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

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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 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 mid-IR space observations

SPECTRAL COVERAGE & RESOLUTION of CASSINI/CIRS and ISO/LWS-SWS

ISO: Infrared Space Observatory
CIRS: Composite Infrared Radiometer Spectrometer
LWS: Long Wavelength Spectrometer
SWS: Short Wavelength Spectrometer
GR: Grating mode
FP: Fabry-Perot mode
fp1,3,4: focal plane 1,3,4

2004
(0.5–20 cm⁻¹)

1997
(0.2 cm⁻¹) (0.5 cm⁻¹) (0.4 cm⁻¹) → 4000 cm⁻¹

1980
(4.3 cm⁻¹)

WAVENUMBER (cm⁻¹)
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 N2, CH4 and H2. Numerous organics were detected, during the Voyager flyby in 1980.
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.
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 μm**
    - LWS: **45 - 200 μm**
  - 1 photometer (ISOPHOT)
    - PHT-S: **2.5-5 & 6-12 μm**
  - 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

ISO/SWS/Grating (1997)

Titan: disk average

Voyager 1/IRIS at Titan (1980)
Sample G (Lat=5° S)
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) CH₄ 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
Titan observed with ISO (1997)
SWS/Grating mode

CH$_3$D and the D/H ratio

CH$_3$D = $6.7 \times 10^{-6}$

D/H = $8.7 \times 10^{-5}$

Evidence for water vapor on Titan

- **Context:**
  - CO$_2$ and H$_2$O 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$_2$O is deposited in the upper atmosphere in the form of icy particles. Then:
    - H$_2$O vaporization & photolysis → OH
    - OH + hydrocarbon radicals (CH$_3$) → CO
    - CO + OH → 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.** | **H₂O Peak flux** | **std dev** | **Det.**

<table>
<thead>
<tr>
<th>μm</th>
<th>cm⁻¹</th>
<th>Jy</th>
<th>Jy</th>
<th>Jy</th>
<th>Jy</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.4</td>
<td>254</td>
<td>56.5</td>
<td>0.6</td>
<td>1.6</td>
<td>0.2</td>
</tr>
<tr>
<td>43.9</td>
<td>227.8</td>
<td>59.5</td>
<td>0.5</td>
<td>2.0</td>
<td>0.25</td>
</tr>
</tbody>
</table>
ISO/SWS: Coustenis et al. (1998)
C.F.($H_2O$): 254 cm$^{-1}$

C.F.($H_2O$): 227.8 cm$^{-1}$

$q_{(H_2O)}$: Lara et al. (1996) * 0.4

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 $4 \times 10^{-10}$ 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
  \[ q(\text{H}_2\text{O}) \sim 8 \times 10^{-9} \]
– The column density is \( \sim 2.5 \times 10^{14} \text{ mol cm}^{-2} \) 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: \( (1.5 - 5) \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \) \( \text{Feuchtgruber et al., 1997} \).
– Then, \( \text{H}_2\text{O} \) flux (Saturn/Titan) \( \sim 0.5 - 6.2 \)
**H₂O sources:**

- We find that H₂O flux on Titan is \( \sim 1.6 \times 10^6 \) mol cm\(^{-2}\)s\(^{-1}\), and flux (Saturn/Titan) \( \sim 0.5 - 6.2 \)  
- These results are 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 \( \sim 10^9 \) years).

- H₂O influx may have two primary sources:
  - Interplanetary dust component in the Solar System: IC  
    H₂O influx predicted by the meteroid ablation model in agreement with this work  
    \[ 2 \times 10^6 \) mol cm\(^{-2}\) s\(^{-1}\]: English & al., 1996\]  
    IC (Saturn/Titan) \( \approx 7.5 \) (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):

\[
\begin{align*}
2(\text{CH}_4 + h\nu & \rightarrow \text{CH}_2+\text{H}_2) \\
2(\text{C}_2\text{H}_2 + \text{CH}_2 & \rightarrow \text{C}_3\text{H}_3+\text{H}) \\
\text{C}_3\text{H}_3 + \text{C}_3\text{H}_3 & \rightarrow \text{n-}[n-] \text{C}_6\text{H}_6 \\
2\text{C}_2\text{H}_2 + \text{CH}_4 & \rightarrow \text{C}_6\text{H}_6 + 2\text{H} + \text{H}_2
\end{align*}
\]
We observed Titan in December 1997 during 1 hr of integration time with a resolving power of ~2000 in the 14.76-14.94 \( \mu \text{m} \) region (dedicated observation). We then clearly observed \( \text{HC}_3\text{N} \) in emission at mid-latitudes at 663 cm\(^{-1}\) and inferred an abundance of about \( 5 \pm 3 \times 10^{-10} \) relevant to the 9-mbar pressure level.
Benzene on Titan

We found an emission feature at 674 cm\(^{-1}\) where the \(\nu_4\) band of \(\text{C}_6\text{H}_6\) occurs. We have found a 3Jy additional flux which can be explained with a benzene emission of about \(4 \pm 3 \times 10^{-10}\) relevant to the 9-mbar region and corresponding to a column density of \(2 \times 10^{15} \text{ mol cm}^{-2}\) (Coustenis et al., 2003).
### Results

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Voyager</th>
<th>ISO</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{C}_2\text{H}_2$</td>
<td>3.0 $10^{-6}$</td>
<td>3-5.5 $10^{-6}$ $\uparrow$ (v.d.)</td>
<td></td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_4$</td>
<td>1.5 $10^{-7}$</td>
<td>1.2 $10^{-7}$</td>
<td>$\rightarrow$</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_6$</td>
<td>1.5 $10^{-5}$</td>
<td>2.0 $10^{-5}$</td>
<td>$\rightarrow$</td>
</tr>
<tr>
<td>$\text{C}_3\text{H}_4$</td>
<td>6.5 $10^{-9}$</td>
<td>1.2 $10^{-8}$</td>
<td>$\rightarrow$</td>
</tr>
<tr>
<td>$\text{C}_3\text{H}_8$</td>
<td>7.0 $10^{-7}$</td>
<td>2.0 $10^{-7}$</td>
<td>$\rightarrow$</td>
</tr>
<tr>
<td>$\text{C}_4\text{H}_2$</td>
<td>1.5 $10^{-9}$</td>
<td>2.0 $10^{-9}$</td>
<td>$\rightarrow$</td>
</tr>
<tr>
<td>$\text{CH}_3\text{D}$</td>
<td>1.1 $10^{-5}$</td>
<td>6.7 $10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$\text{D}/\text{H}$</td>
<td>1.5 $10^{-4}$</td>
<td>8.7 $10^{-5}$</td>
<td>$\rightarrow$</td>
</tr>
<tr>
<td>$\text{C}_3\text{H}_4$ (allene)</td>
<td>$&lt;2.0$ $10^{-9}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{C}_6\text{H}_6$ (benzene)</td>
<td>4 $10^{-10}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{HCN}$</td>
<td>2.0 $10^{-7}$</td>
<td>3.0 $10^{-7}$</td>
<td>$\rightarrow$</td>
</tr>
<tr>
<td>$\text{HC}_3\text{N}$</td>
<td>$&lt;1$ $10^{-9}$</td>
<td>5 $10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>$\text{C}_2\text{N}_2$</td>
<td>$&lt;1$ $10^{-9}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{CO}_2$</td>
<td>1.5 $10^{-8}$</td>
<td>2.0 $10^{-8}$</td>
<td>$\rightarrow$</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}$ @ 400 km</td>
<td>1.5 $10^{-8}$</td>
<td>8 $10^{-9}$</td>
<td></td>
</tr>
</tbody>
</table>

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
### Table 1. Atmospheric composition of Titan

<table>
<thead>
<tr>
<th>Gas</th>
<th>Mole fraction</th>
<th>Comments - Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_2</td>
<td>0.85 - 0.98</td>
<td>Inferred indirectly (a)</td>
</tr>
<tr>
<td>Ar</td>
<td>&lt; 0.07</td>
<td>Inferred indirectly (b)</td>
</tr>
<tr>
<td>CH_4</td>
<td>0.005 - 0.034</td>
<td>In the stratosphere (b)</td>
</tr>
<tr>
<td></td>
<td>0.03 - 0.085</td>
<td>Near the surface (b, l)</td>
</tr>
</tbody>
</table>

**In situ measurements**

<table>
<thead>
<tr>
<th></th>
<th>Equator (c)</th>
<th>North Pole (d)</th>
<th>Disk-average (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 20 mbar</td>
<td>~ 0.1 mbar</td>
<td>~ 1.5 mbar</td>
<td>0.5 - 20 mbar</td>
</tr>
<tr>
<td>C_2H_2</td>
<td>2.85 x 10^-6</td>
<td>4.7 x 10^-6</td>
<td>2.3 x 10^-6</td>
</tr>
<tr>
<td>C_2H_4</td>
<td>1.5 x 10^-7</td>
<td>3 x 10^-7</td>
<td>1.2 x 10^-7</td>
</tr>
<tr>
<td>C_2H_6</td>
<td>1.5 x 10^-6</td>
<td>1.5 x 10^-7</td>
<td>1.0 x 10^-7</td>
</tr>
<tr>
<td>ethylene</td>
<td>6.5 x 10^-9</td>
<td>6.2 x 10^-7</td>
<td>2.0 x 10^-7</td>
</tr>
<tr>
<td>C_2H_4</td>
<td>7.0 x 10^-7</td>
<td>5.0 x 10^-7</td>
<td>2.0 x 10^-7</td>
</tr>
<tr>
<td>C_2H_6</td>
<td>1.5 x 10^-9</td>
<td>4.2 x 10^-9</td>
<td>2.7 x 10^-9</td>
</tr>
<tr>
<td>C_2H_6</td>
<td></td>
<td></td>
<td>2.0 x 10^-10</td>
</tr>
<tr>
<td>HCN</td>
<td>1.95 x 10^-7</td>
<td>2.3 x 10^-7</td>
<td>4.0 x 10^-7</td>
</tr>
<tr>
<td>HC_3N</td>
<td>&lt;= 1 x 10^-7</td>
<td>2.5 x 10^-7</td>
<td>8.4 x 10^-7</td>
</tr>
<tr>
<td>C_2N_2</td>
<td>&lt;= 1 x 10^-7</td>
<td>1.6 x 10^-7</td>
<td>5.5 x 10^-7</td>
</tr>
<tr>
<td>C_4N_2</td>
<td></td>
<td></td>
<td>1.5 x 10^-9</td>
</tr>
</tbody>
</table>

**Solid compounds**

<table>
<thead>
<tr>
<th></th>
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<th>Solid phase</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H_2O</td>
<td></td>
<td></td>
<td>8 x 10^-9</td>
</tr>
<tr>
<td>CO_2</td>
<td>1.45 x 10^-4</td>
<td>&lt;= 7 x 10^-9</td>
<td>2 x 10^-4</td>
</tr>
<tr>
<td>CO</td>
<td></td>
<td></td>
<td>(2.2 - 4.2) x 10^-5 In the troposphere (h)</td>
</tr>
<tr>
<td>CO</td>
<td></td>
<td></td>
<td>(2.3 - 0.9) x 10^-5 In the lower and in the higher stratosphere (i)</td>
</tr>
<tr>
<td>CO_2</td>
<td></td>
<td></td>
<td>4.6 x 10^-5 In the higher stratosphere (j)</td>
</tr>
</tbody>
</table>

From Flasar et al., 2004
Table 1. 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.

<table>
<thead>
<tr>
<th>Studied Compounds</th>
<th>Strongest signatures</th>
<th>Upper limit of mean mixing ratio in Titan’s stratosphere using Voyager IRIS spectra</th>
<th>Upper limit of mean mixing ratio in Titan’s stratosphere using ISO disk-averaged data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (cm⁻¹)</td>
<td>Band strength at 300 K (cm⁻²·atm⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Hydriocarbons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂H₂CC₂H₂</td>
<td>356</td>
<td>65</td>
<td>5 \times 10^{-7} (a)</td>
</tr>
<tr>
<td></td>
<td>845</td>
<td>407</td>
<td></td>
</tr>
<tr>
<td>C₅H₄</td>
<td>629</td>
<td>288</td>
<td>7 \times 10^{-10} (c)</td>
</tr>
<tr>
<td>C₆H₂</td>
<td>622</td>
<td>428</td>
<td>4.4 \times 10^{-10} (d)</td>
</tr>
<tr>
<td>C₈H₂</td>
<td>621.5</td>
<td>496</td>
<td>4 \times 10^{-10} (e)</td>
</tr>
<tr>
<td>Nitriles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂H₃CN</td>
<td>362†</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>C₂H₃CHCN</td>
<td>230</td>
<td>10</td>
<td>8.4 \times 10^{-8} (g)</td>
</tr>
<tr>
<td></td>
<td>954</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>C₂H₅CH₂CN</td>
<td>207</td>
<td>15</td>
<td>2.5 \times 10^{-7} (a)</td>
</tr>
<tr>
<td></td>
<td>1075</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>C₂H₅CH₂CH₃CN</td>
<td>728/742</td>
<td>3.5</td>
<td>5 \times 10^{-7} (a)</td>
</tr>
<tr>
<td>(C₂H₅)₂CHCN</td>
<td>538</td>
<td>3.3</td>
<td>2 \times 10^{-7} (a)</td>
</tr>
<tr>
<td></td>
<td>726</td>
<td>19</td>
<td>1.5 \times 10^{-7} (a)</td>
</tr>
<tr>
<td></td>
<td>818</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>C₂H₅CCC₃N</td>
<td>338</td>
<td>100</td>
<td>1.0 \times 10^{-8} (a)</td>
</tr>
<tr>
<td></td>
<td>499</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>C₂H₅CHCHCN</td>
<td>728</td>
<td>230</td>
<td>2.5 \times 10^{-7} (a)</td>
</tr>
<tr>
<td>C₂H₅CHCH₂CN</td>
<td>557</td>
<td>64</td>
<td>4 \times 10^{-8} (h)</td>
</tr>
<tr>
<td></td>
<td>942</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>C₂H₅C(C₂H₅)CN</td>
<td>535</td>
<td>33</td>
<td>7.5 \times 10^{-8} (h)</td>
</tr>
<tr>
<td></td>
<td>928</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>C₄N₂</td>
<td>614</td>
<td>34.4</td>
<td>5.6 \times 10^{-9} (i)</td>
</tr>
<tr>
<td>NCCHC₂H CN (trans)</td>
<td>947</td>
<td>178</td>
<td>1 \times 10^{-3} (j)</td>
</tr>
<tr>
<td>Other N organics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂H₅CN</td>
<td>526</td>
<td>8.8</td>
<td>1.3 \times 10^{-9} (k)</td>
</tr>
<tr>
<td>C₂H₅N₂</td>
<td>419</td>
<td>144</td>
<td>5.0 \times 10^{-9} (k)</td>
</tr>
<tr>
<td>C₂H₅N₃</td>
<td>250</td>
<td>9</td>
<td>5.4 \times 10^{-9} (k)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
† Feature not yet observed. C₂H₃CN detected in millimeter-wave observations (l), with a derived mole fraction 1.5 \times 10^{-9} at 1 mbar.

From Flasar et al., 2004
New species for Cassini?? - not any more!

Fig. 9 (a) Detectability of benzene (C₆H₆) by CIRS horizontal viewing in the $\nu_4$ band ($Q=675.5 \text{ cm}^{-1}$), 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?

P = 1.5 atm

Goo

Ice

Ethane fog?

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

- Leading
- Trailing

2.75 µm window
Griffith et al., 2003
ISO- PHT Titan 2-5 micron

Titan’s flux observed with ISO/PHT in the 2.5-4.9 μm 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 flux observed with ISO/SWS and ISO/PHT in the 2.5-3.0 µm 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, gives 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 \(\mu m\) range

See Poster by Negrao et al.
TITAN’S SPECTRUM FROM 2-5 MICRON
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 μm 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.
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’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
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

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

PUEO images taken in 1998 at 1.29 (J1) and 1.18 (J2) µm (Coustenis et al., 2001).
### Narrow-band filters used for Titan

<table>
<thead>
<tr>
<th>Name</th>
<th>$\lambda$ (µm)</th>
<th>Lower levels probed in the center of the image</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.834 ± 0.097</td>
<td>Stratosphere + troposphere</td>
</tr>
<tr>
<td>NB_1.04</td>
<td>1.040 ± 0.075</td>
<td>Tropopause</td>
</tr>
<tr>
<td>HeI</td>
<td>1.083 ± 0.004</td>
<td>Surface + lowest troposphere</td>
</tr>
<tr>
<td>PaGamma</td>
<td>1.094 ± 0.005</td>
<td>Surface + lower troposphere</td>
</tr>
<tr>
<td>J2</td>
<td>1.181 ± 0.064</td>
<td>Stratosphere</td>
</tr>
<tr>
<td>Jcont</td>
<td>1.207 ± 0.007</td>
<td>Lower strato + troposphere</td>
</tr>
<tr>
<td>J1</td>
<td>1.293 ± 0.070</td>
<td>Surface + lower troposphere</td>
</tr>
<tr>
<td>Hcont</td>
<td>1.570 ± 0.010</td>
<td>Surface + troposphere</td>
</tr>
<tr>
<td>H1</td>
<td>1.600 ± 0.080</td>
<td>Surface + lower troposphere</td>
</tr>
<tr>
<td>H2</td>
<td>1.640 ± 0.050</td>
<td>Surface + troposphere</td>
</tr>
<tr>
<td>FeII</td>
<td>1.644 ± 0.007</td>
<td>Stratosphere (200 km)</td>
</tr>
<tr>
<td>NB_1.75</td>
<td>1.748 ± 0.013</td>
<td>Stratosphere (140 km)</td>
</tr>
<tr>
<td>K'</td>
<td>2.120 ± 0.170</td>
<td>Stratosphere + troposphere</td>
</tr>
<tr>
<td>H2 (1-0)</td>
<td>2.122 ± 0.010</td>
<td>Troposphere</td>
</tr>
<tr>
<td>BrGamma</td>
<td>2.166 ± 0.010</td>
<td>Stratosphere (165 km)</td>
</tr>
<tr>
<td>K</td>
<td>2.200 ± 0.168</td>
<td>Stratosphere + troposphere</td>
</tr>
<tr>
<td>Kcont</td>
<td>2.260 ± 0.030</td>
<td>Stratosphere (260 km)</td>
</tr>
</tbody>
</table>

**Diffraction limits:**

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>PU’EO</th>
<th>NAOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.28 µ</td>
<td>0.08”</td>
<td>0.033”</td>
</tr>
<tr>
<td>1.64 µ</td>
<td>0.10”</td>
<td>0.042”</td>
</tr>
<tr>
<td>2.12 µ</td>
<td>0.12”</td>
<td>0.055”</td>
</tr>
</tbody>
</table>

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

Surface

Bright atmospheric feature

N-S asymmetry inversion

Bright atmospheric feature
It’s big, it’s fast, it’s bright!!

PUEO: November 2002
NAOS: November 2002

now you see it

2.12 micron

now you don’t

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 \( \mu \)m 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 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 CH₄ 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

- **Surface features:**
  - $110^\circ$: bright continent
  - $350^\circ$: 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


• 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
**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 Coates 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\(^3\)CN, CO, CH\(_4\), H\(^2\)CN, and H\(_2\)O are indicated. After Constenius 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!