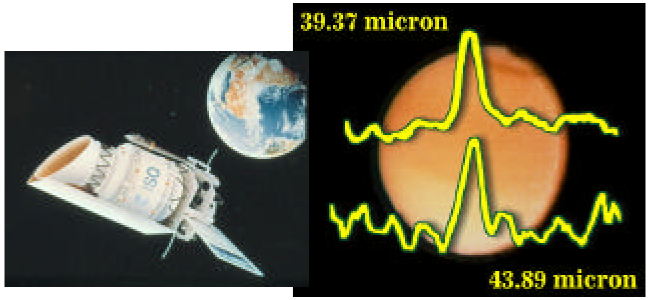
Fig. 9 *(a) Detectability of benzene (C_6H_6) by CIRS horizontal viewing in the ν_4 band (Q=673.5 cm^{-1}), and (b) detectability of allene in two different bands, with a spectral resolution of 0.5 cm^{-1} (ISO grating mode).*

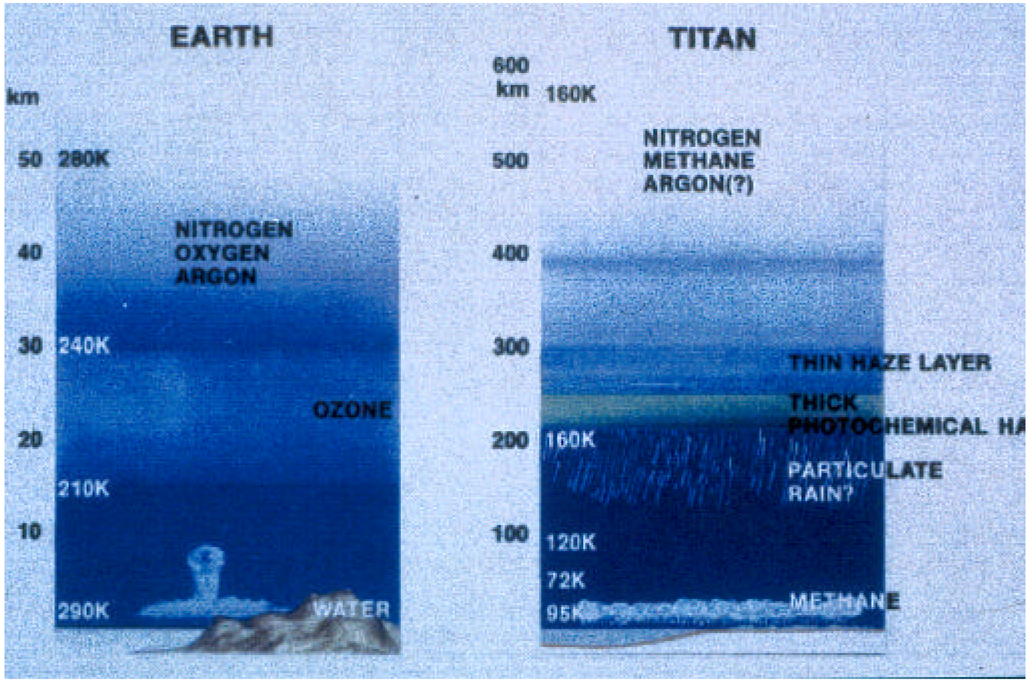
ISO : Coustenis et al., 2003

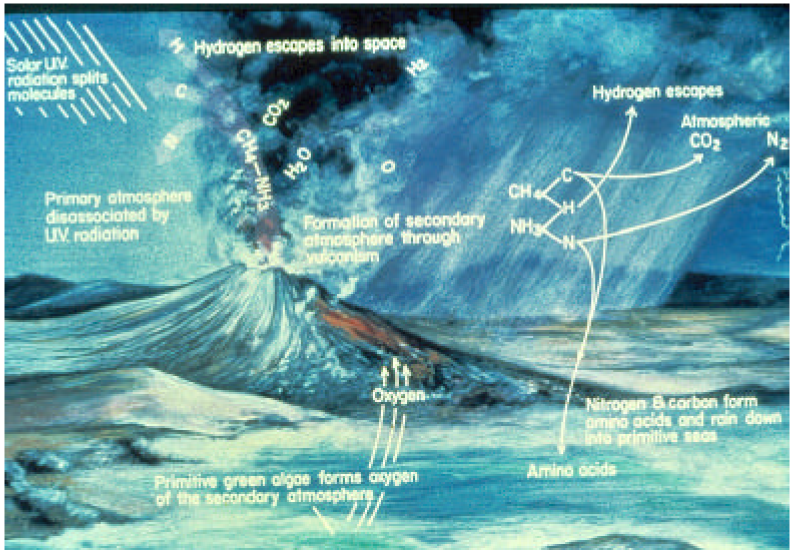
TEXES :Roe et al., 2004

Titan vs Earth









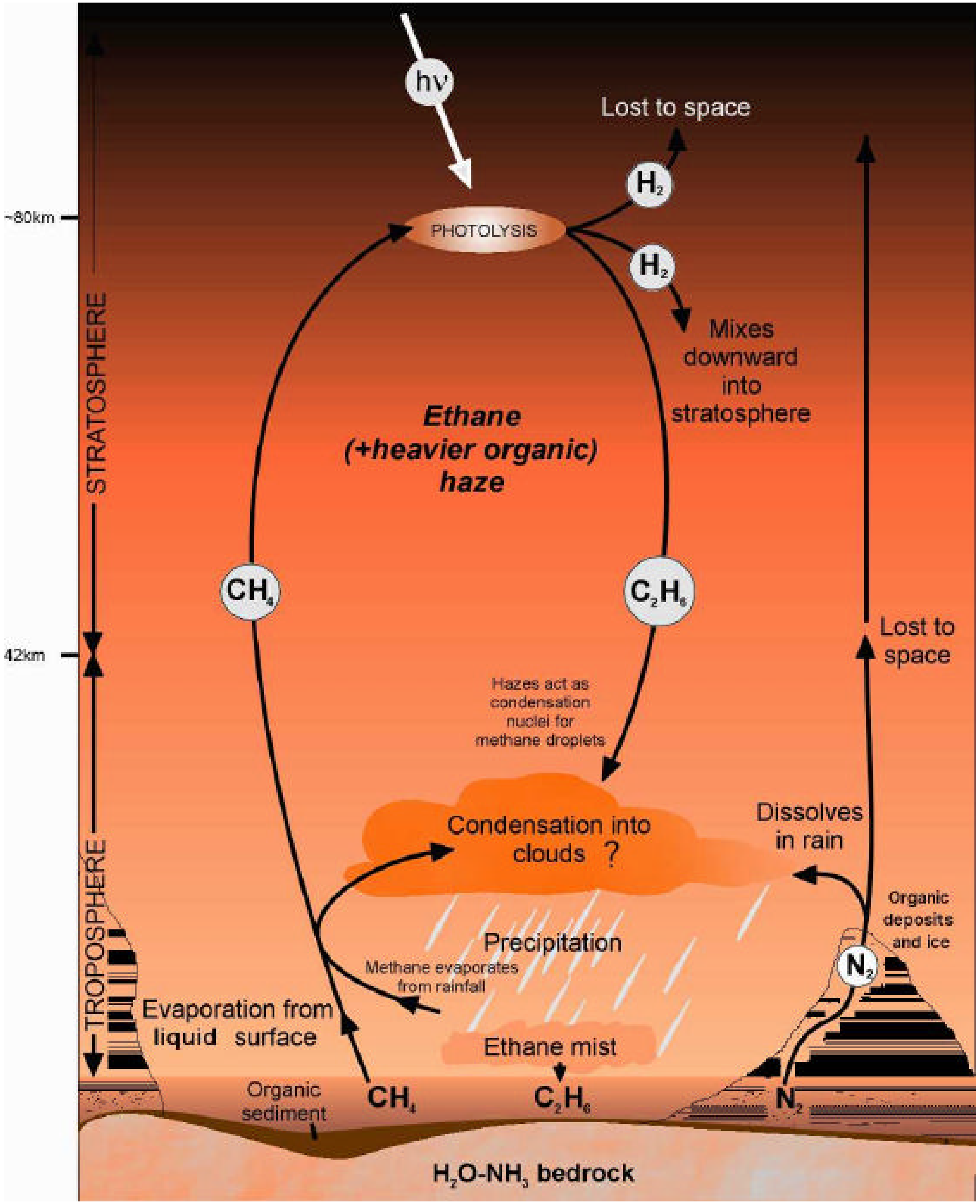
« A planetary-scale natural laboratory for the study of conditions prevailing on the primitive Earth »

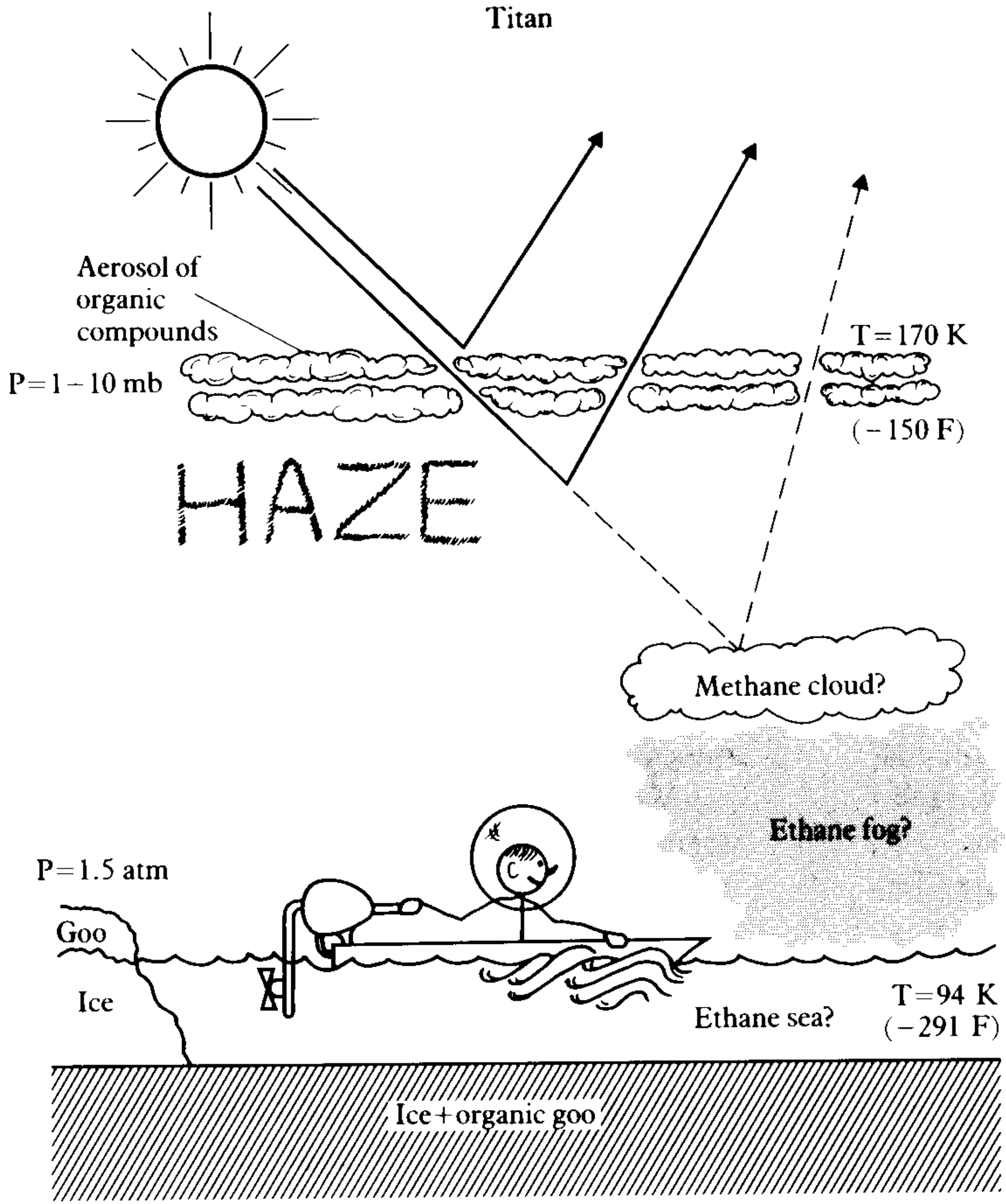
Titan's surface

- Global ocean unrealistic
  - Radar echos
  - Tide effects
  - Images & spectra

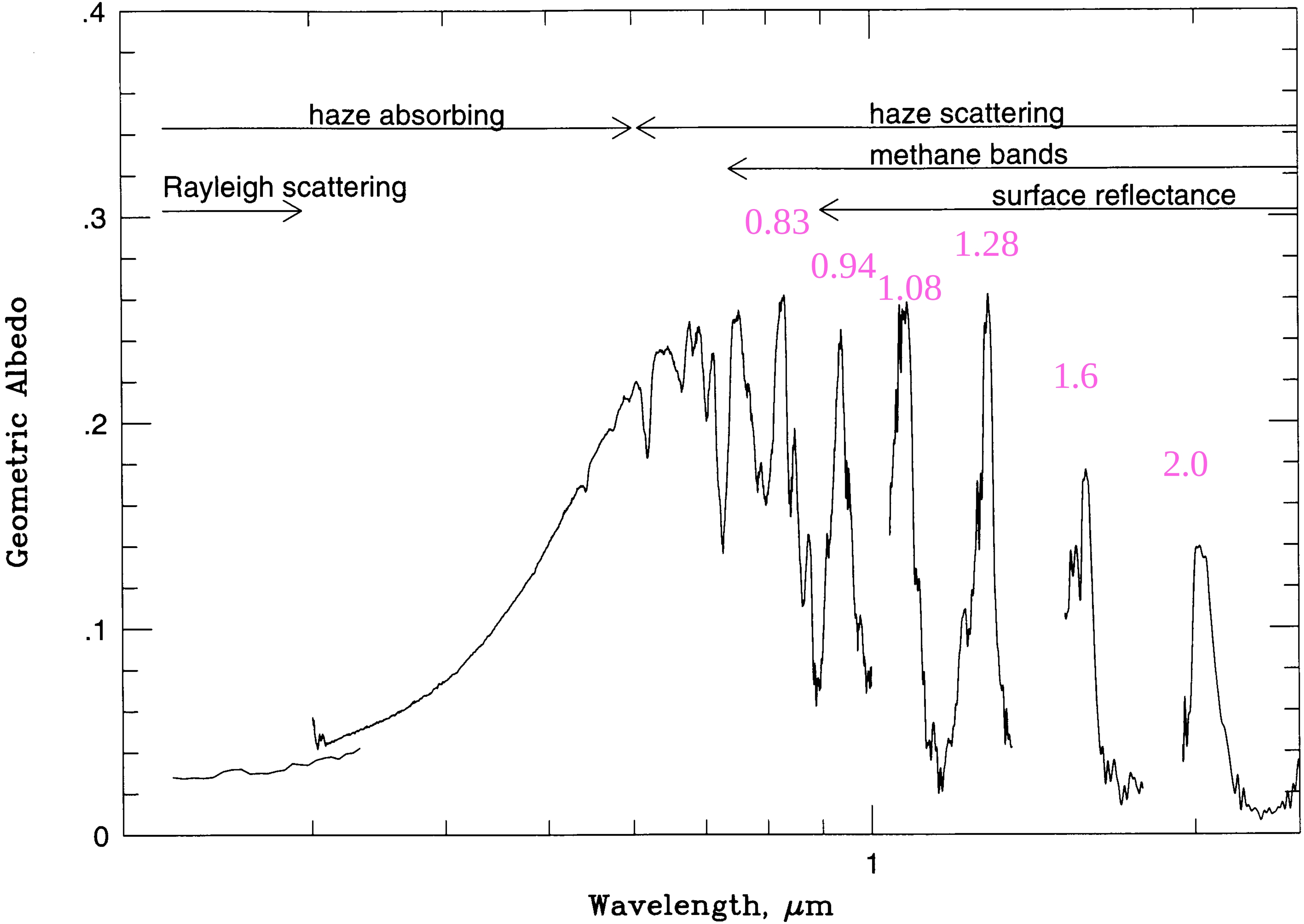
⇒Local hydrocarbon liquid extents? Mountains? Rocks ? Ice?

⇒Investigating in the near-IR

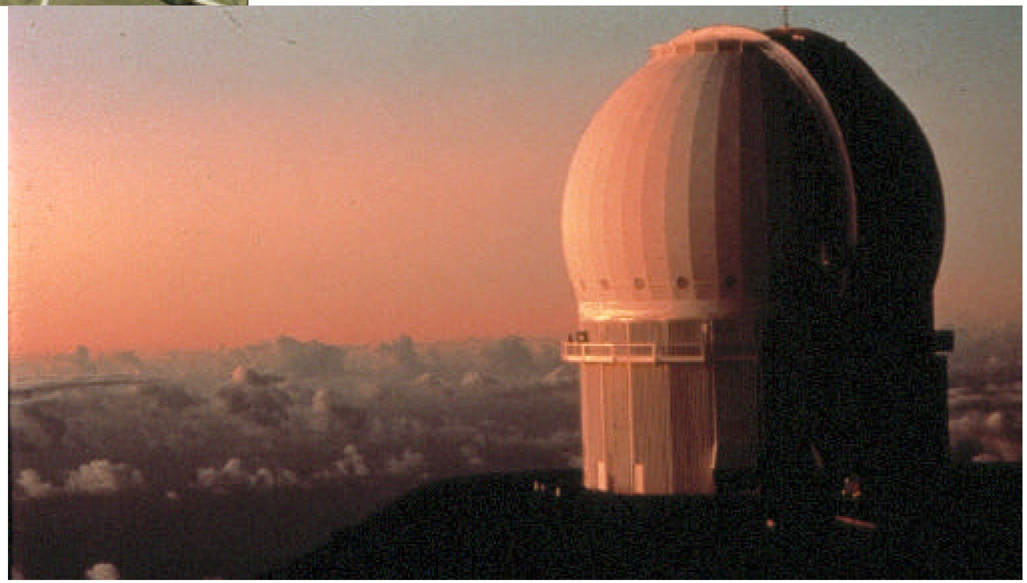



Titan
Aerosol of organic compounds
P = 1 – 10 mb
T = 170 K
(– 150 F)
HAZE
Methane cloud?
Ethane fog?
P = 1.5 atm
Goo
Ice
Ethane sea?
T = 94 K
(– 291 F)
Ice + organic goo

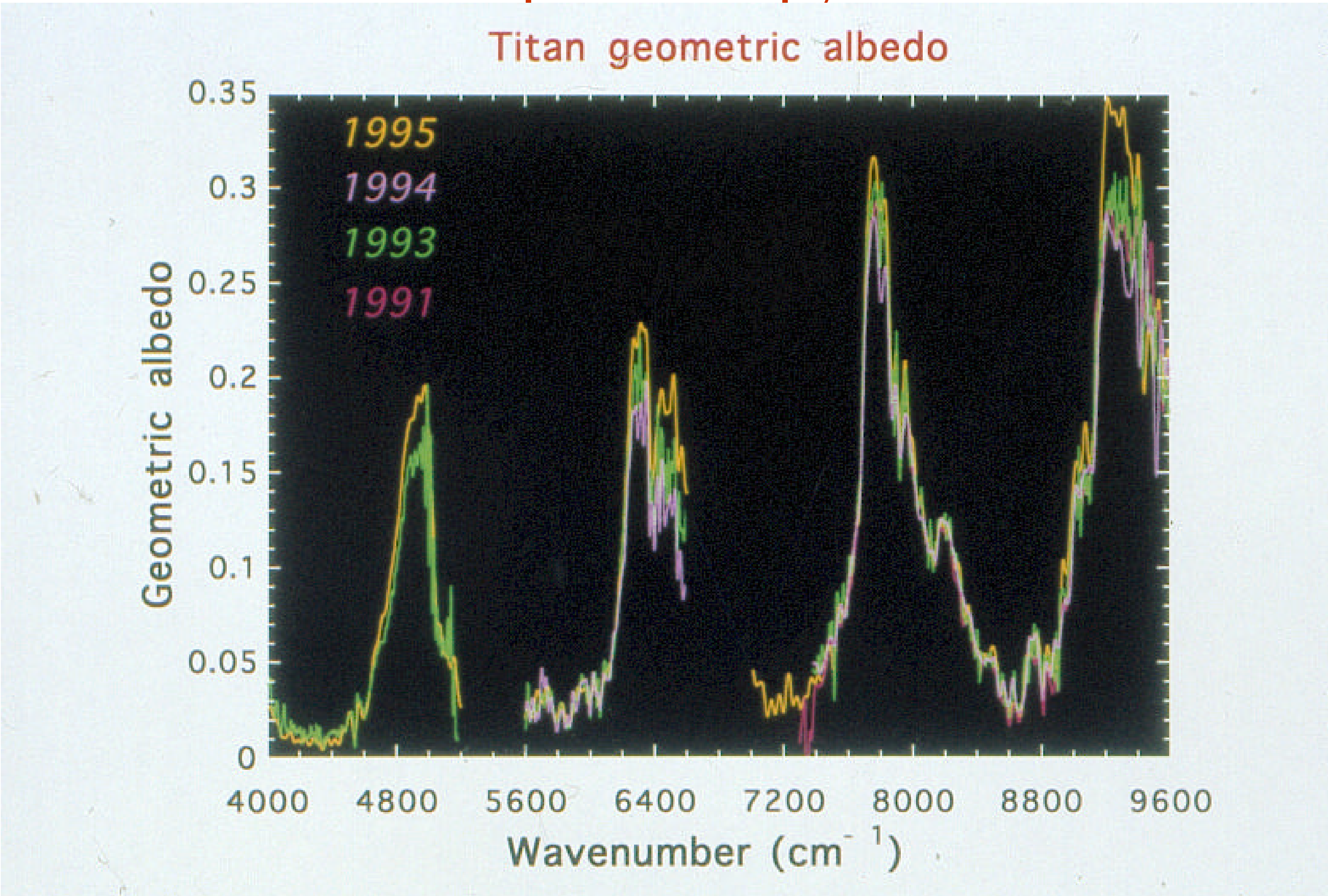
Titan's UV and near-IR spectrum



Titan Earth-based near-IR observations

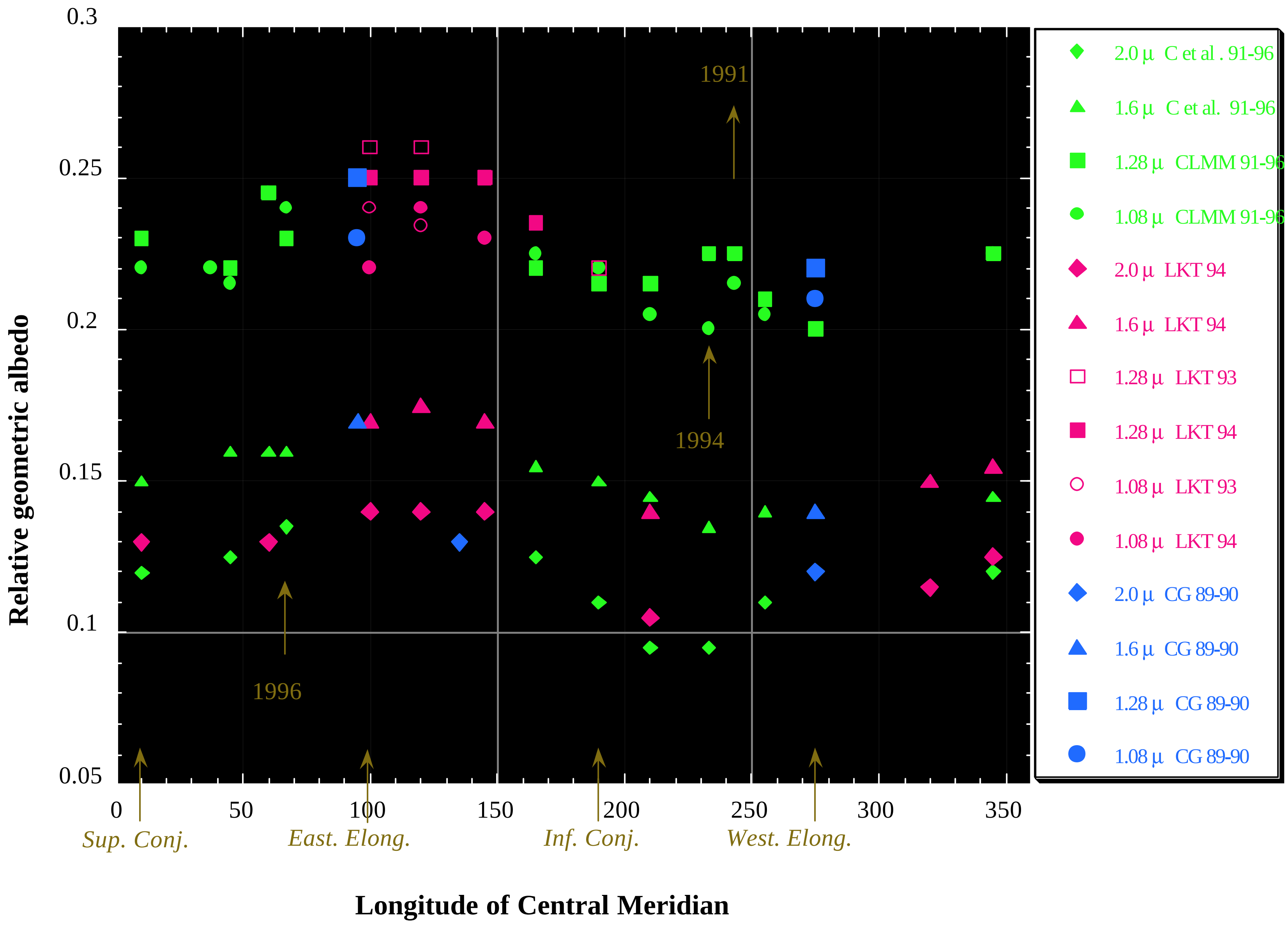


Ground-based spectroscopy in the near IR

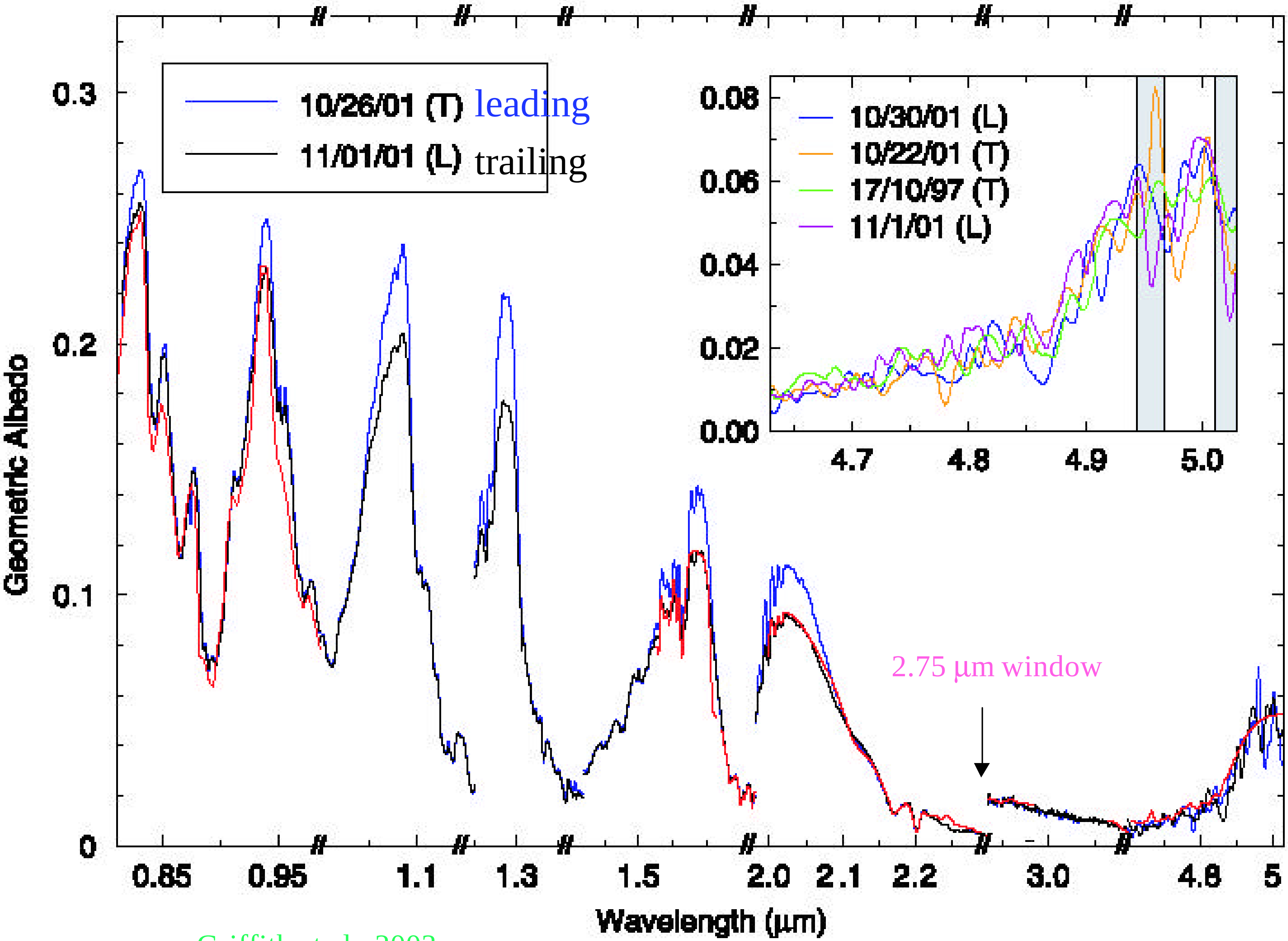


CFHT/FTS : Coustenis et al., 1995

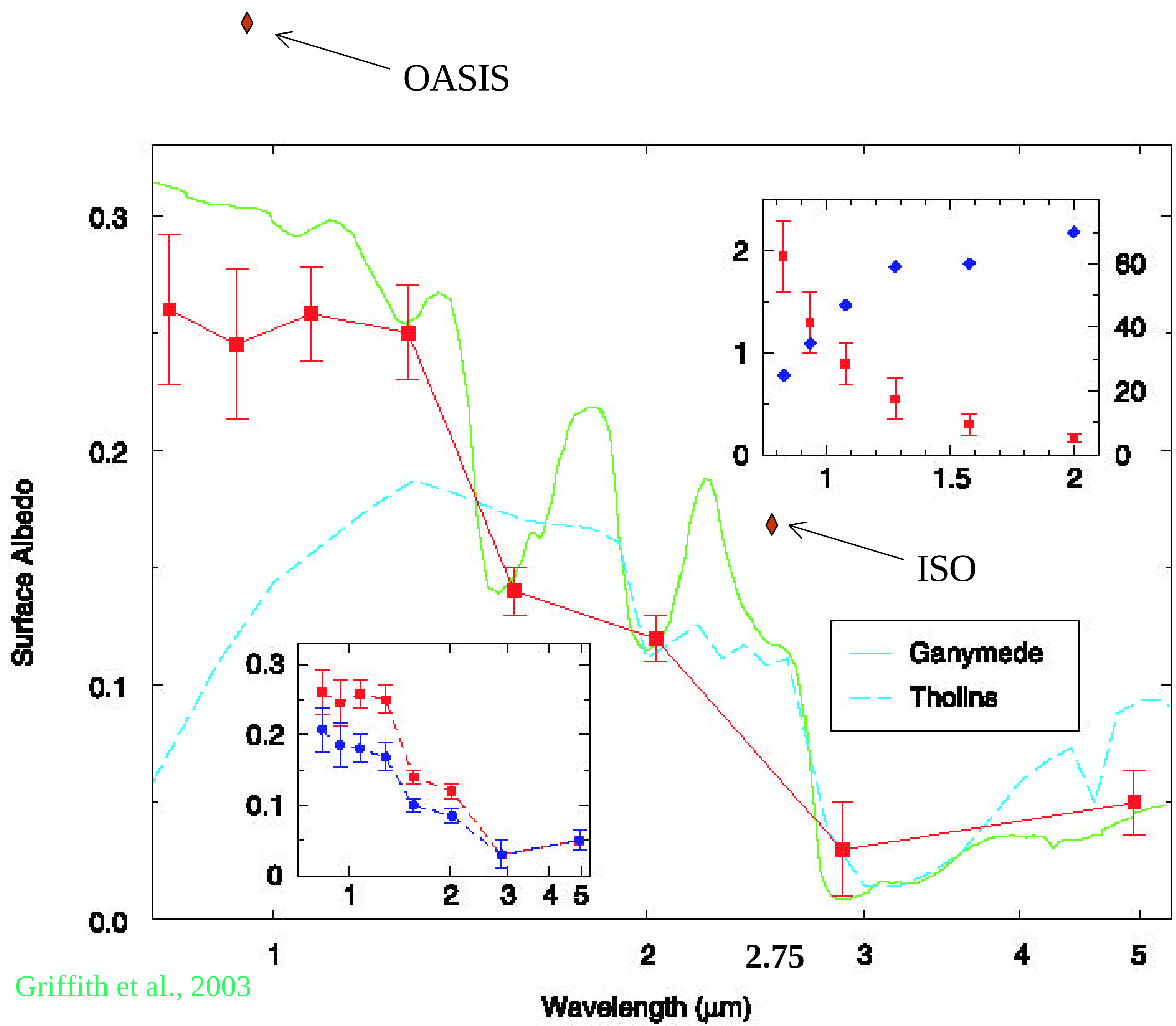
TITAN GEOMETRIC ALBEDO 1989-1996



Griffith & al., 1998, Coustenis et al., 1995 Lemmon & al., 1993

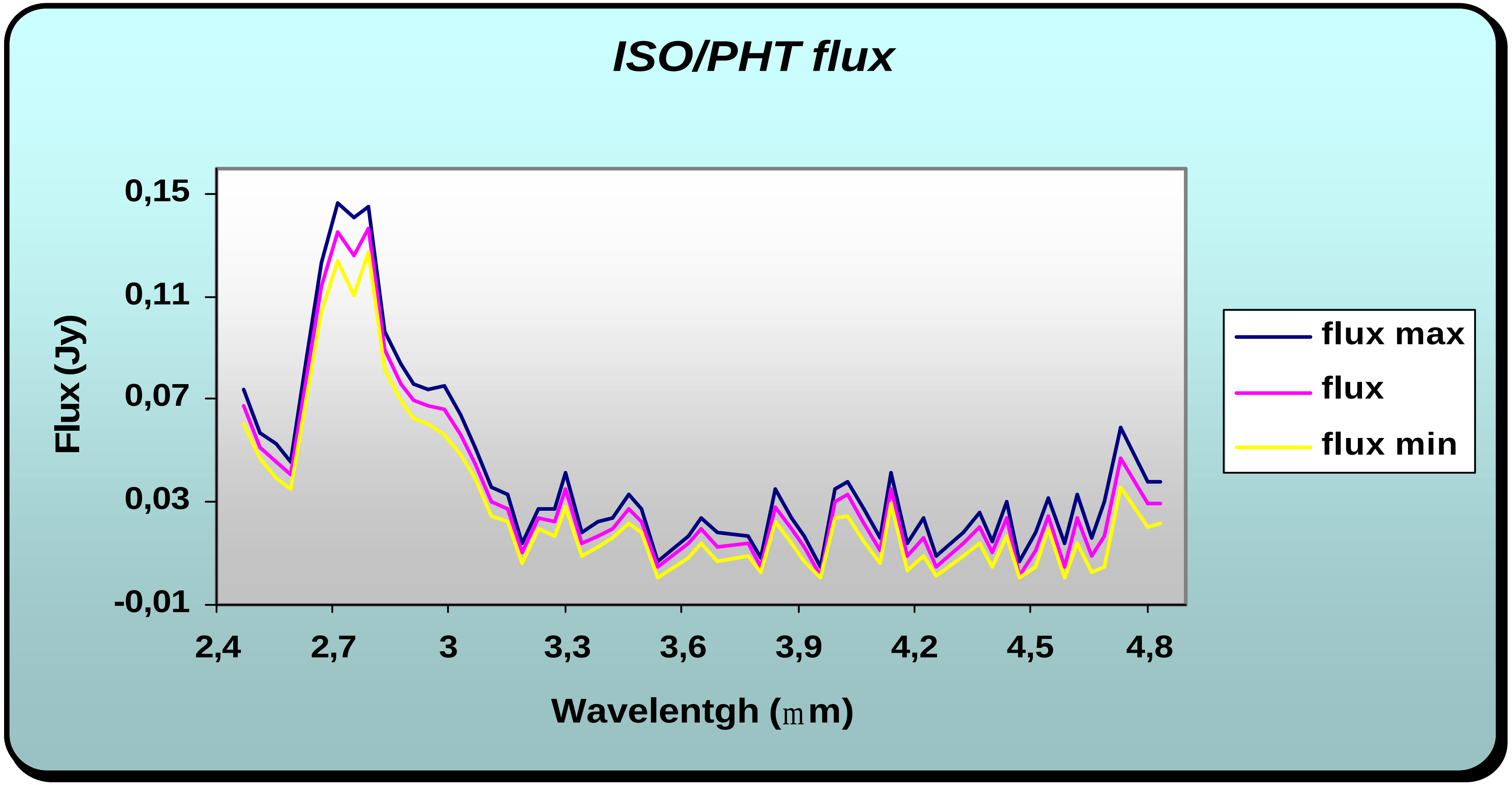


Griffith et al., 2003



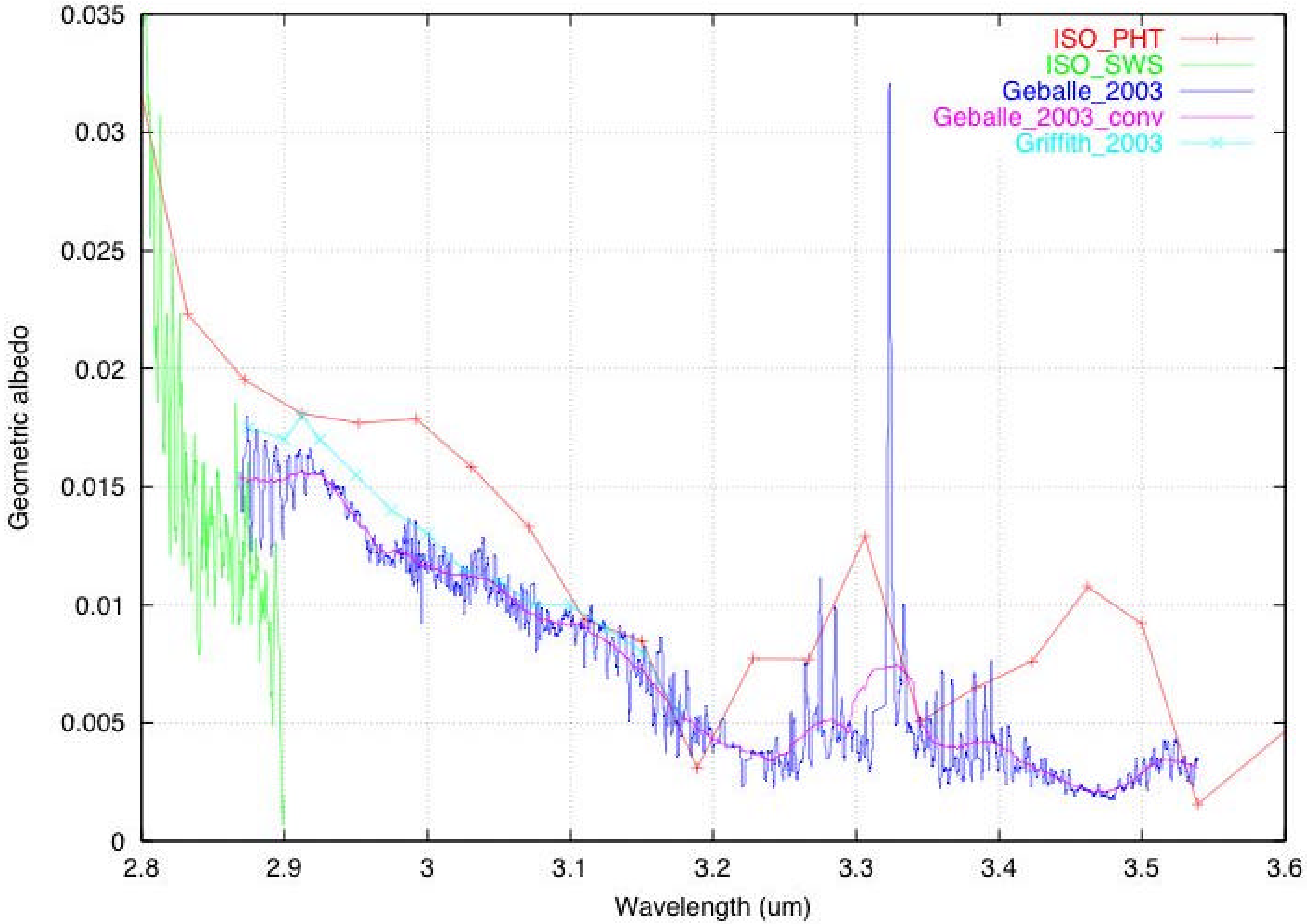
OASIS
ISO
0.3
0.2
0.1
0.0
Surface Albedo
1
2
2.75
3
4
5
Wavelength (µm)
Ganymede
Tholins
60
40
20
0
1.5
4
Griffith et al., 2003

ISO- PHT Titan 2-5 micron



Titan's flux observed with ISO/PHT in the 2.5-4.9 *mm* range

Titan’s 3 micron region

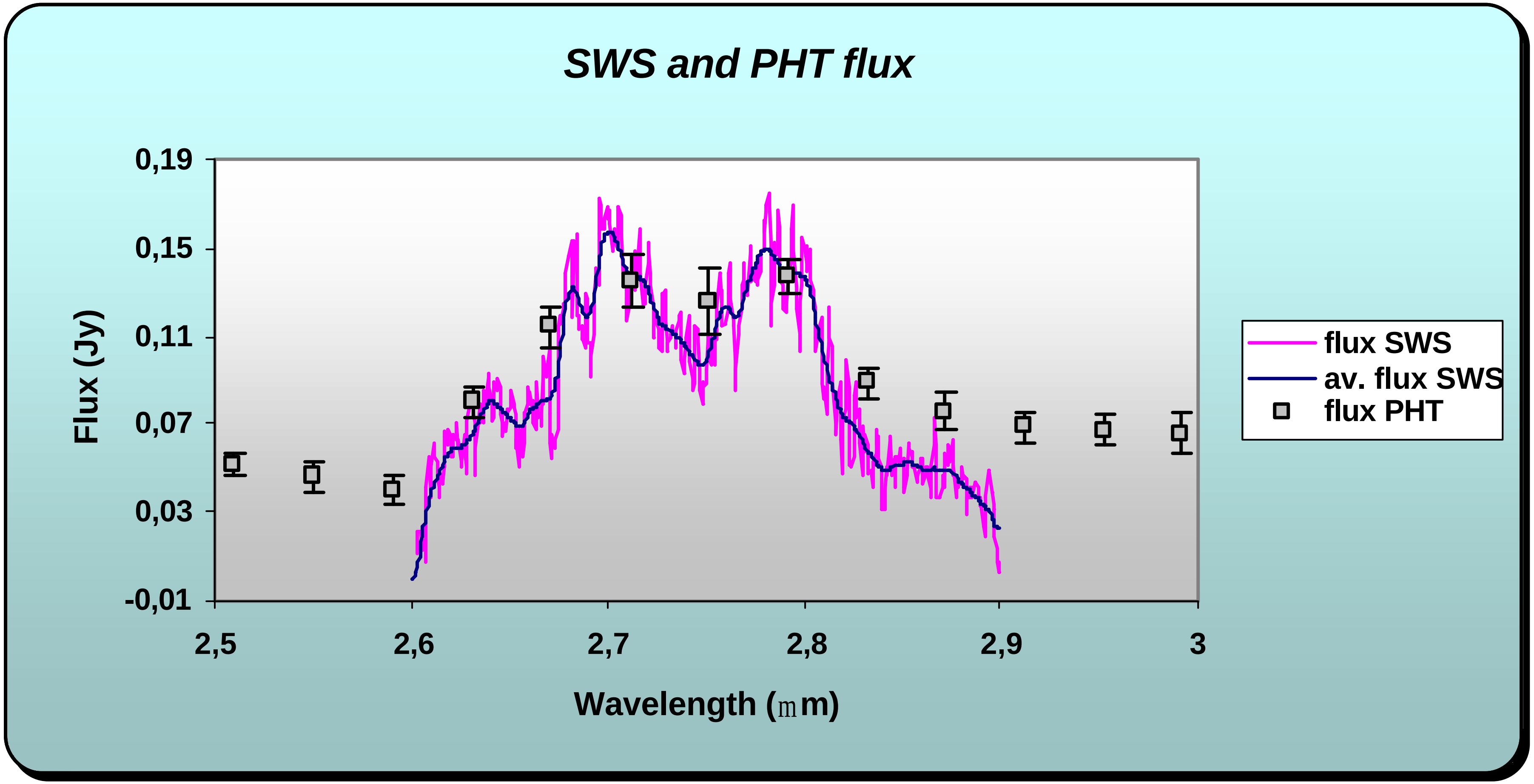


Titan’s flux observed with ISO/SWS and ISO/PHT in the 2.8-3.6 *mm* range

---

Part of this window (the 2.9 -3.1 μm region) has been observed from the ground [Griffith et al., 1998; Geballe et al., 2003] who reported a geom. albedo of 0.02 on a normal night and 0.05 in the case of a sudden increase at 3 micron, interpreted as a cloud in Titan’s troposphere.

Titan's 2.75 micron window



Titan's flux observed with ISO/SWS and ISO/PHT in the 2.5-3.0 *mm* range

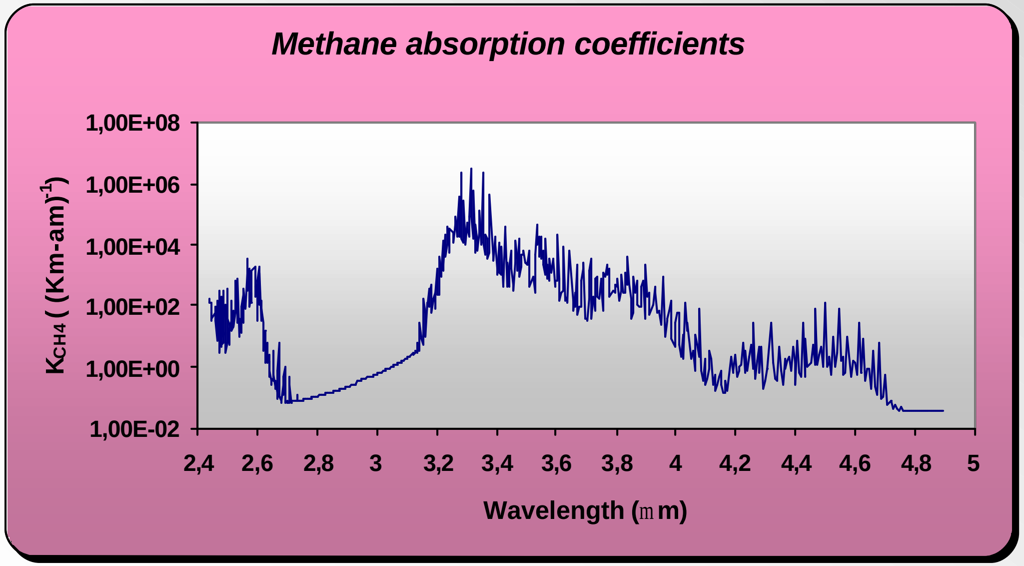
– The maximum flux in the 2.8-µm window is 0.14 Jy at 2.7 and 2.78 µm, yielding a geometric albedo of 0.04 in the center of the window and 0.01 at 3 micron.

⇒ compatible with hydrocarbon lakes and water ice-rock mixtures on the surface. No tropospheric clouds observed by ISO.

MODEL

We use a radiative transfer model to simulate Titan's geometric albedo from an updated version of McKay *et al.*'s (1989) code (which considers spherical aerosols). In this version of the code we work with fractal aerosols (Rannou *et al*. 1997, 2003).

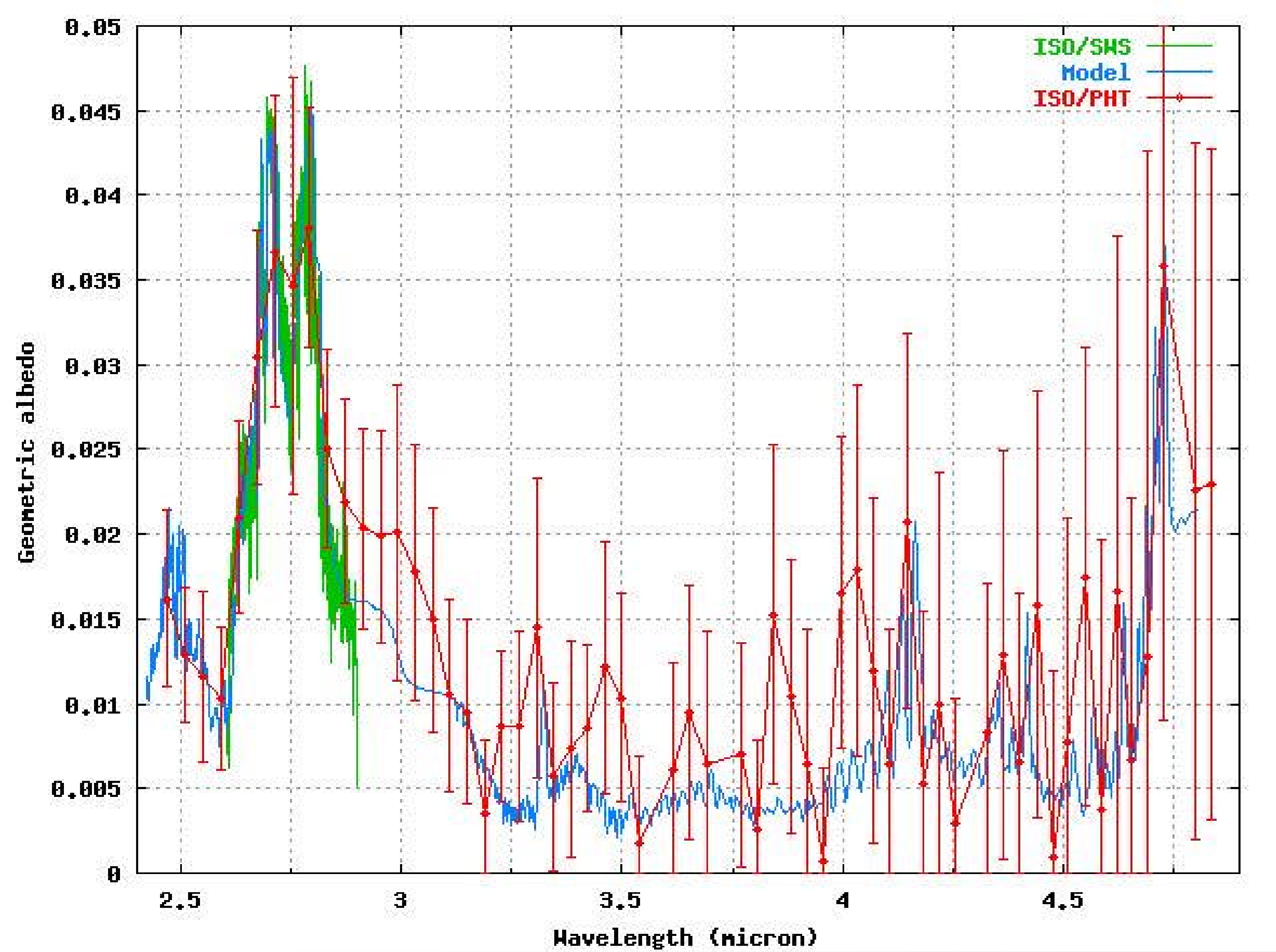
The main parameters needed to define the aerosol distribution are the haze production rate, the haze production pressure, the aerosol charging rate and the eddy diffusion coefficient. For the geometric albedo we also need the aerosol imaginary refractive index (Khare *et al*. 1984), the ground reflectivity, the methane vertical profile (Lellouch *et al*. 1989) and the methane absorption coefficients. These were obtained from the Hilico *et al*. (1994) database. This database, built from a theoretical model of the methane-methane interactions, give an update of all methane's absorption lines between 0.01 and 6200 cm^{-1} (fig. 3).



Methane absorption coefficients from the Hilico *et al*. (1994) database in the 2.4-4.9 μm range

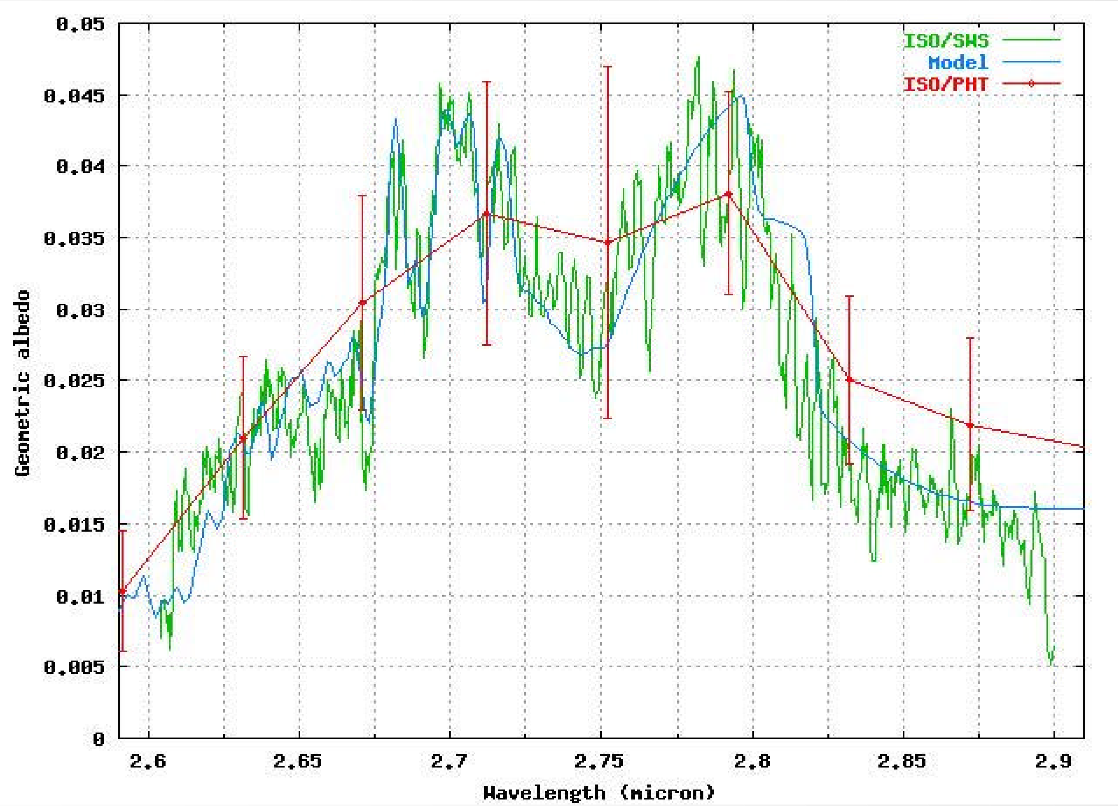
See Poster by Negrao et al.

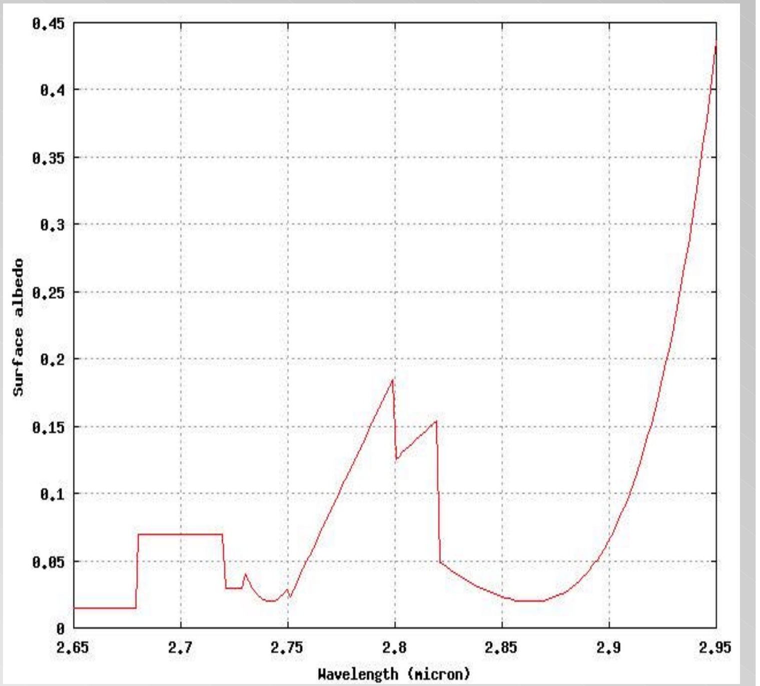
TITAN'S SPECTRUM FROM 2-5 MICRON



Model vs ISO/PHT and ISO/SWS

TITAN'S 2.75-MICRON SURFACE ALBEDO

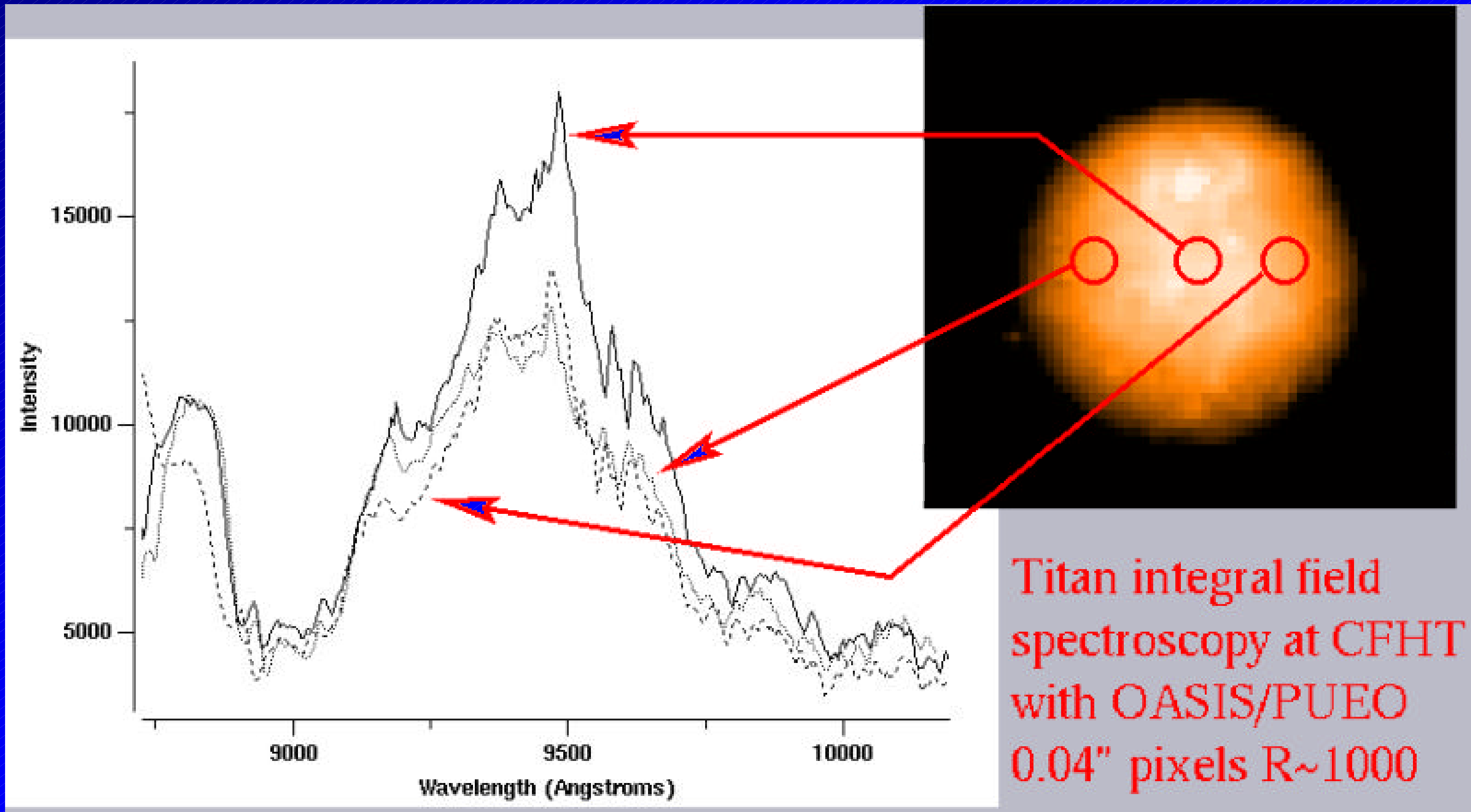




Surface albedo vs wavelength in the 2.65-2.95 *mm* range

Titan's surface albedo from the 2.75 micron window is found to be in the 0.001-0.17 range (Coustenis et al., 2004; Negrao et al., 2004)

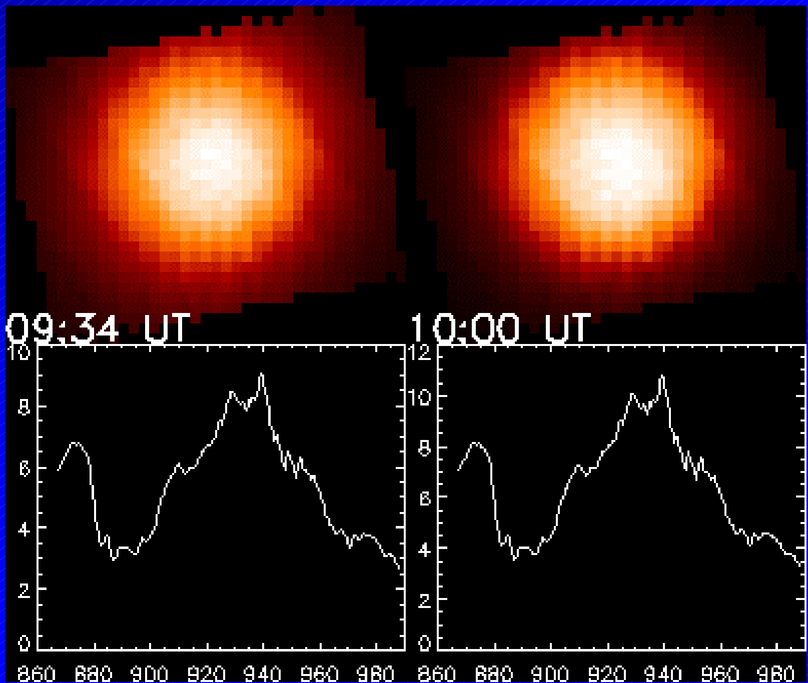
The 0.94 mm window on Titan with OASIS



OASIS Spectro-imaging: Resolved Titan's disk from 0.86 to 1.03 micron

Hirtzig et al. (2004, PSS in press and see poster)

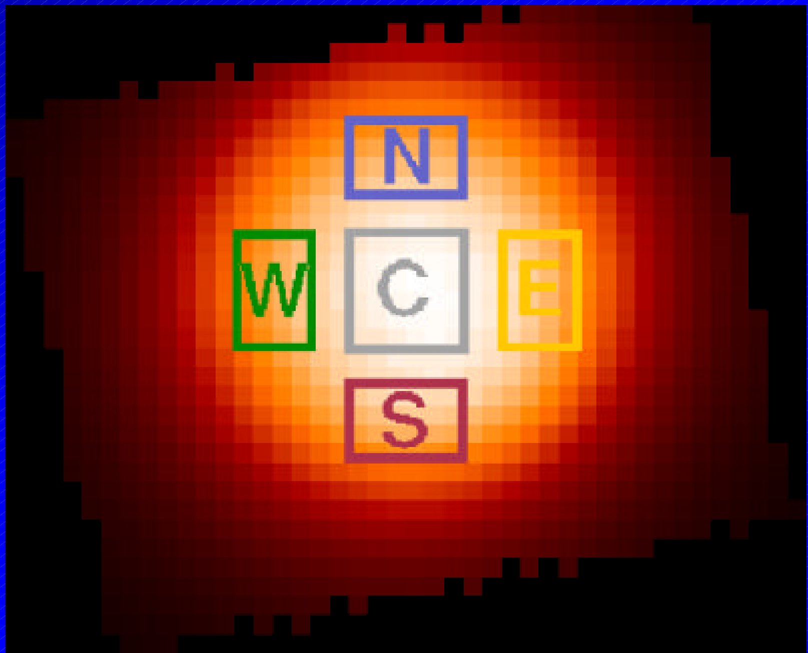
Fully processed images of Titan.



The two datacubes of Titan acquired on 2000 Nov 17th. On the top panel are plotted the wavelength-averaged disks of Titan.

The bottom panel shows the average spectrum for each datacube in flux (10^{-16} erg/s/cm^2/Angst/arcsec^2) vs wavelength (nm).

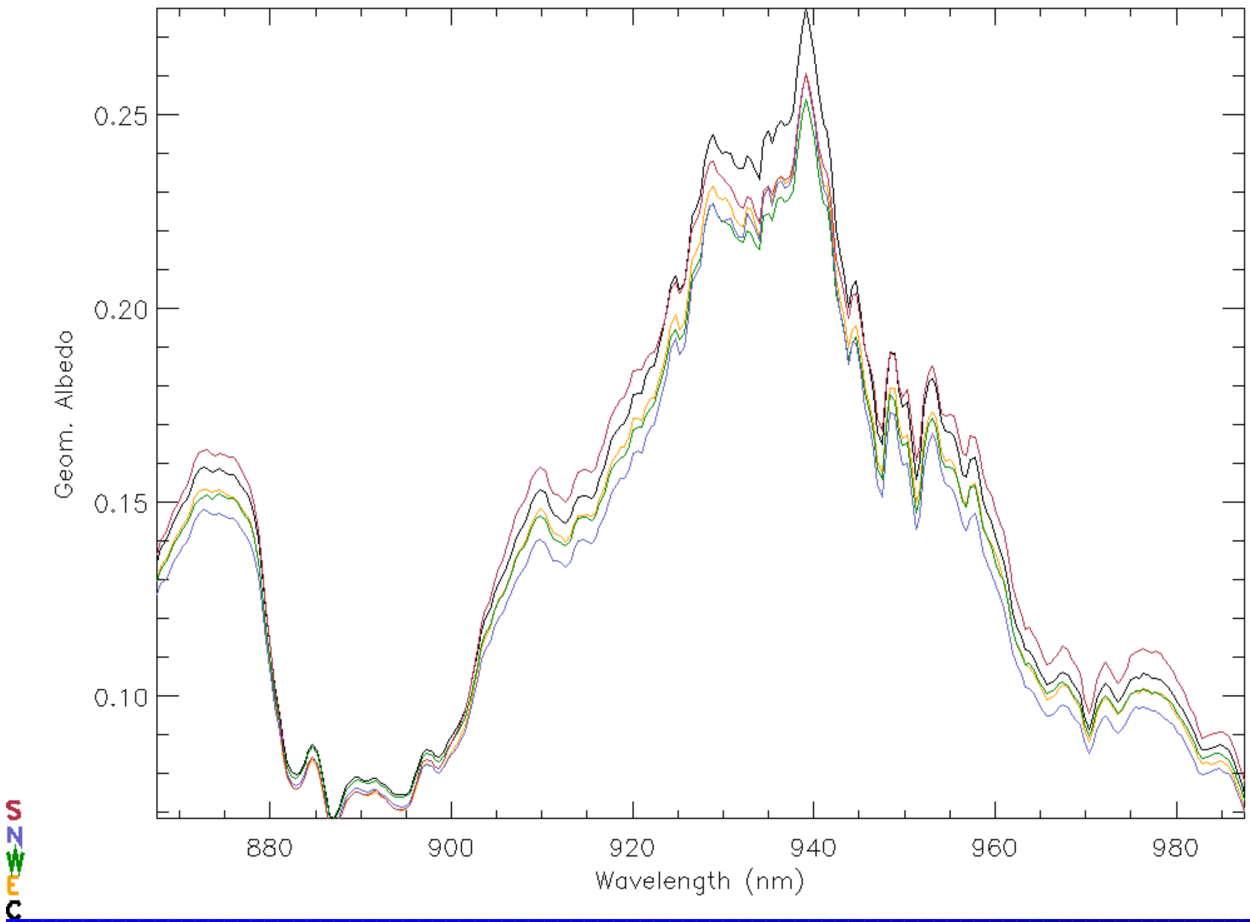
Spatial analysis



- Spectral averages in some areas
- Intercomparison of resulting spectra

See Poster by Hirtzig et al.

Spatial analysis



Spectra from Titan, extracted from the merged datacube. Quantities plotted are geometric albedo vs wavelength (nm). Each colour correspond to one area on Titan's disk.

Center (C) is black, North (N) is blue, South (S) is red, West (W) is green and East (E) is yellow.

Titan's surface at 0.94 μm

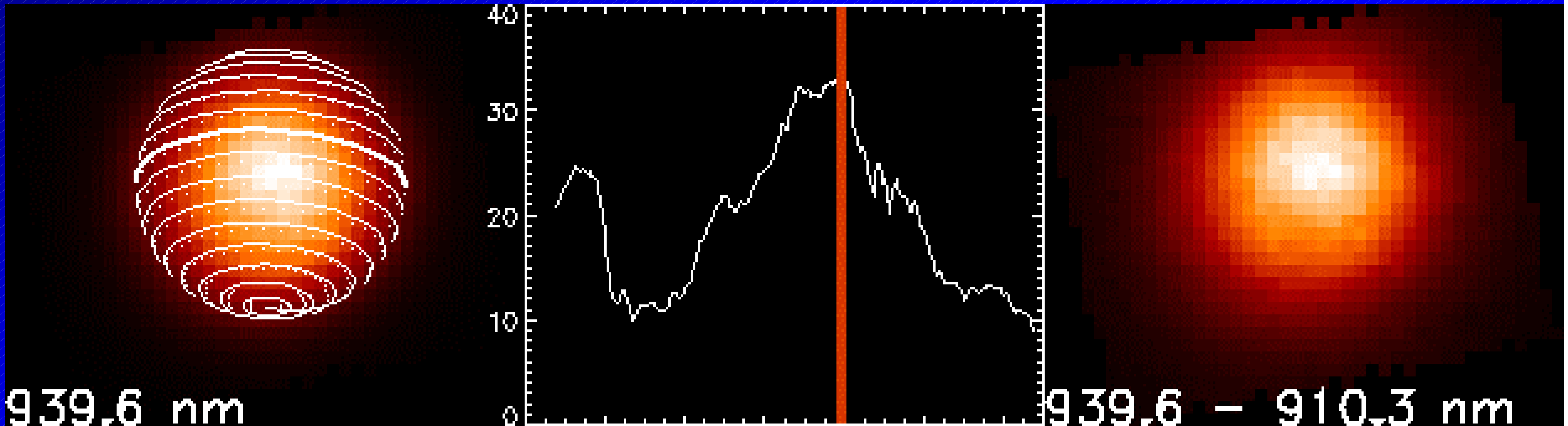
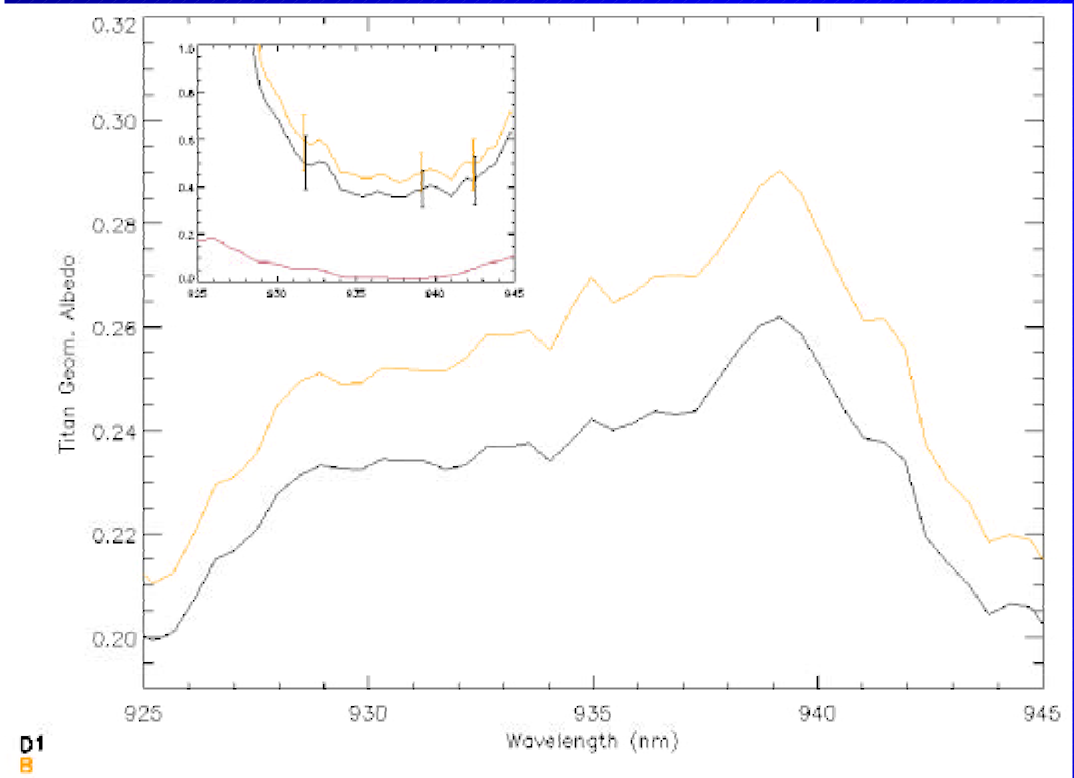


Image of Titan's surface in the center of the methane window (at 939.6 nm). Contrast (left image only) is enhanced by a square law. The spectrum shown here is taken from the central pixel on Titan's disk, with a reddish cursor indicating the current wavelength probed in the center panel. The third panel returns the image in the methane window after the subtraction of an atmospheric image (here 910 nm).

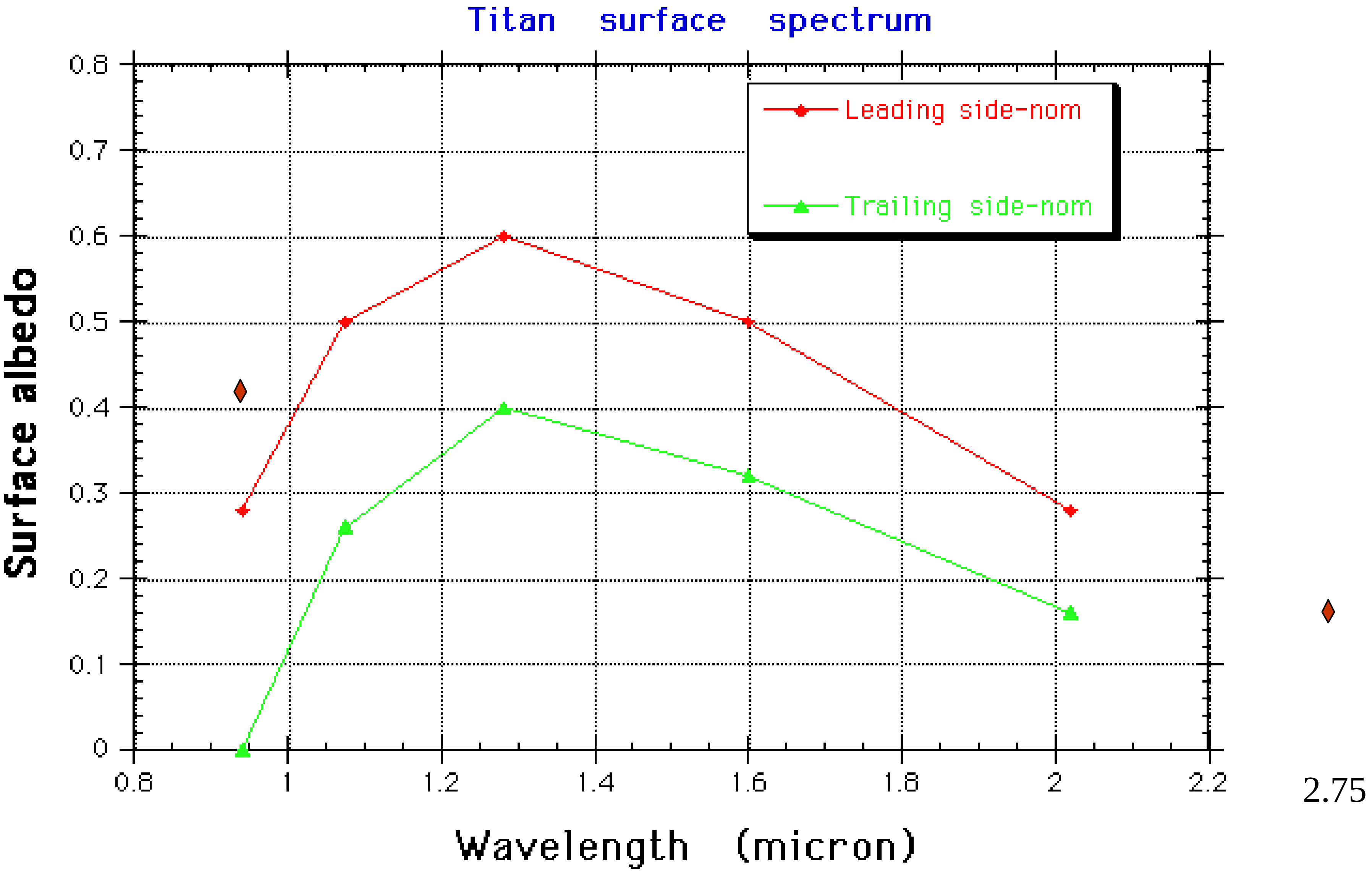
Titan’s albedo

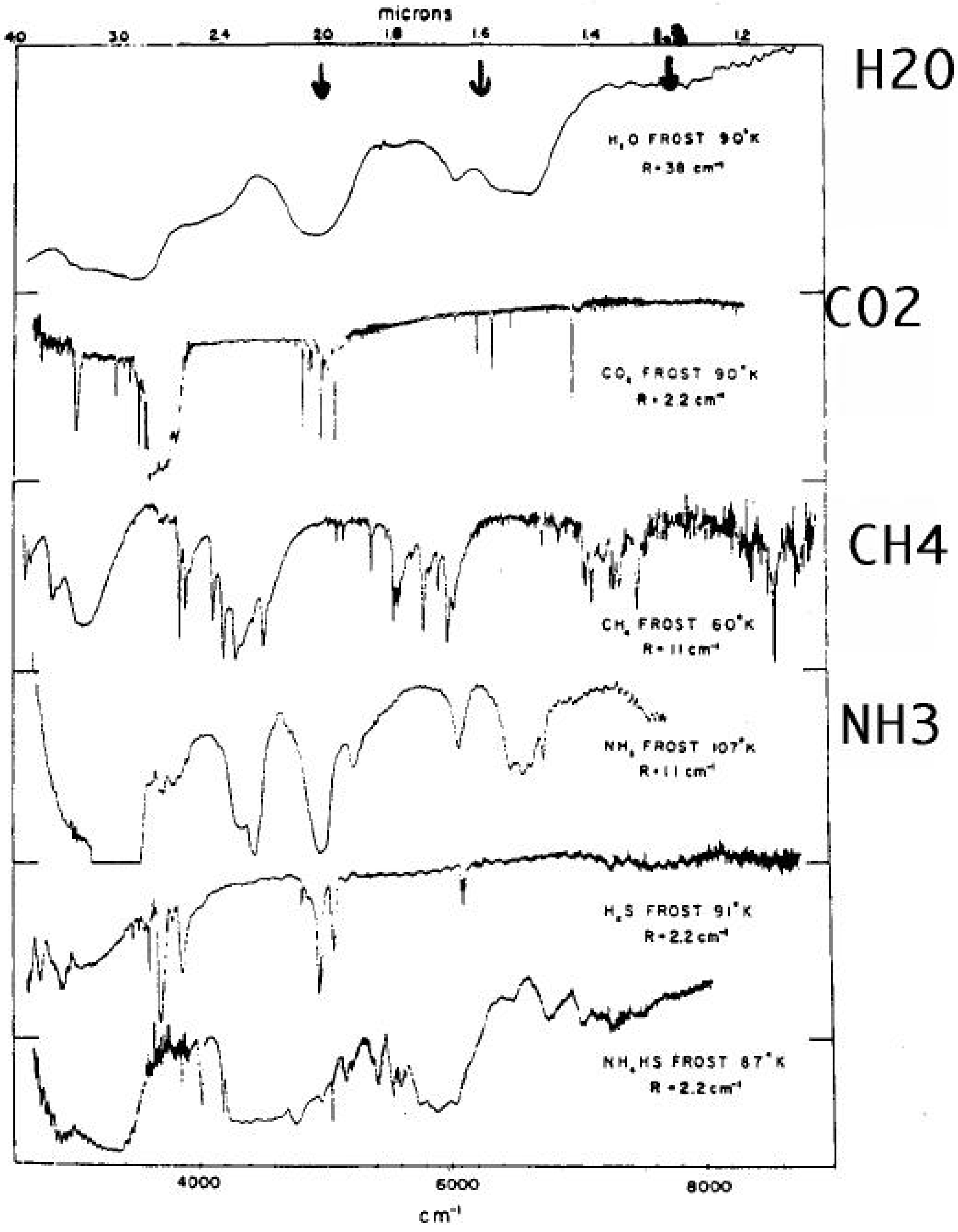


Titan's albedos in the 0.94 μm window, from 920 to 950 nm, representative of the surface contribution.

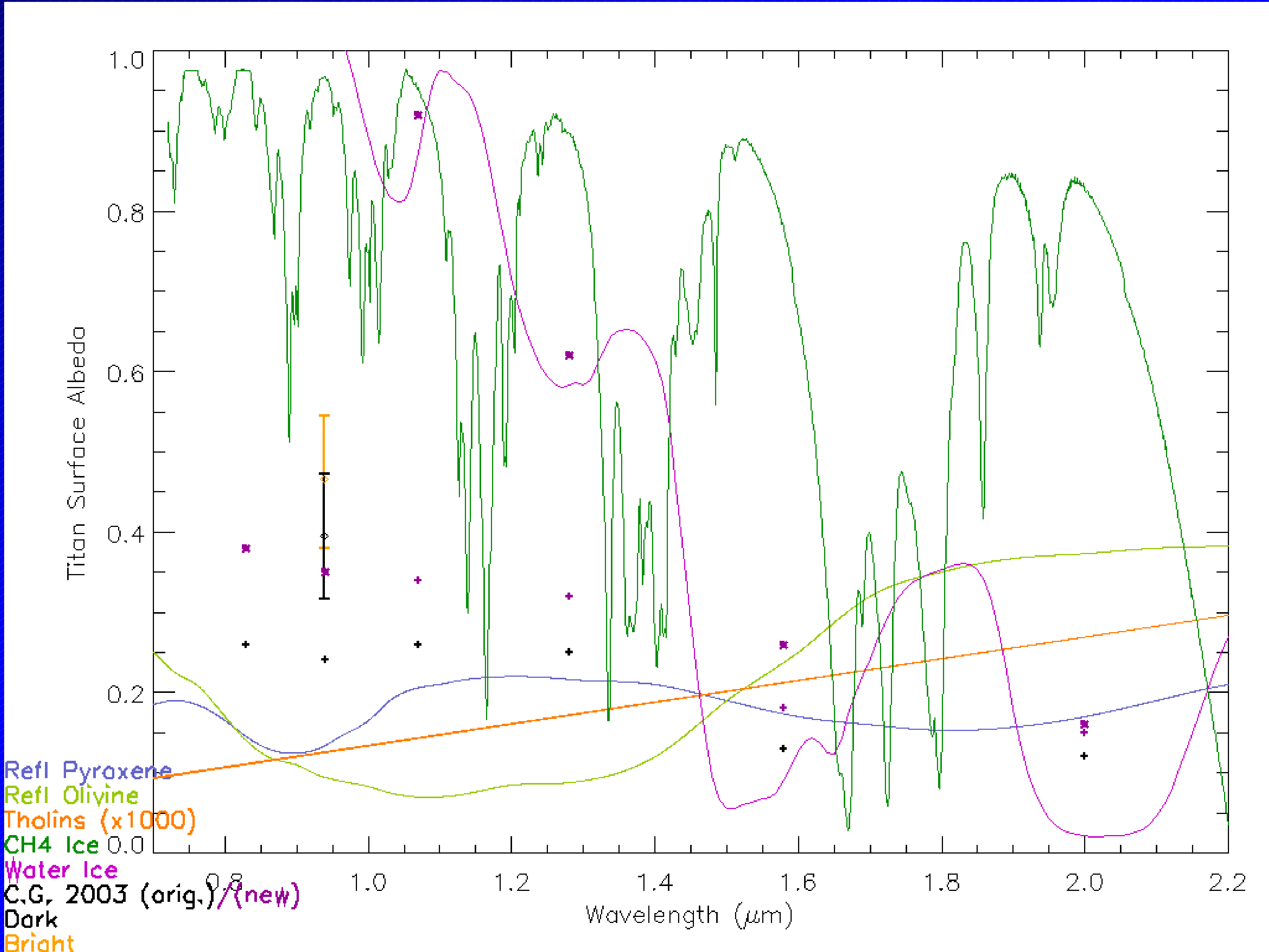
The main graph shows Titan's geometric albedos for the brightest and darkest regions on Titan.

The insert shows the surface albedos computed with our radiative transfer code for these two regions, as well as the methane spectrum as determined by Karkoschka 1994 (in km.am^{-1}) in red.

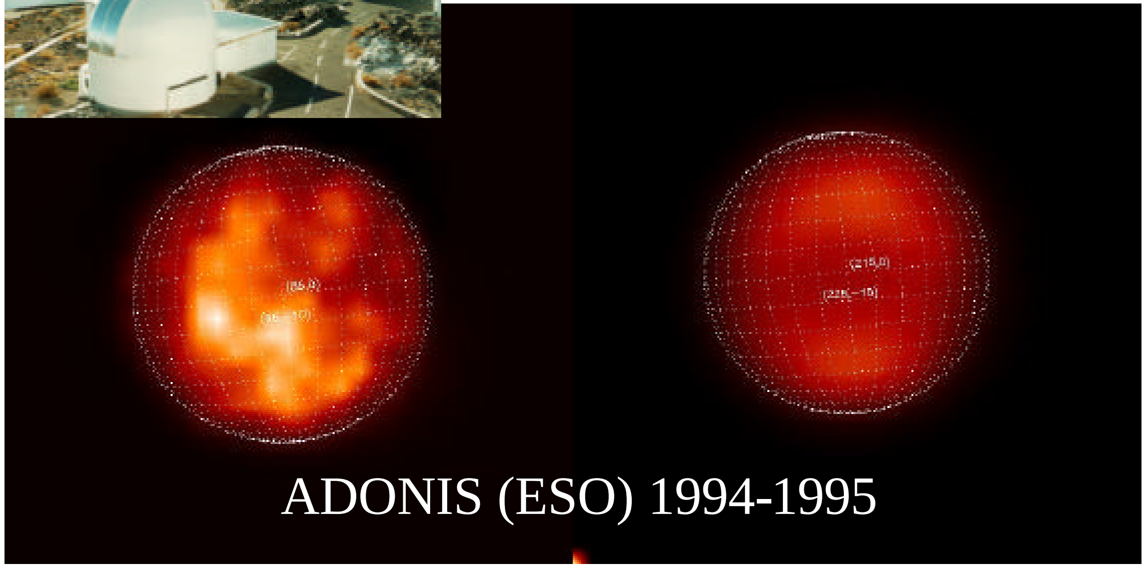

Titan surface spectrum
Leading side-nom
Trailing side-nom
Surface albedo
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.75
Wavelength (micron)


microns
40
3.0
2.4
2.0
1.8
1.6
1.4
1.2
H20
H_2O FROST 90°K
R = 38 cm^{-1}
CO2
CO_2 FROST 90°K
R = 2.2 cm^{-1}
CH4
CH_4 FROST 60°K
R = 11 cm^{-1}
NH3
NH_3 FROST 107°K
R = 11 cm^{-1}
H_2S FROST 91°K
R = 2.2 cm^{-1}
NH_4HS FROST 87°K
R = 2.2 cm^{-1}
4000
6000
8000
cm^{-1}

Titan's surface albedo

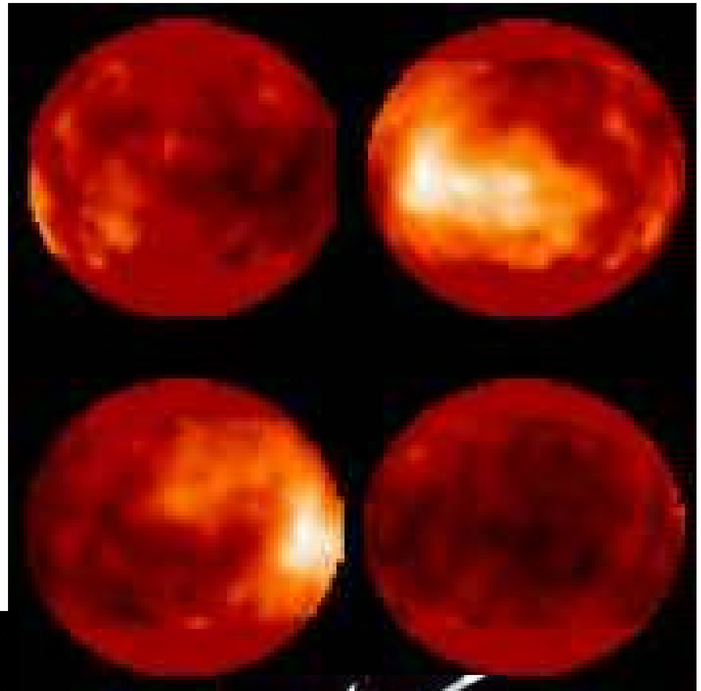


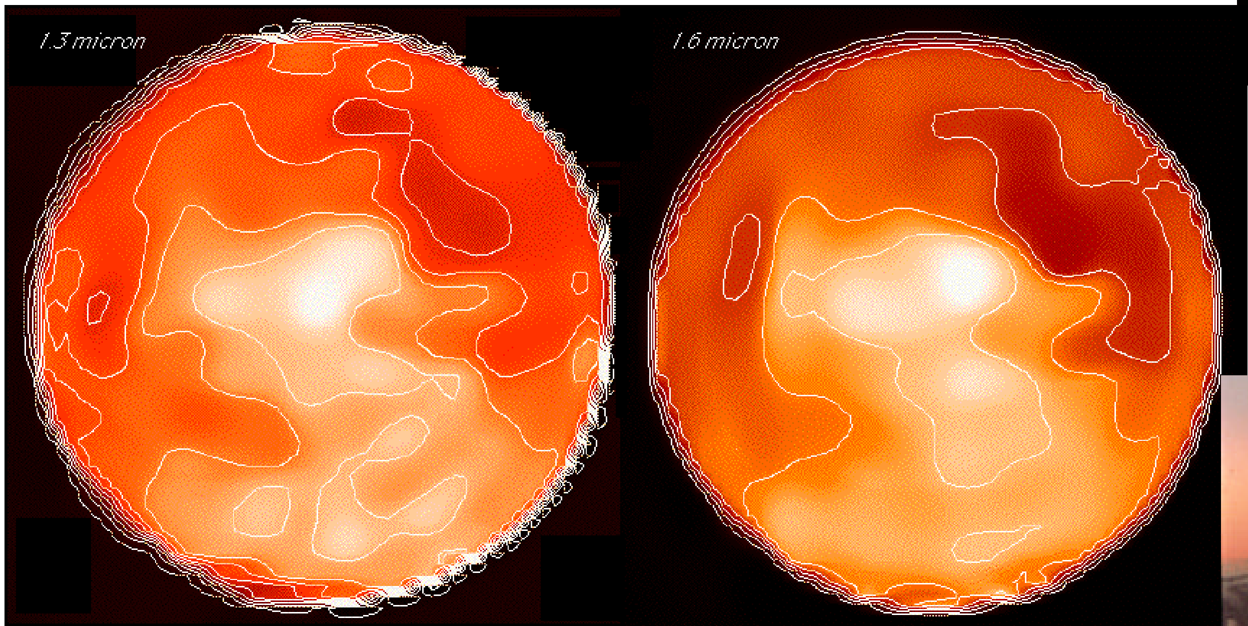
Titan imaging



ADONIS (ESO) 1994-1995

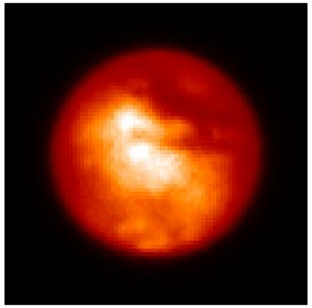
HST 1994



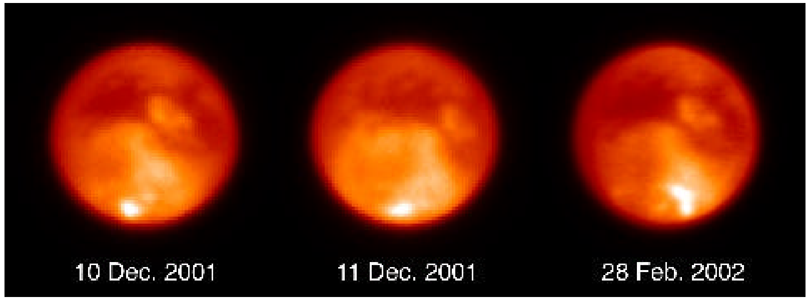


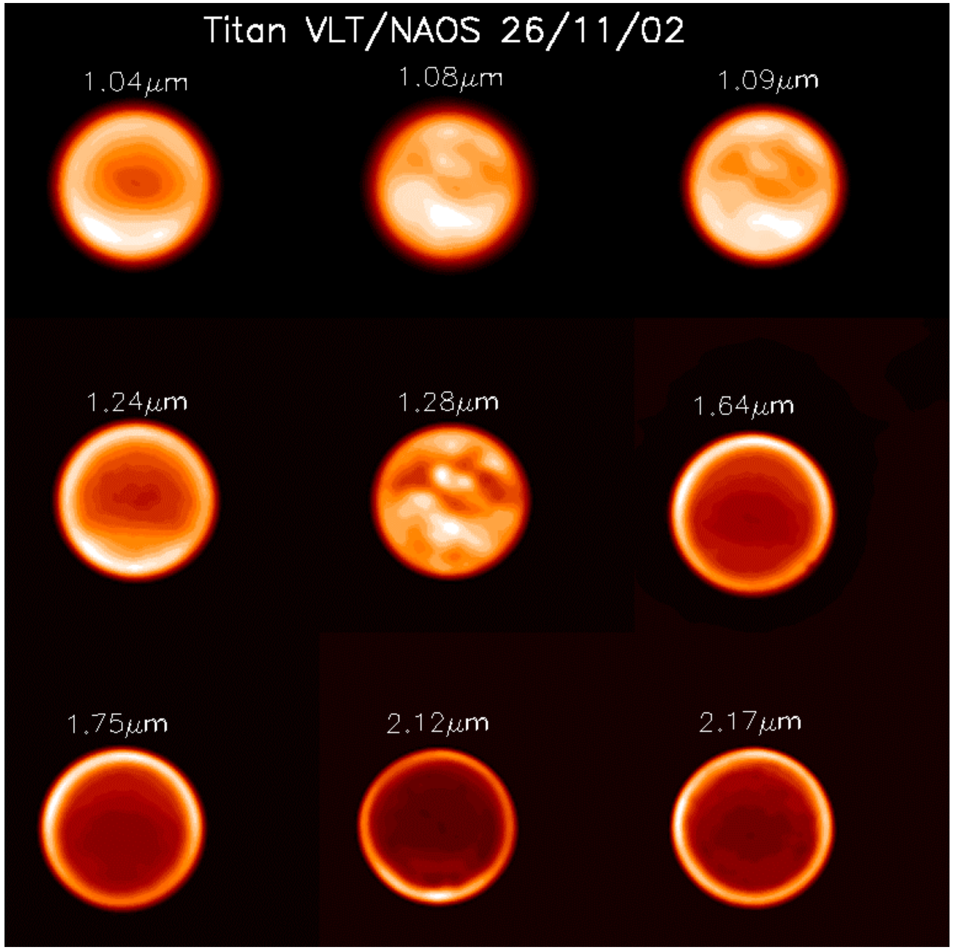
PUEO (CFHT) 1998

Titan's new faces 2001-2002 with bigger telescopes



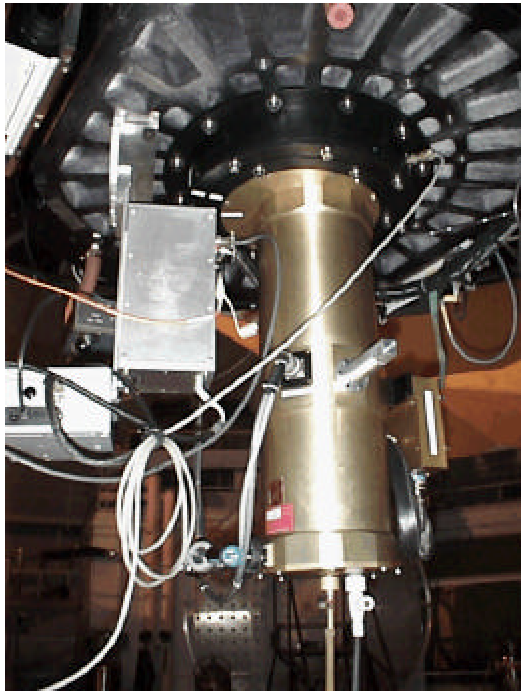
Keck images of Titan from work by
Roe et al., & Brown & al. (2002)





ESO/Very Large Telescope
NAOS adaptive optics system
Gendron et al. (2004, A&A,in press)

Adaptive optics systems



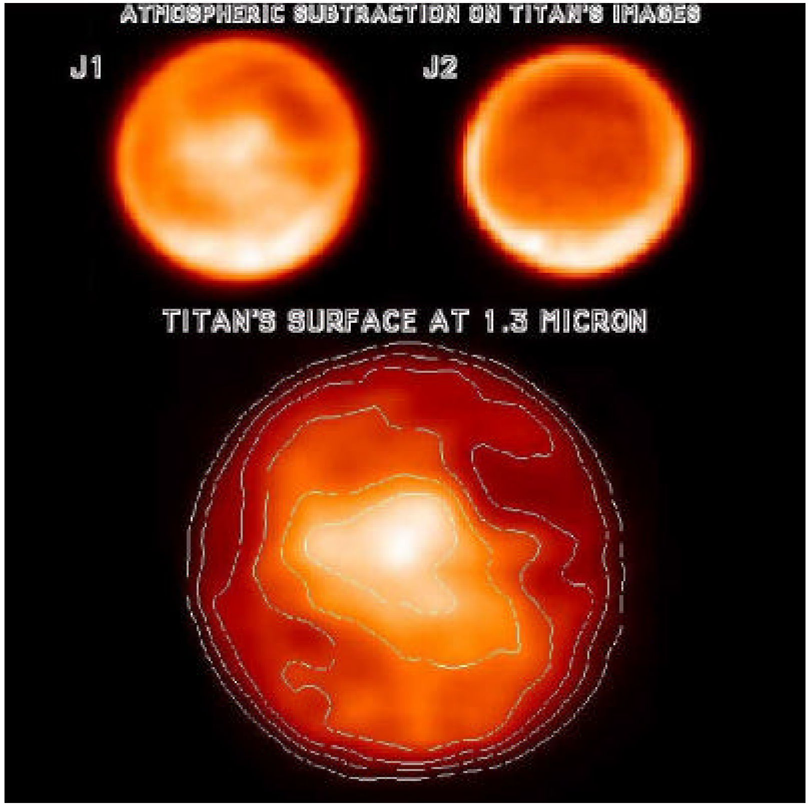
PU'EO /KIR

- 3,6-m CFHT (Hawaii)
- bandpass 0,7 - 2,5µm
- CCD 1024x1024
- 0.0348 "/pixel

NAOS/CONICA

- 8-m VLT/UT4 (Chile)
- bandpass 0,9 - 5µm
- CCD 1024x1024
- 0.01325 "/pixel

Titan's leading side in 1998: PU'EO



PUEO images taken in 1998 at 1.29 (J1) and 1.18 (J2) µm (Coustenis et al., 2001).

Atmosphere:

•bright southern pole (smile)

•bright feature on the Western (morning) limb

– Phase effect? No - should be on the other side
– Interpreted as diurnal effect (morning fog)

Surface:

•Bright equatorial region surrounded by darker areas

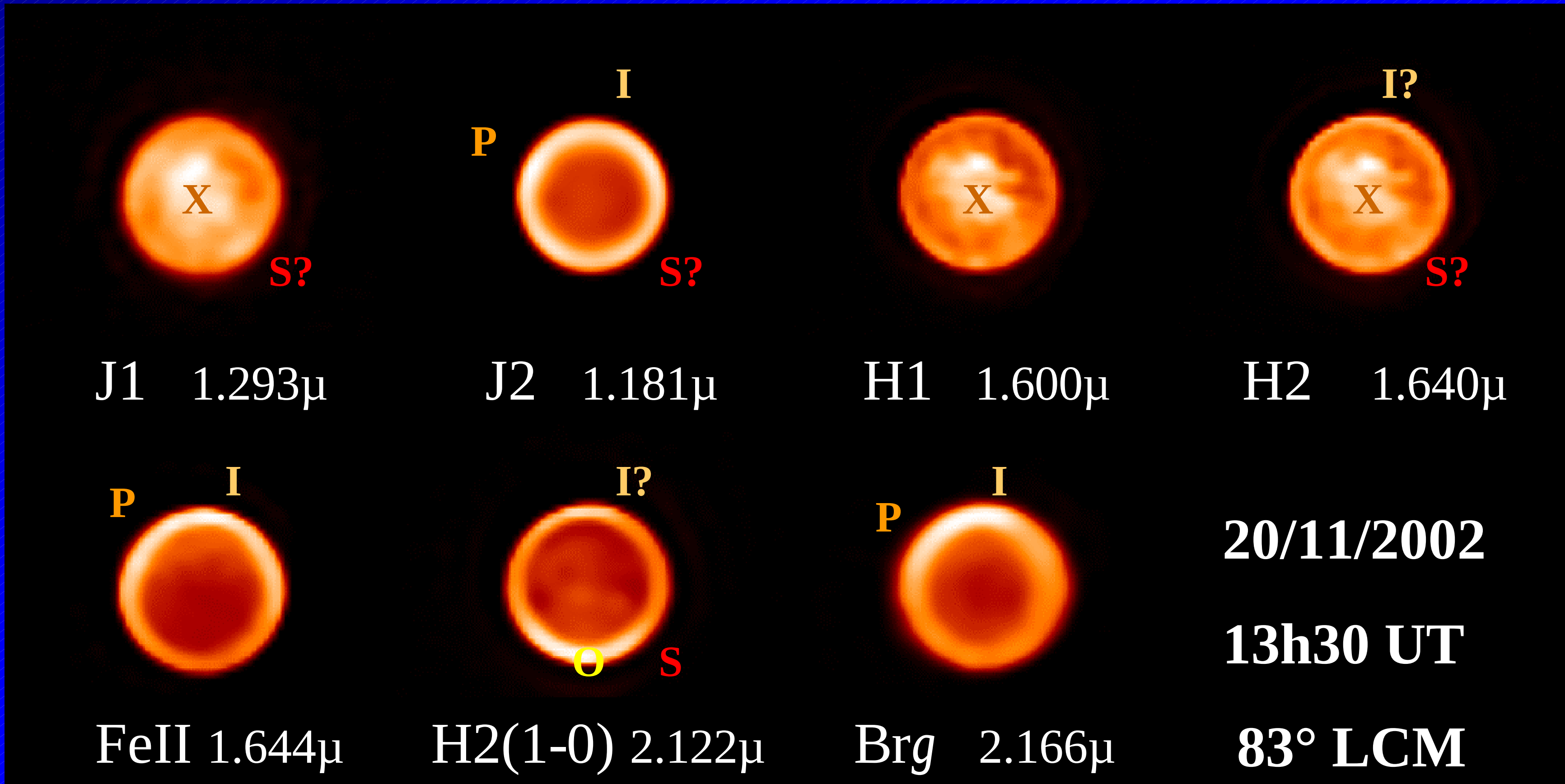
Narrow-band filters used for Titan

Name	*l* (µm)	**Lower levels probed in the center of the image**
I	0,834 ± 0,097	Stratosphere + troposphere
NB_1.04	1.040 ± 0,075	Tropopause
HeI	1,083 ± 0,004	Surface + lowest troposphere
PaGamma	1,094 ± 0,005	Surface + lower troposphere
J2	1,181 ± 0,064	Stratosphere
Jcont	1,207 ± 0,007	Lower strato + troposphere
J1	1,293 ± 0,070	Surface+lower troposphere
Hcont	1,570 ± 0,010	Surface + troposphere
H1	1,600 ± 0,080	Surface + lower troposphere
H2	1,640 ± 0,050	Surface+troposphere
FeII	1,644 ± 0,007	Stratosphere (200 km)
NB_1.75	1.748 ± 0,013	Stratosphere (140 km)
K'	2,120 ± 0,170	Stratosphere + troposphere
H2 (1-0)	2,122 ± 0,010	Troposphere
BrGamma	2.166 ± 0,010	Stratosphere (165 km)
K	2,200 ± 0,168	Stratosphere + troposphere
Kcont	2,260 ± 0,030	Stratosphere (260 km)

Diffraction limits:	λ	PU'EO	NAOS
	1.28 µ	0.08"	0.033"
	1.64 µ	0.10"	0.042"
	2.12 µ	0.12"	0.055"

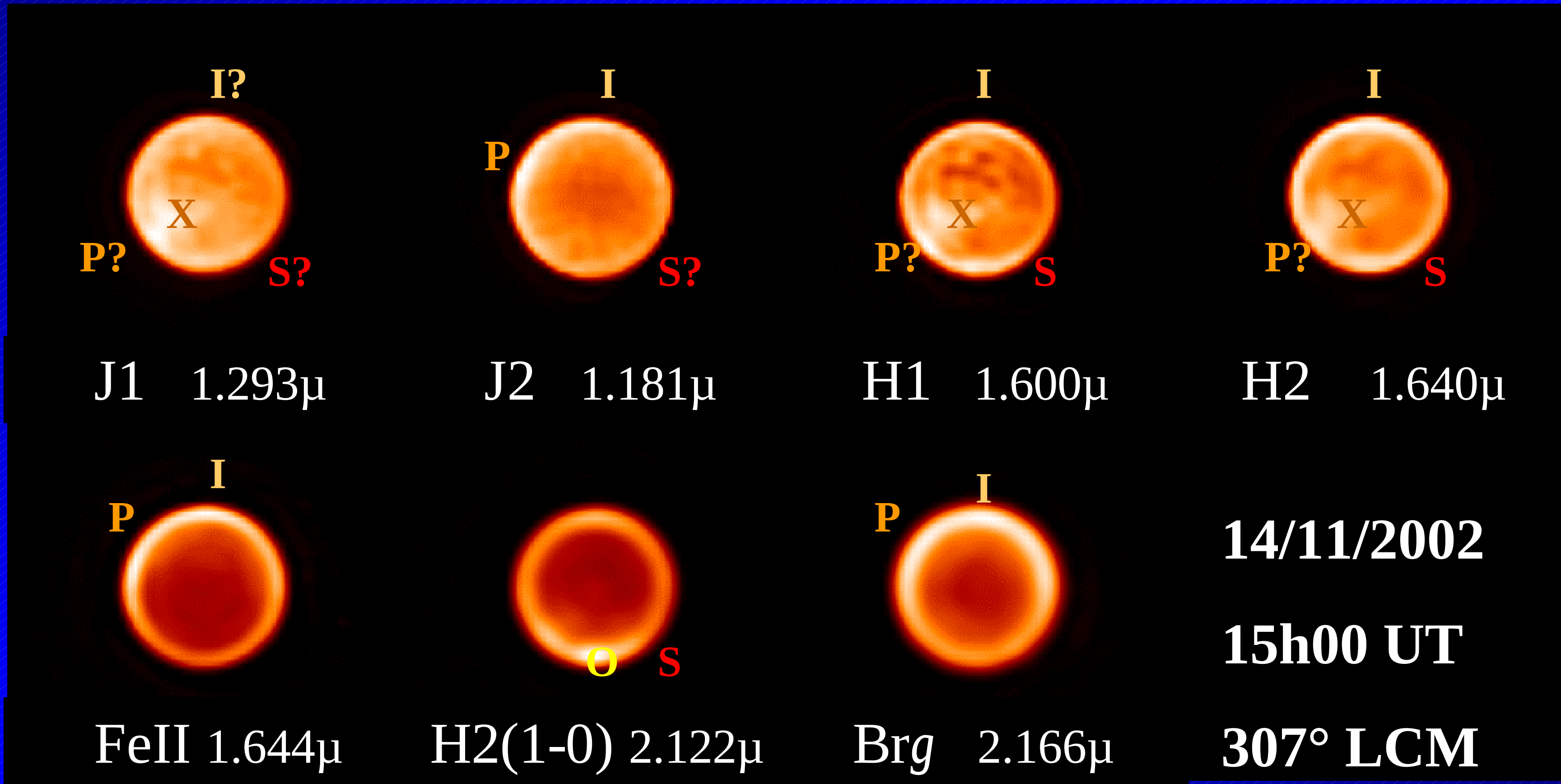
About 20 pixels across Titan's disk at best

The PUEO 2002 data: Titan at GEE

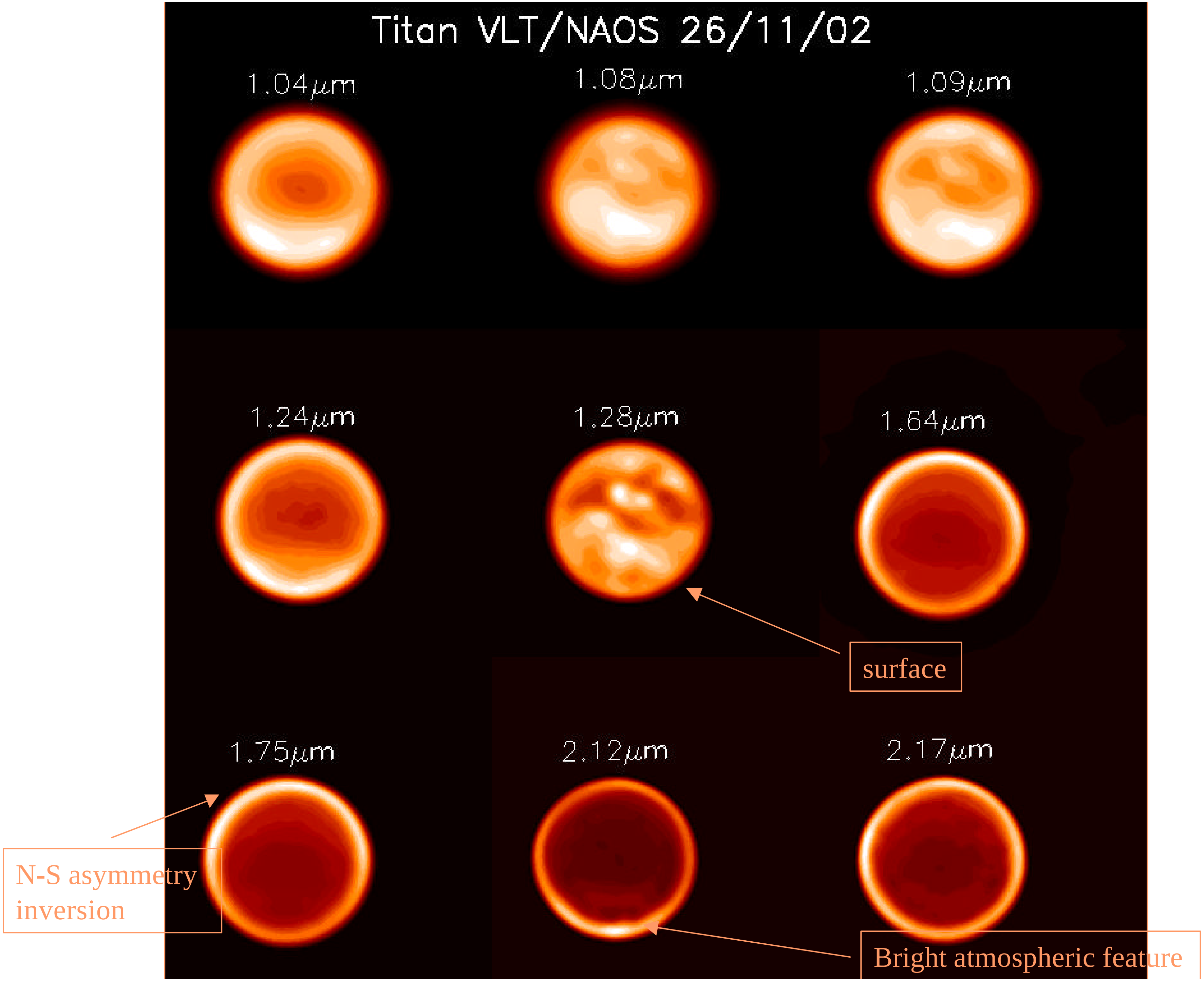


Surface **X** Smile **S** Phase **P** Inversion **I** Feature ? **O**

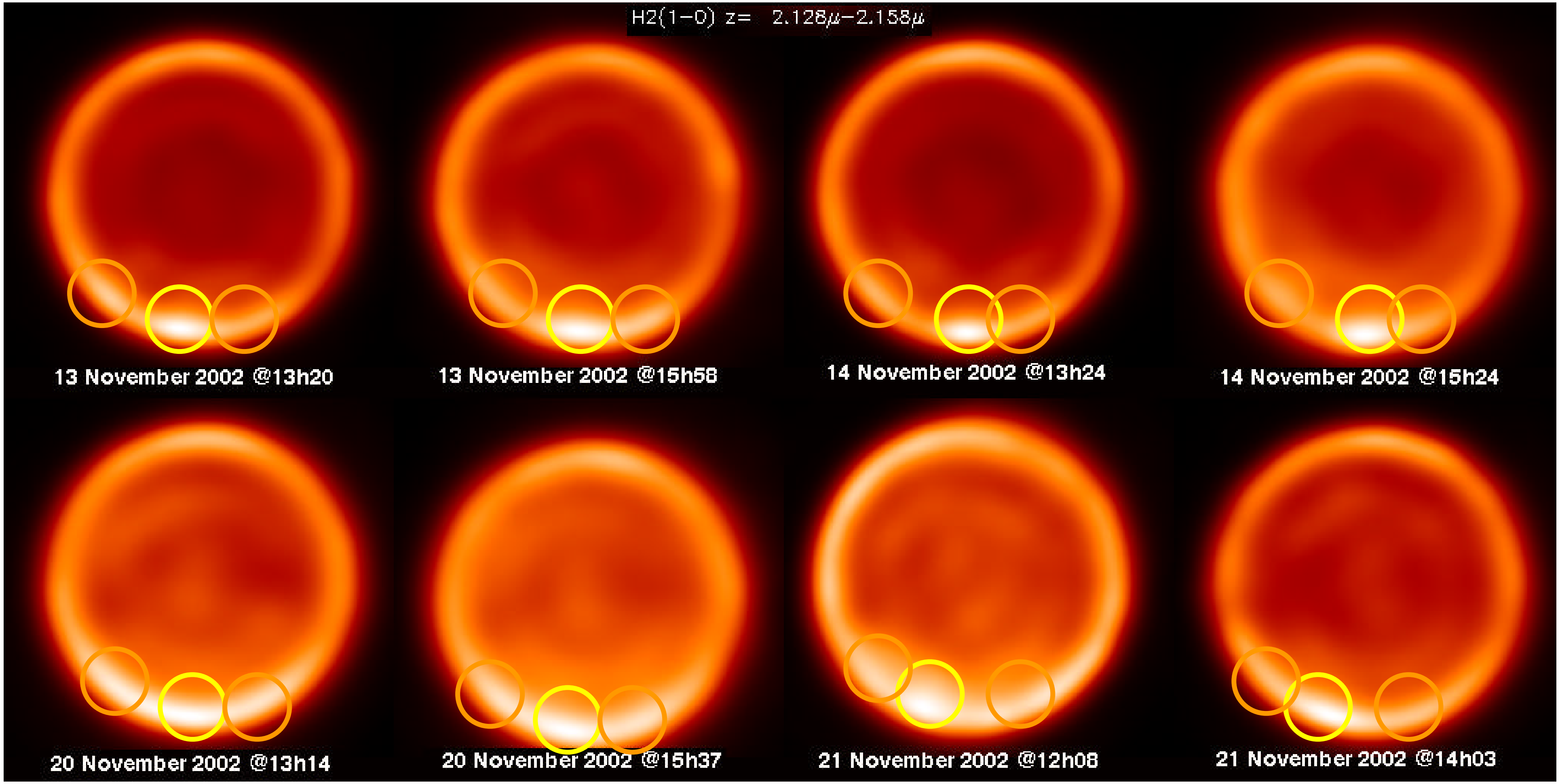
The PUEO 2002 data: Titan at GWE+2



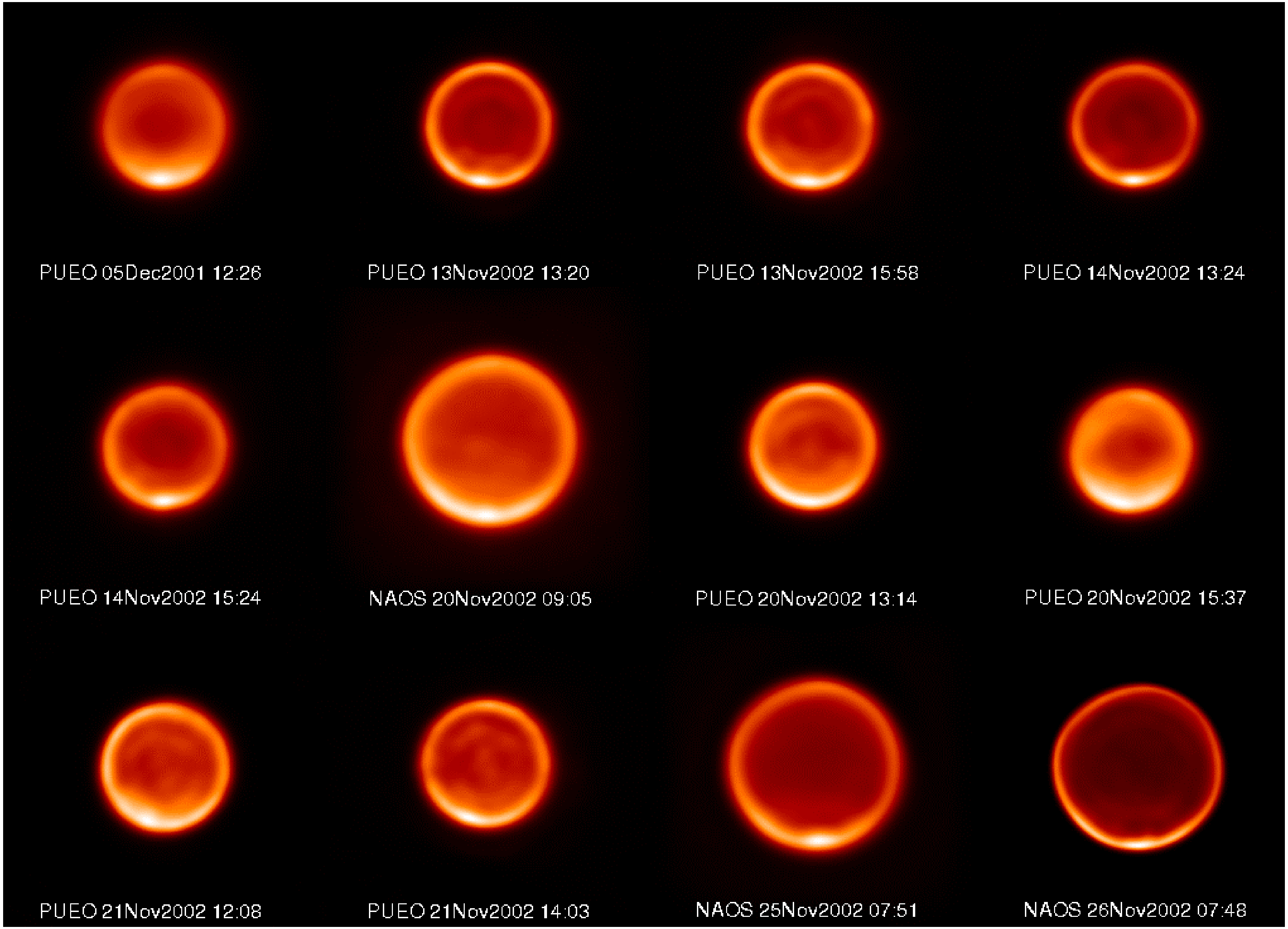
Surface **X** Smile **S** Phase **P** Inversion **I** Feature ? **O**


Titan VLT/NAOS 26/11/02
1.04μm
1.08μm
1.09μm
1.24μm
1.28μm
1.64μm
surface
1.75μm
2.12μm
2.17μm
N-S asymmetry inversion
Bright atmospheric feature

It’s big, it’s fast, it’s bright !!



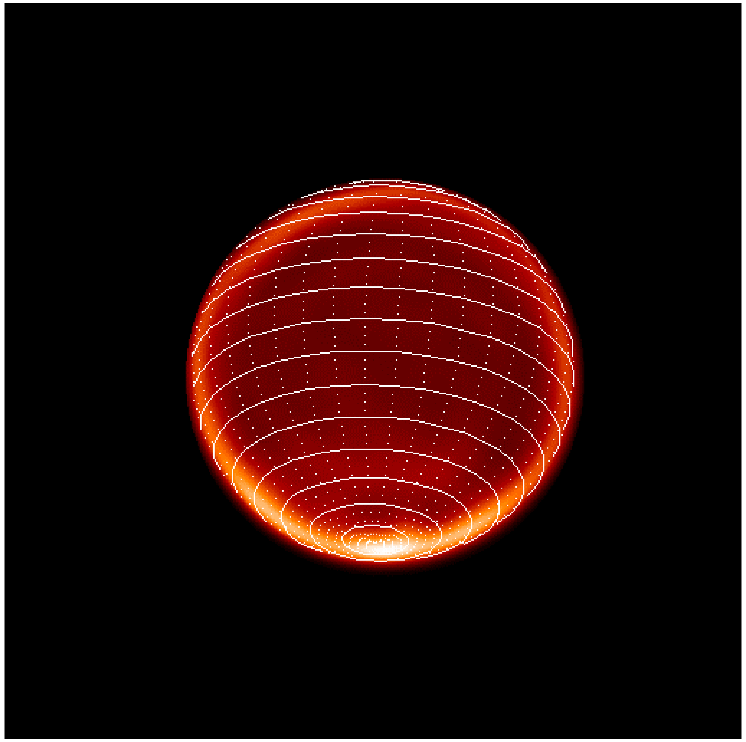
PUEO: November 2002


PUEO 05Dec2001 12:26
PUEO 13Nov2002 13:20
PUEO 13Nov2002 15:58
PUEO 14Nov2002 13:24
PUEO 14Nov2002 15:24
NAOS 20Nov2002 09:05
PUEO 20Nov2002 13:14
PUEO 20Nov2002 15:37
PUEO 21Nov2002 12:08
PUEO 21Nov2002 14:03
NAOS 25Nov2002 07:51
NAOS 26Nov2002 07:48

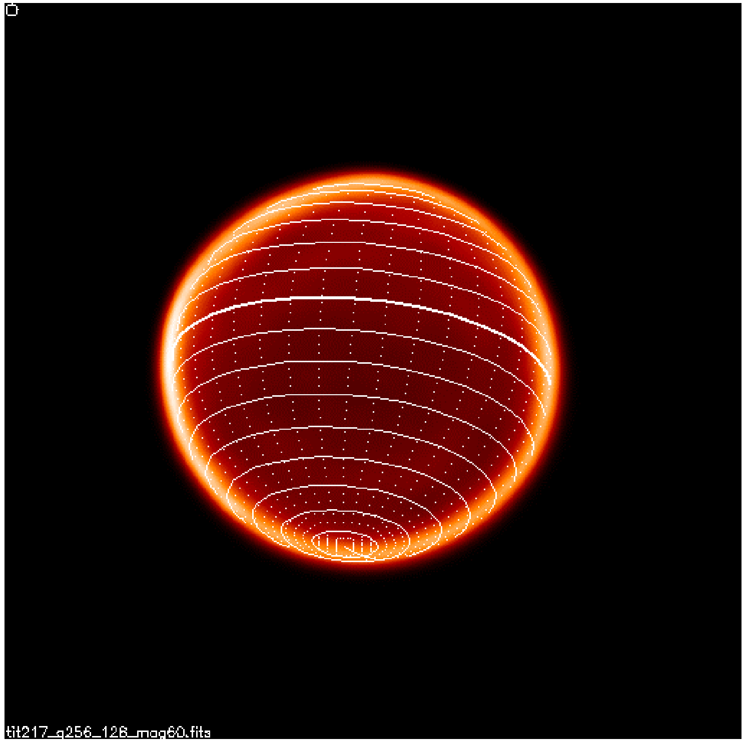
NAOS: November 2002

now you see it - now you don’t

2.12 micron

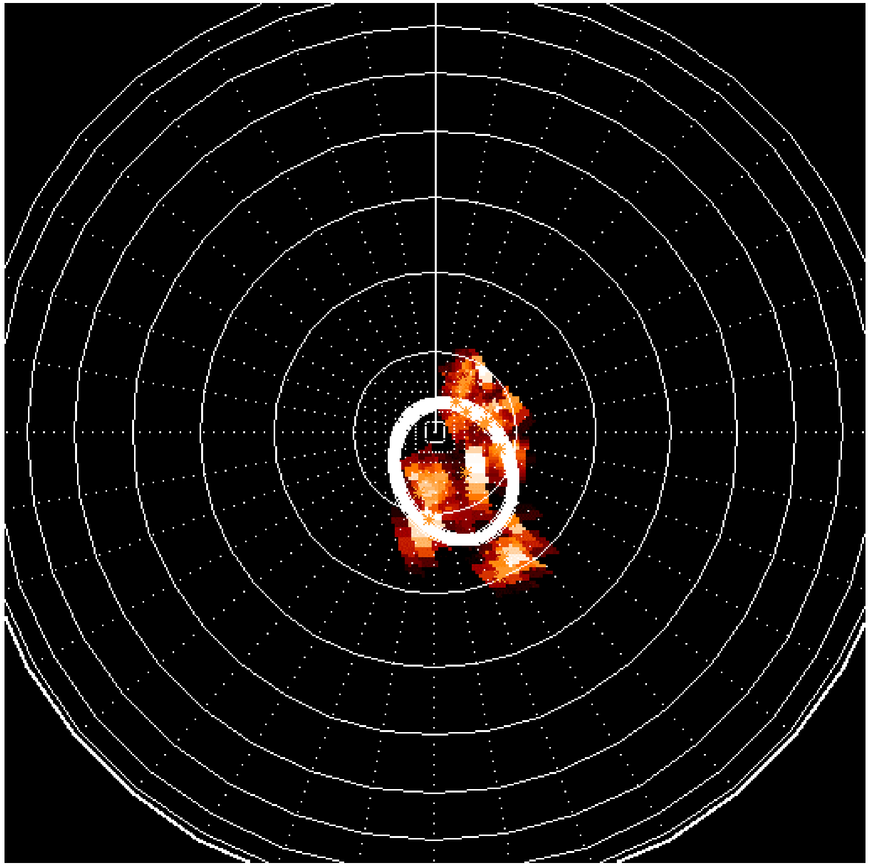


2.17 micron



The feature’s source is located between 15 and 140 km in altitude

How does it move ?

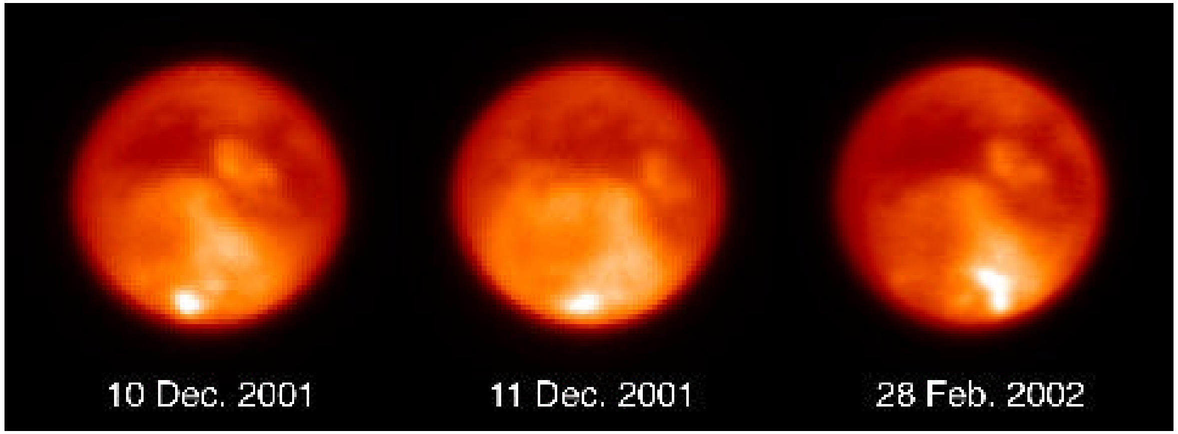


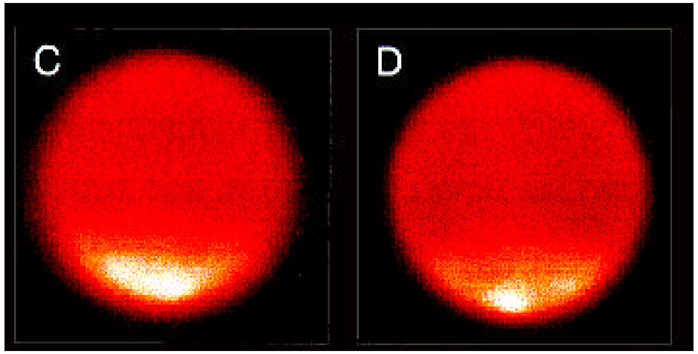
Trajectory: Ellipse ? → seems confined mostly within the 80°S parallel

Rotation: PROGRADE

Speed: 10°/h i.e. 125 m/s
(Surface motion is 22 degrees per day (i.e. about 10 m/s))

Clouds and vortices…

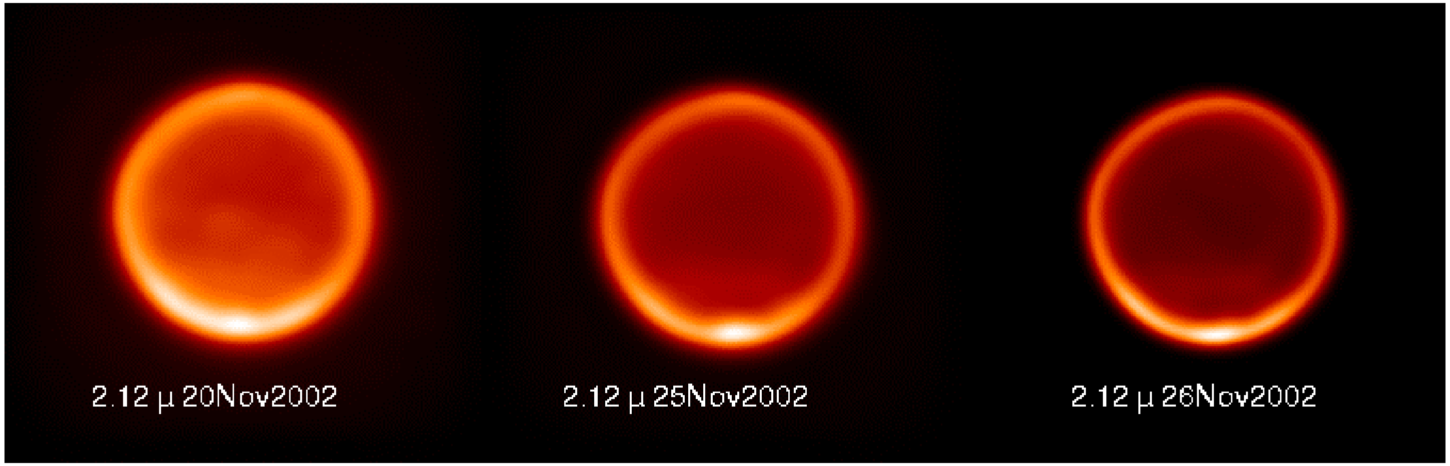




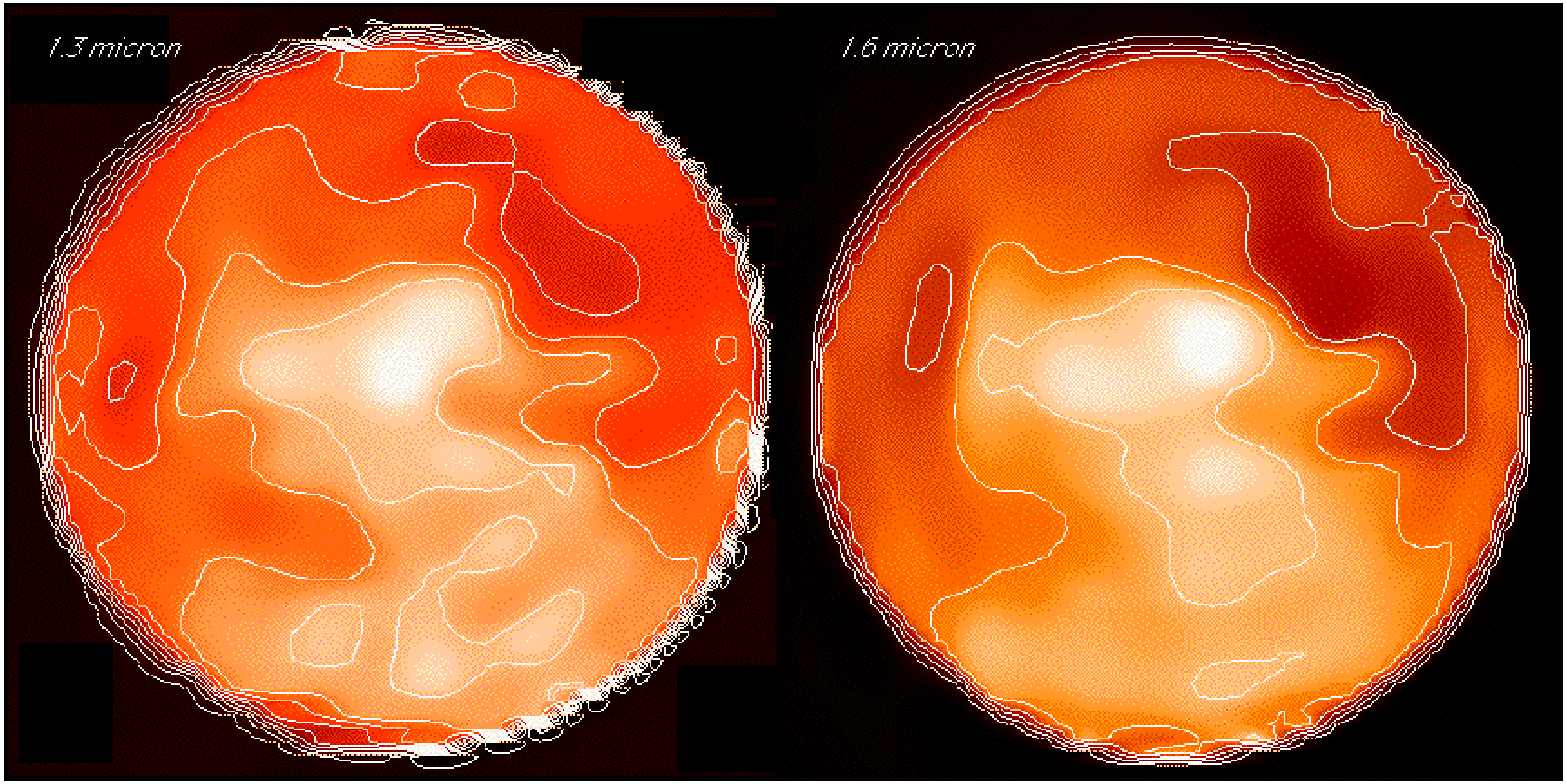
Keck cloud images at 2 µm and Gemini images in the H2(1-0) filter

Roe et al., & Brown & al. (2002)

NAOS images in the H2(1-0) filter : *Gendron et al. (2003)*



Titan's surface in 1998

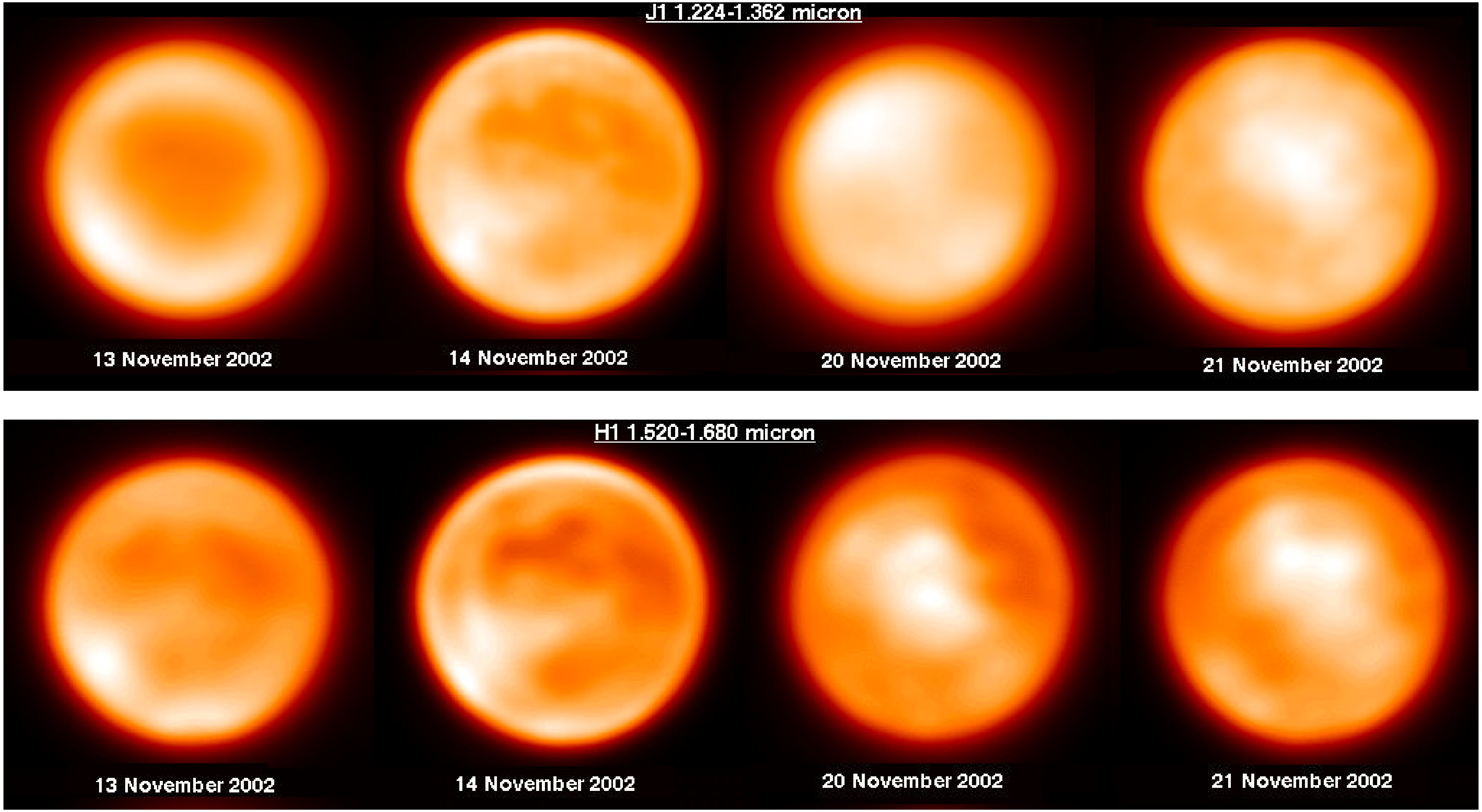


Titan's surface on the leading hemisphere observed with PUEO. The bright equatorial feature, appearing bright both in J and in H, probably related to ices connected with topography (relief). Dark areas are visible in the North-East and to the West of the images, suggesting the presence of additional surface components (Coustenis et al., 2001).

GWE

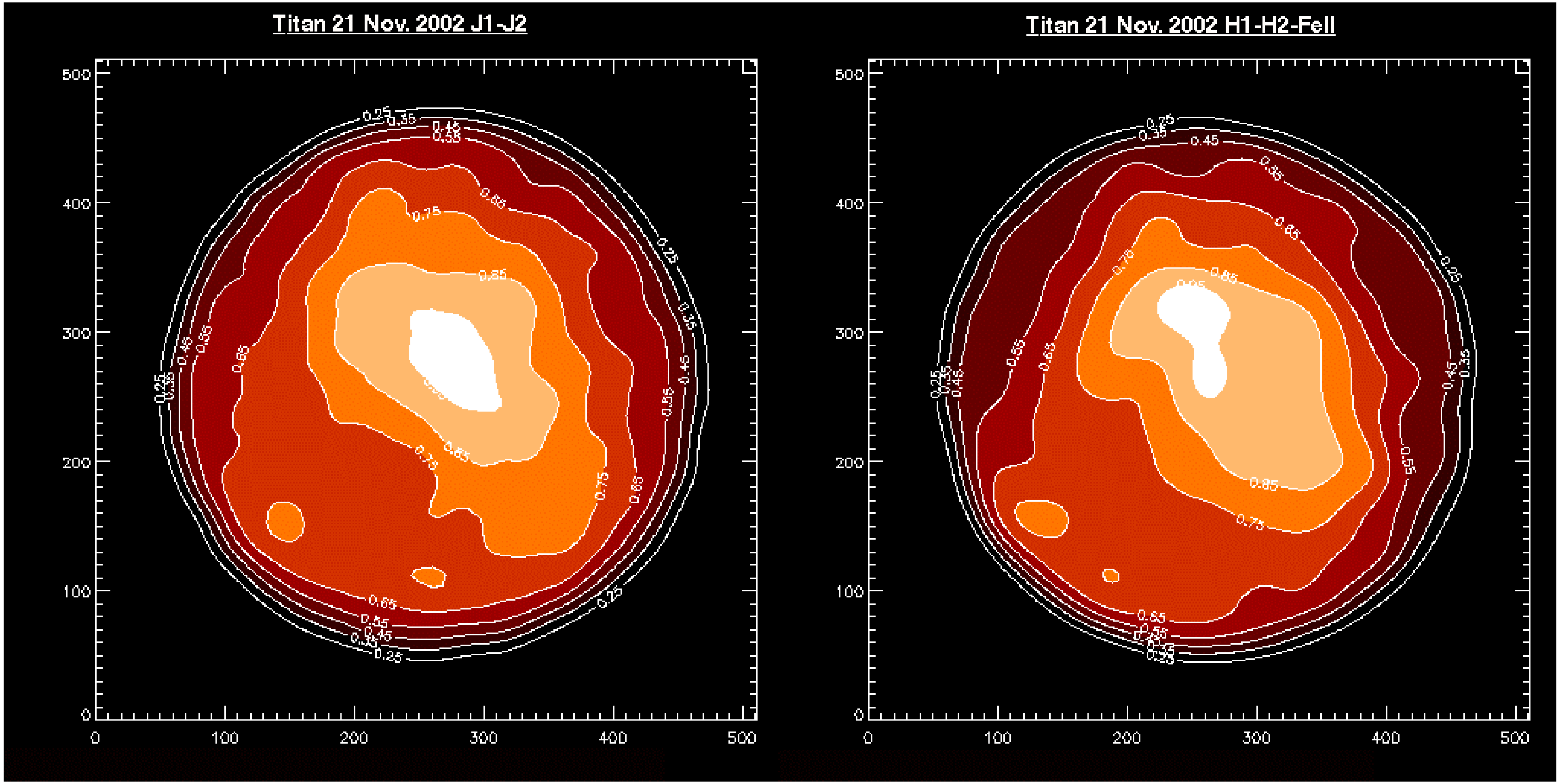
Always bright …

GEE



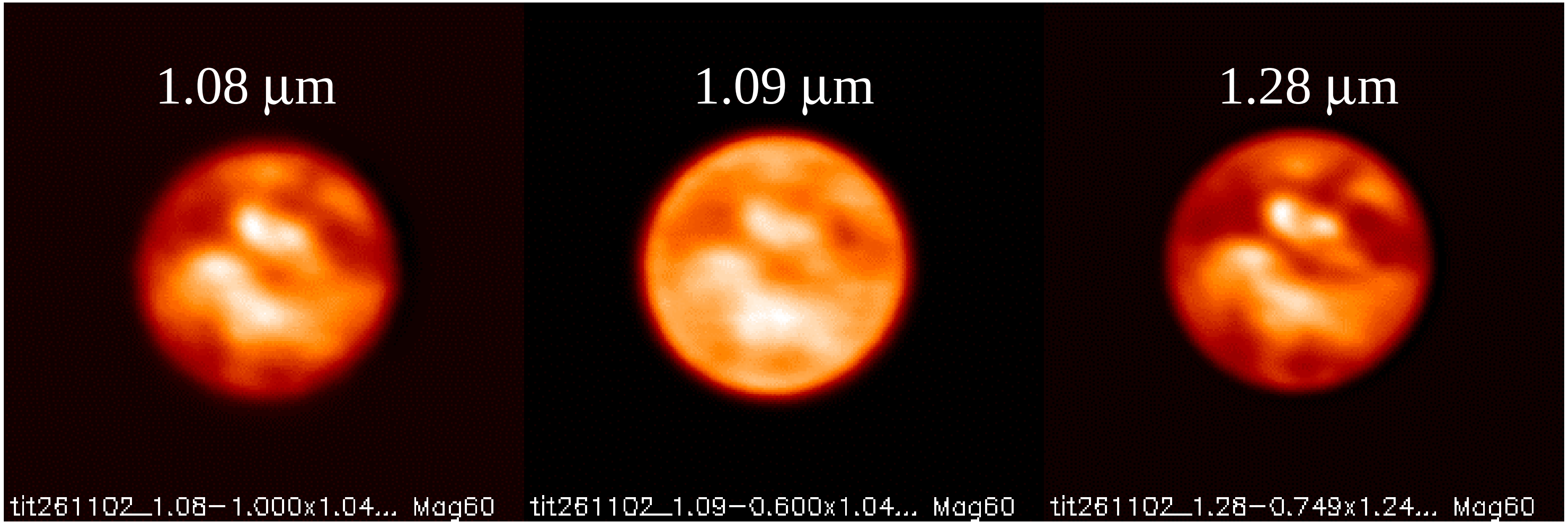
PUEO: November 2002

Titan at GEE : surface albedos

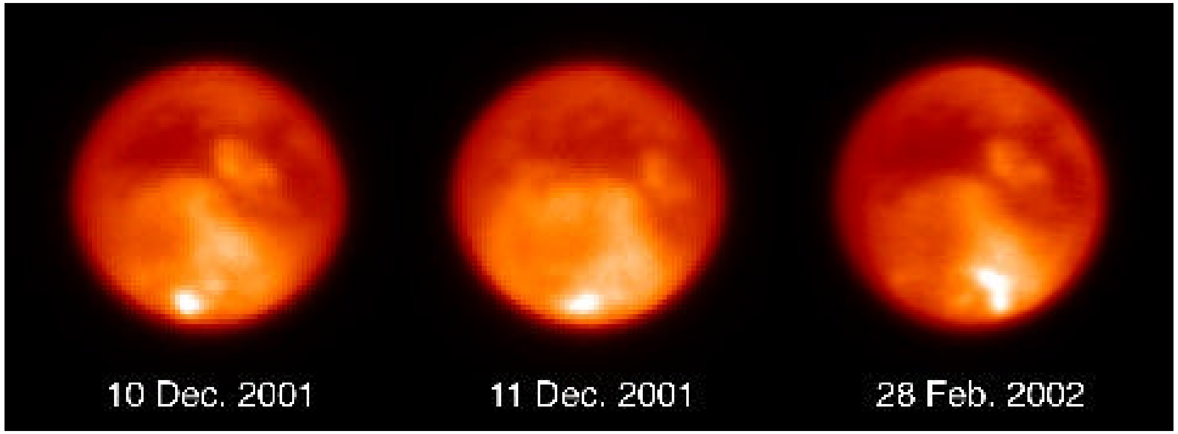


PUEO 2002

Titan's trailing surface in 2002



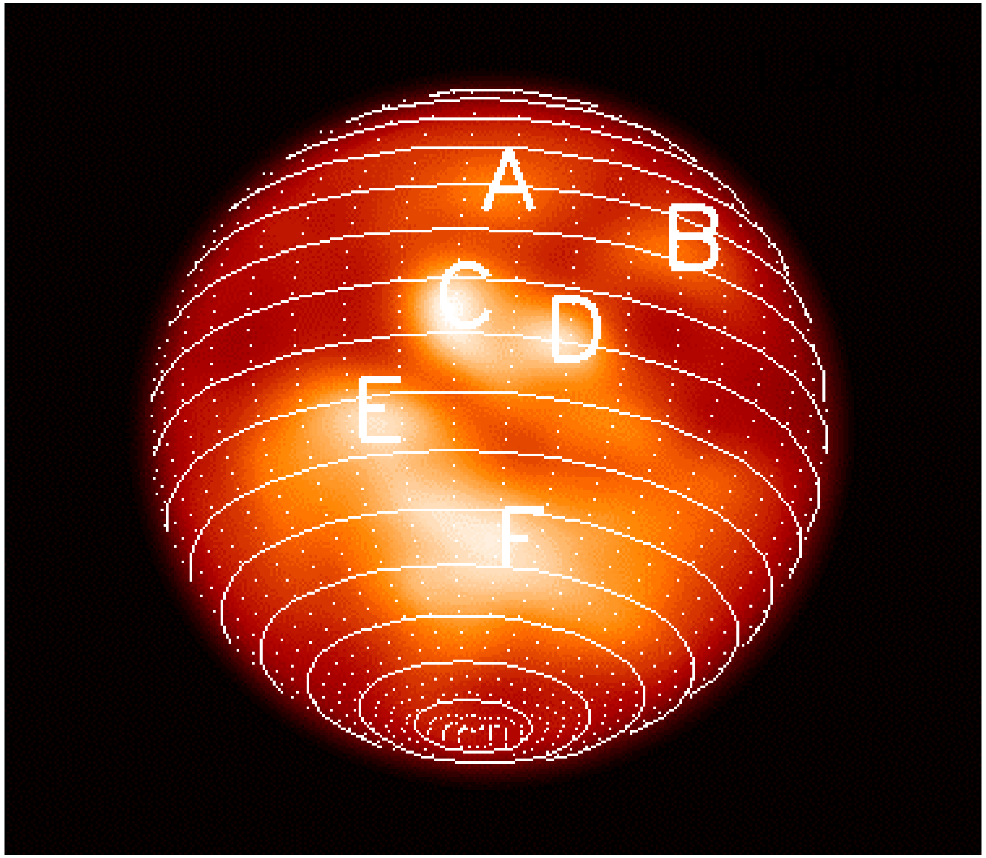
Titan's surface on the trailing hemisphere observed with NAOS in 2002. The images here were obtained after deconvolution and subtraction among the "window" filters and near-by ones in the CH_4 band: 1.08-1.04, 1.09-1.04 and 1.28-1.24 µm. There are bright spots at several locations near the center and in the N-E side (Gendron et al., 2004).

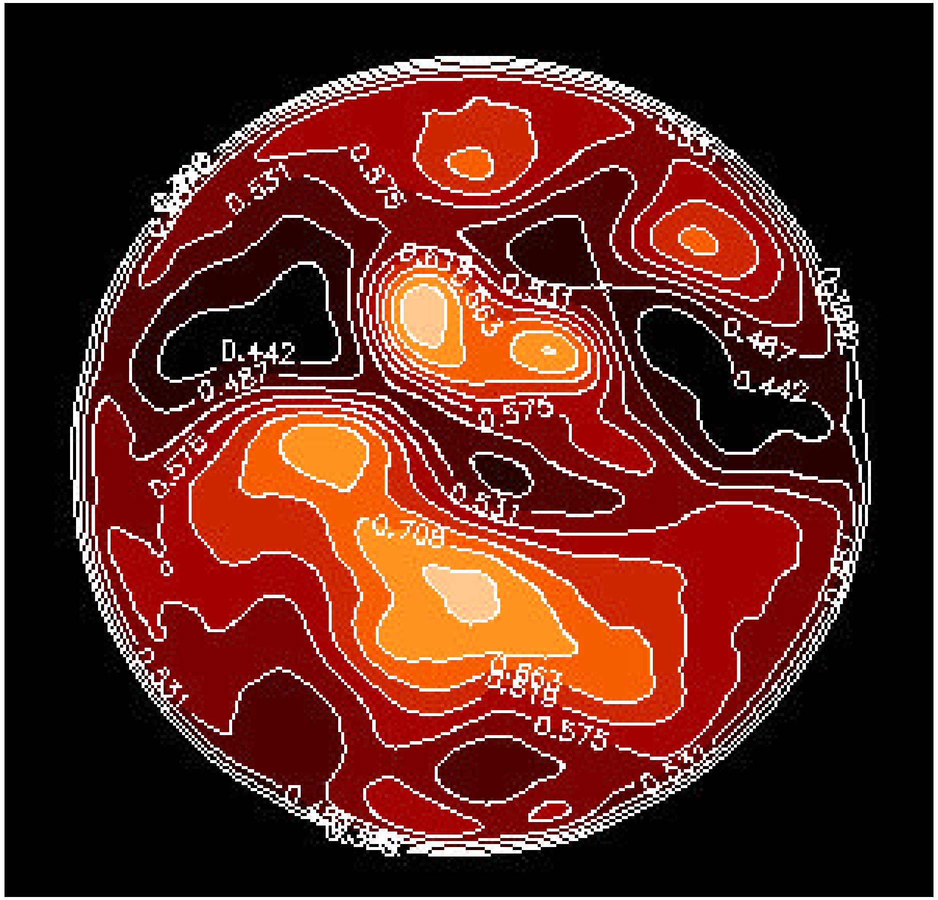


Keck images

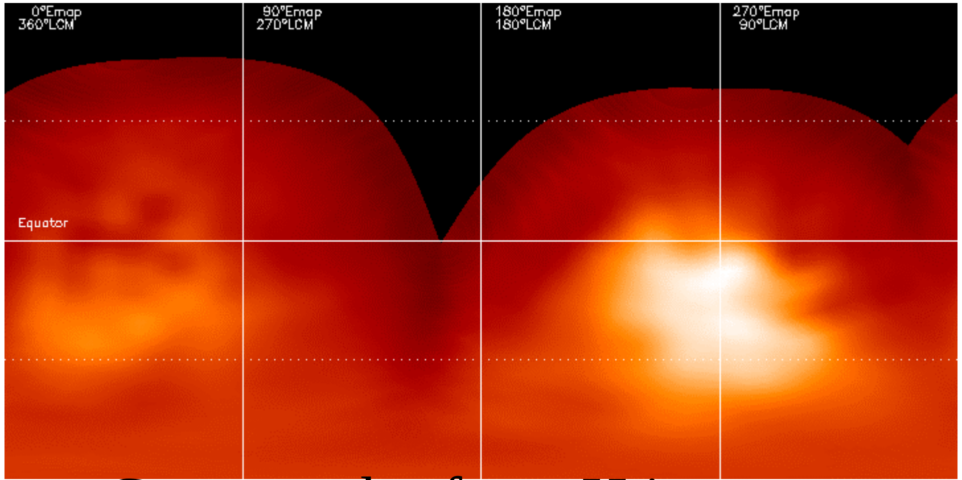
(Brown et al., 2002; Roe et al., 2002)

The « dark » side of Saturn's moon

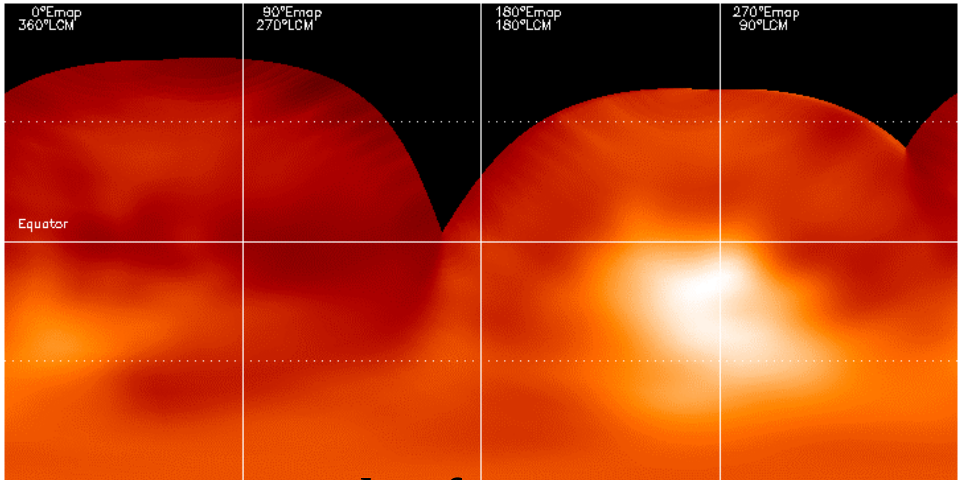




The Surface of Titan from PUEO



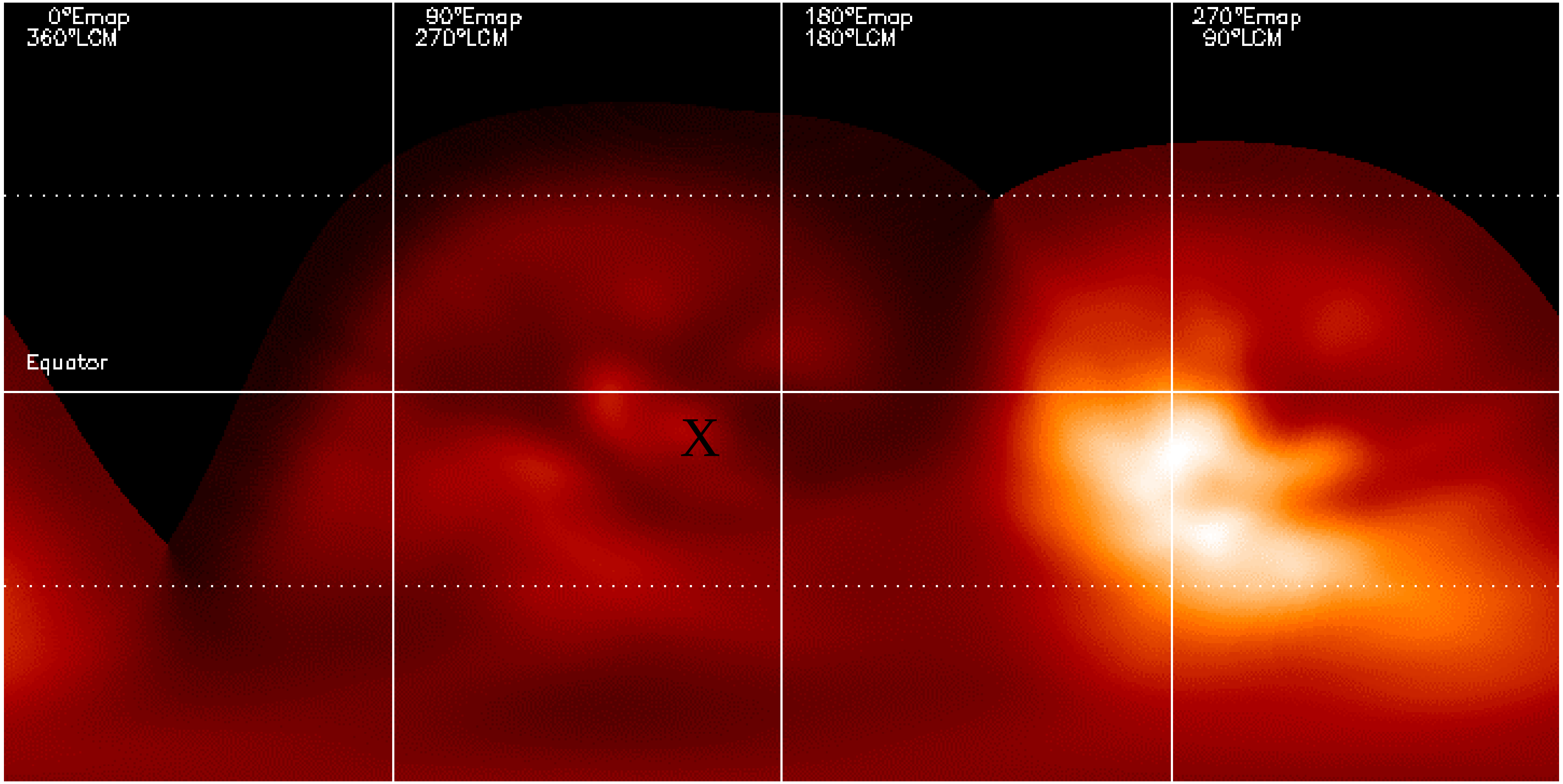
Cartography from H images



Cartography from J images

- Surface features:
  - 110° : bright continent
  - 350° : large bright feature capped with dark area
- Comparison of maps at different wavelengths :
  - Similarly bright areas possibly contain CH4/C2H6 ices (and topography)
  - Brightest peaks are not exactly at the same position
  - Signature of surface chemical composition?

Map of Titan's surface by NAOS



Yes ! Huygens will still land on a very exciting site

Conclusions

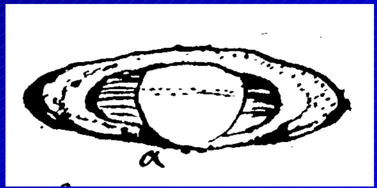
Atmosphere:

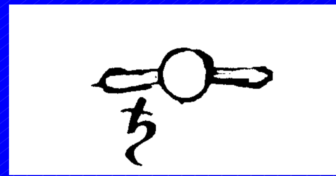
- Asymmetry inversion in progress detected/confirmed at high altitudes
- "New" atmospheric bright features observed on the limb: Vortex? Cloud? Aurora? Permanent or reforming? Its source? Its energy?
- Morning fog seen in 1998: not definitely confirmed in 2001-2. But it's not a phase effect and perhaps some hints. We need more high-quality data with a low phase effect on the evening side.

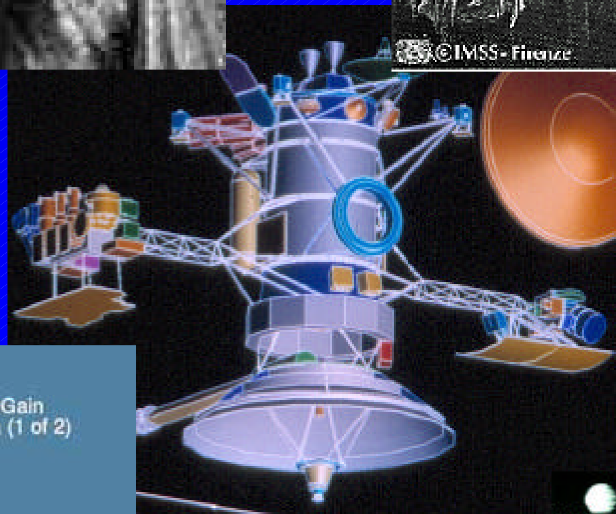
Surface:

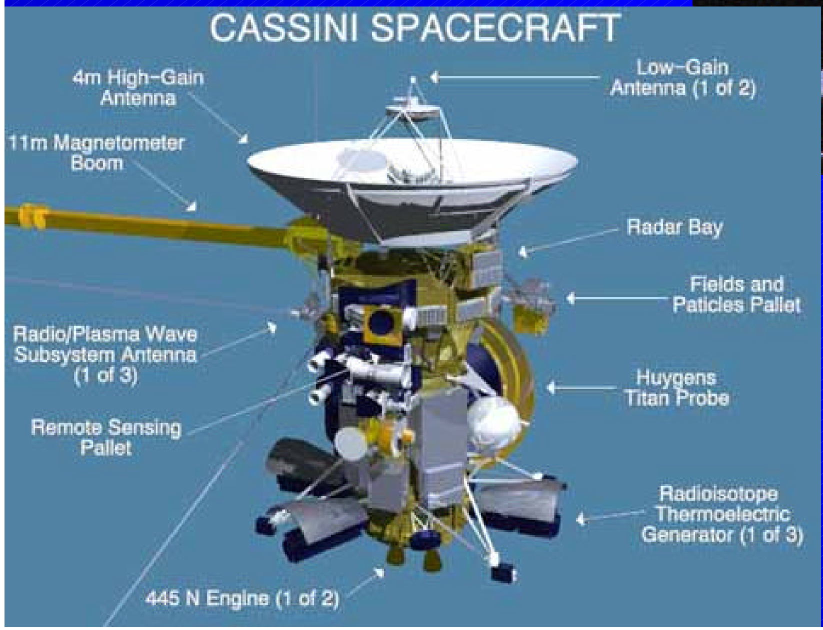
- confirmation of previously observed: bright area (probably related to relief) at 10°S and 110°E
- Bright at all observed wavelengths (close to 1.3, 1.6 and 2 μm).
- Bright areas observed on the trailing side: the new map is very complex and not interesting only at GEE.

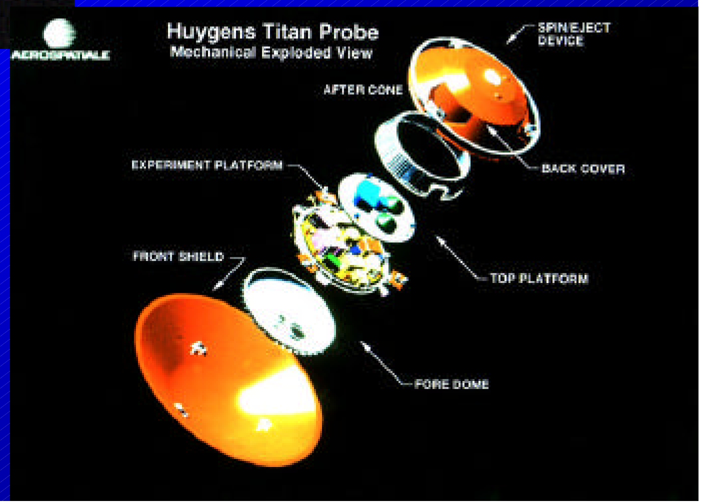
The Cassini/Huygens mission





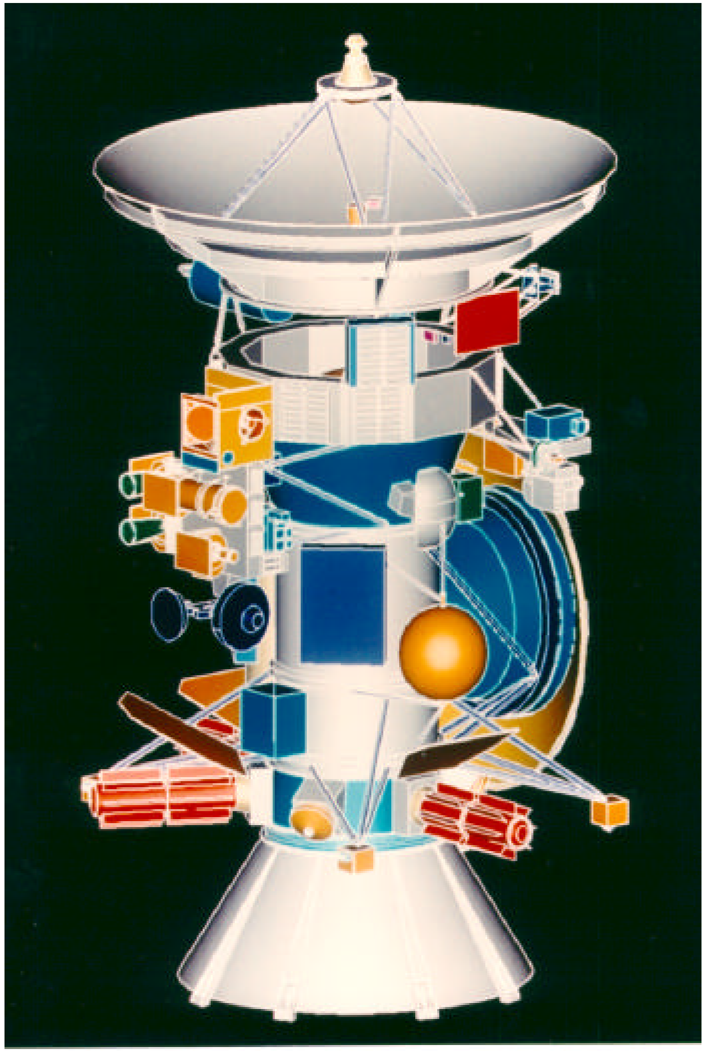


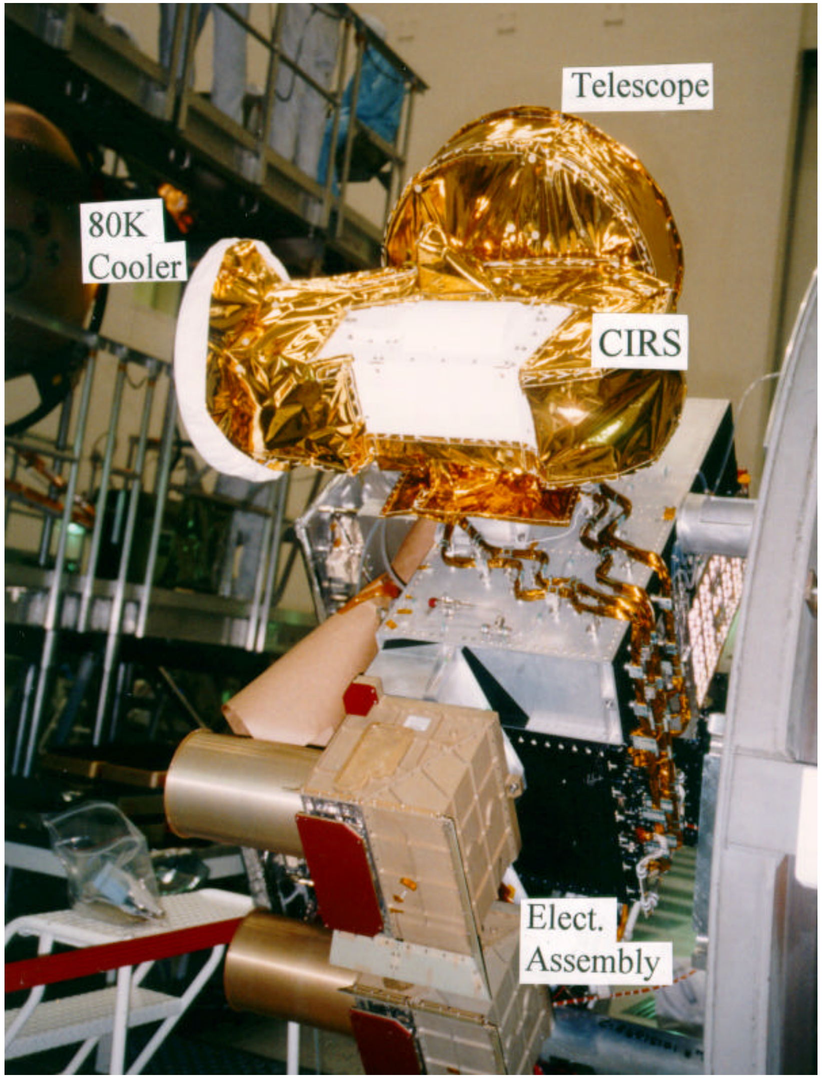




Cassini S/C – CIRS Location

CIRS—>





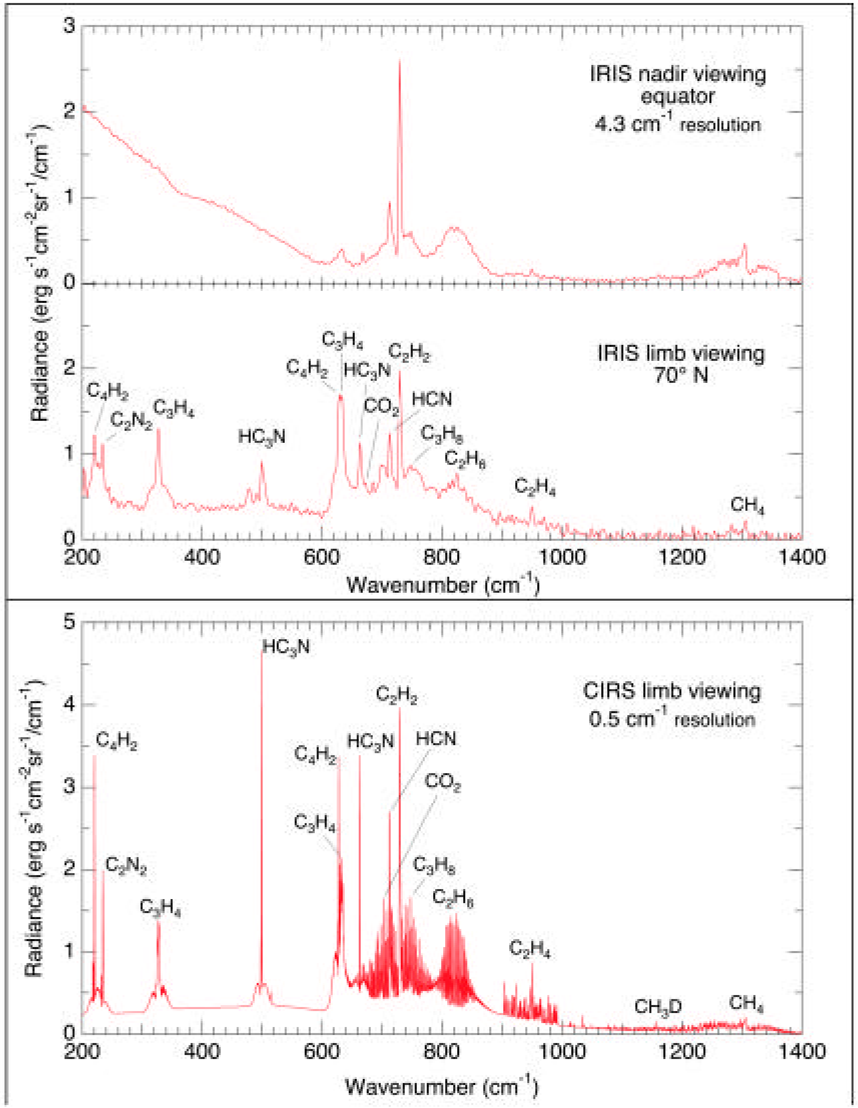


Fig. 7 *Top panel*: Voyager IRIS low- and high-latitude averaged Titan spectra at 4.3 cm^{-1} resolution, with several emission bands identified. *Bottom panel*: Simulation of CIRS limb viewing at an altitude of 125 km with 0.5 cm^{-1} resolution. After Coustenis *et al*. (1993).

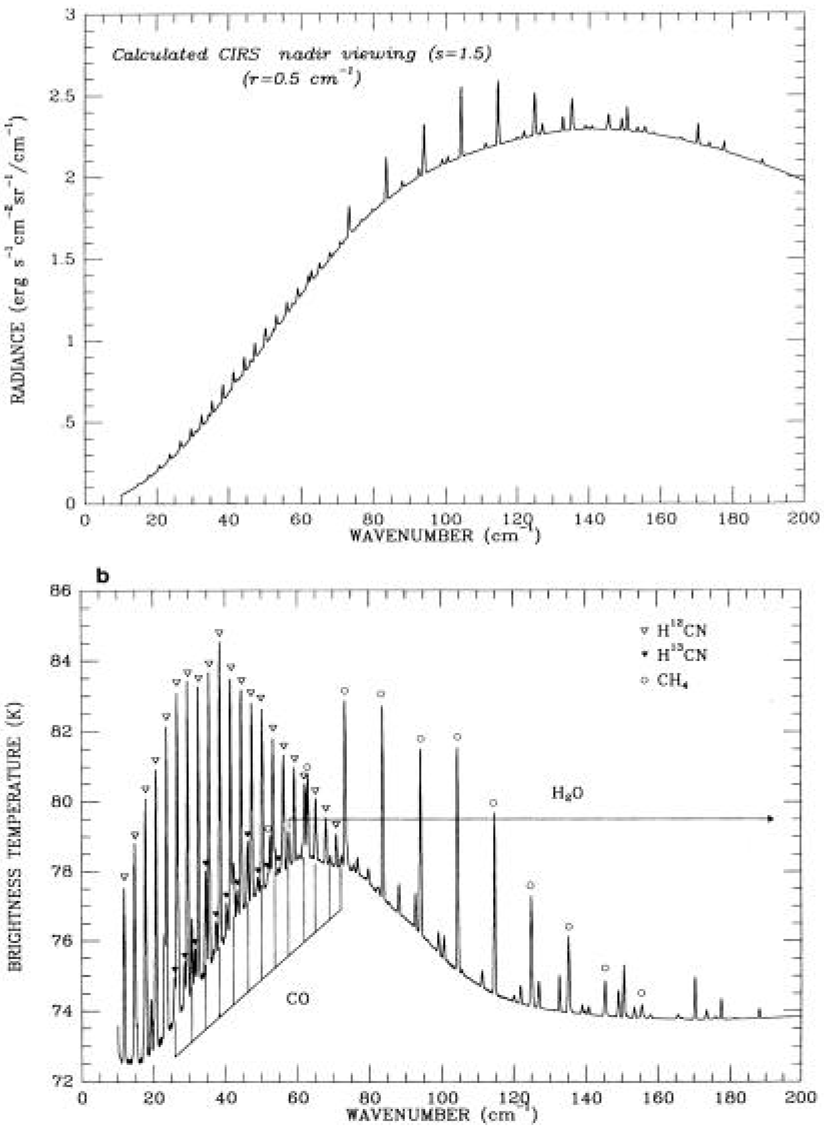
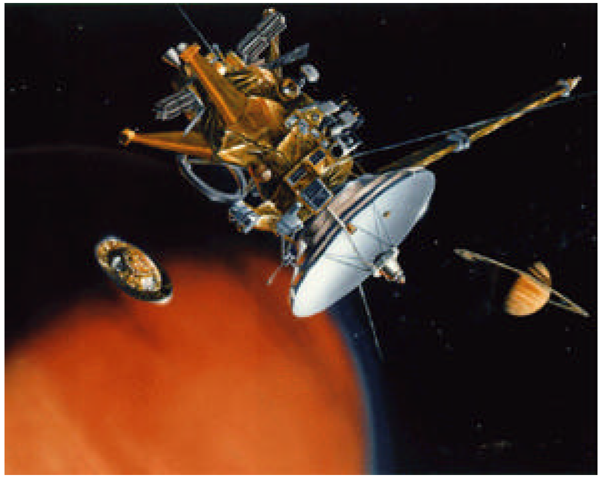
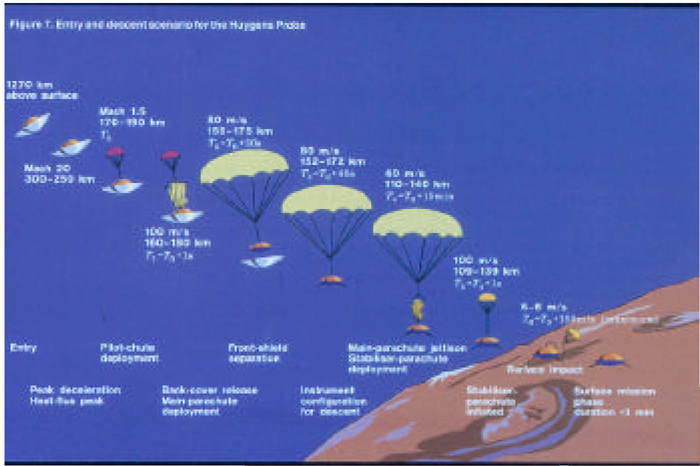
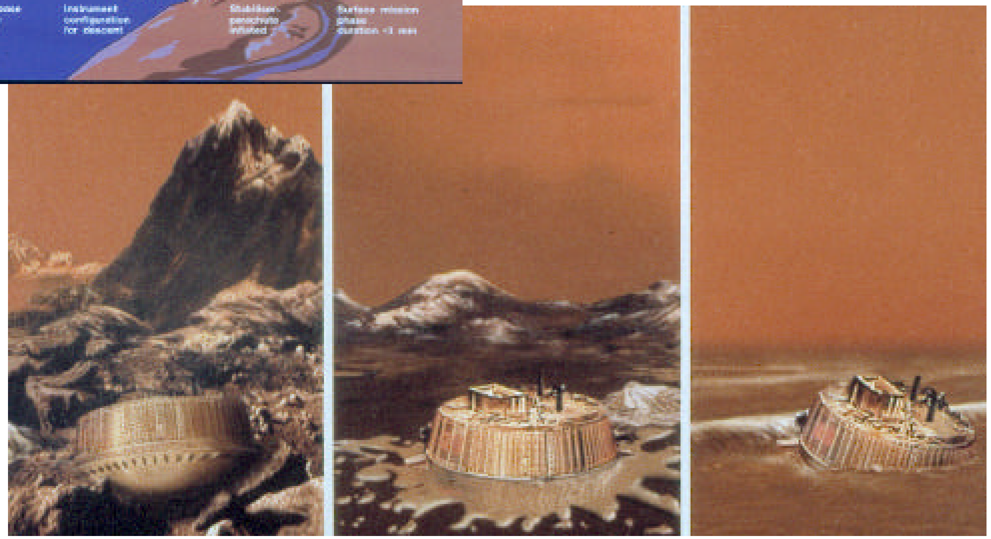


Fig. 9 Synthetic Titan spectrum at 10-200 cm^{-1}, with viewing at an emission angle of 48°. (a) radiances, (b) brightness temperatures. Rotational lines of $H^{12}CN$, CO, CH_4, $H^{13}CN$, and H_2O are indicated. After Coustenis *et al*. (1993).

The Huygens probe







Perspectives

Adaptive optics:

- PUEO/CFHT : new data with more filters and at more phases to complete cartography and atmospheric investigation

  (new observations in Jan. 2004 and request for time in Dec 04 &Jan. 05)

- NAOS & ISAAC @VLT

  After first GT Titan observations :

  (new GT allocation : spectroscopy & imaging April 2004 & new application for end 04-05)

Spectro-imaging:

- WHT/OASIS : time application for

  new observations in Jan. 2005

Cassini/Huygens:

a few more months to go!