PAST AND FUTURE SPACE OBSERVATIONS OF TITAN IN THE INFRARED AND SUBMM RANGES: ISO, CASSINI AND FIRST

A. Coustenis[1], A. Salama[2], B. Schulz[2], E. Lellouch[1], Th. Encrenaz[1], S. Ott[2], M.F. Kessler[2], H. Feuchtgruber[3], and Th. de Graauw[4]

[1]DESPA - Observatoire de Paris-Meudon, 92195 Meudon Cedex, France
[2]ISO Data Centre, Astrophysics Division, ESA, Villafranca del Castillo, P.O. Box 50727, 28080 Madrid, Spain
[3]Max-Planck Institute, Garching, Germany
[4]SRON, Groningen, The Netherlands

Abstract

After a first view of Titan obtained by the Voyager missions in the 1980s, Saturn's largest satellite remains a mysterious object. In particular, its lower atmosphere and surface are still largely unknown. The degree of complexity achieved by the chemistry in its stratosphere has not been clearly evaluated by previous space missions, due to low spectral resolution and/or sensitivity. With ISO, in 1997, we have enhanced our knowledge of the chemical composition of the atmosphere, but have failed to acquire full scans in the submm range, where the Saturnian straylight was too important. The CIRS instrument aboard the Cassini mission will considerably increase our knowledge in 2004, but may well be complemented by FIRST observations in 2007, thanks to the higher resolution and sensitivity that PACS, SPIRE and HIFI have to offer.

Key words: Titan, ISO, Cassini, solar system, IR, submm

1. Introduction

Titan, Saturn's largest satellite has been observed in the IR from space with Voyager (1980) and with ISO (1997). The Voyager/IRIS spectrometer covered the 200-1500 cm^{-1} (7-50 micron) range with a resolution of 4.3 cm^{-1}. The data produced a complete, yet moderately precise, model of Titan's atmosphere in terms of temperature and composition in the stratosphere (e.g. Coustenis & Bézard 1995).

A new opportunity for studying Titan appeared with ISO in 1997. All the instruments aboard ISO were used to observe Titan, with more or less success. For instance, the SWS aboard ISO produced a full scan of Titan's 7 to 27 μm spectral region with resolving powers of 1000-3000 (Fig. 1) in about 2,5 hours. This dataset gave us a precise evaluation of the mean stratospheric composition and temperature of Titan's disk-average (Coustenis et al. 1999, Coustenis et al. 2000a), as well as the vertical distribution of C_2H_2 (Coustenis et al. 2001). Additional dedicated observations of about 4 hours in the region around 40 micron yielded the first detection of water vapor in Titan's atmosphere (Coustenis et al. 1998).

Currently on its way to Saturn and Titan, is the ESA/NASA Cassini/Huygens spacecraft. launched in 1997 and planned to arrive in late 2004. Aboard the orbiter, the Composite Infrared Radiometer Spectrometer (CIRS) will perform measurements of Titan's upper and lower stratosphere by taking spectra in the 10-1500 cm^{-1} (7 to 1000 μm) range. CIRS will thus provide a lot of information on Titan's composition, temperature and dynamics, with spatial resolution, but at moderate spectral resolution.

Thus, the advent of FIRST offers the possibility to acquire Titan observations with high spectral resolutions in the far-IR and submm range in order to enhance our understanding of this mysterious body of our Solar System.

2. The ISO Titan observations

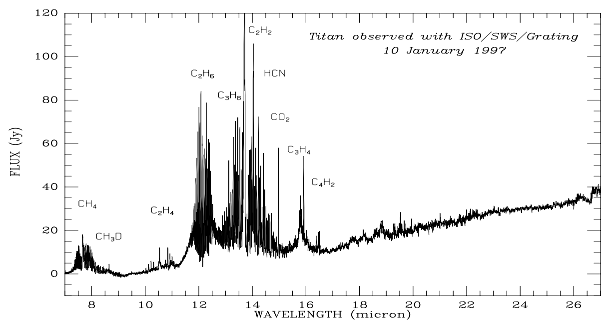

Figure 1. The spectrum of Titan as observed by ISO in 1997 with the Short Wavelength Spectrometer in the Grating mode.

The ISO Titan data were disk-averages, as opposed to the spatial information recovered by Voyager, but they afforded higher spectral resolution. Observations of Titan in the thermal and near infrared were performed by ISO on January 10 and December 27 1997, using the Grating mode of the Short Wavelength Spectrometer (SWS) in the 7-27 micron region, the spectrometer of ISOPHOT in the 2.5-5 and 6-12 μm region and the CVF mode of ISOCAM in the 7 to 8.5 μm range. The resolving powers ranged from 40 (CAM/CVF) to 2000 (SWS).

The major new discovery from the SWS data was the detection of the water vapour emission bands near 40 micron (Coustenis et al. 1998). The analysis of the ISO spectra also provided information on both Titan's atmospheric structure and on Titan's surface. Thus, a mean temperature profile for Titan's disk was inferred from the analysis of the 7.7 μm CH_4 band (Coustenis et al. 1999). The CH_3D abundance was estimated to be 8.2 $\times 10^{-6}$, for a D/H ratio of 8.75 $\times 10^{-5}$ (Coustenis et al. 2000a, Coustenis et al.

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ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

2001). The 2.9 methane "window" on Titan was observed in its full shape for the first time. It shows two peaks at 2.7 and 2.8 μm, and an absorption feature at 2.75 μm, which may be the spectral signature of a surface component on Titan (Coustenis et al. 2000a, Coustenis et al., 2000b).

Yet, the ISO/SWS part of the spectrum in the 17-27 μm (220-600 cm^{-1}) region was not exploitable (Fig. 1) due to the low S/N and to problems with the Saturn straylight. This was also the case with the ISO/LWS, which was inefficient in the 45-200 μm range for Titan, where a number of constituents (such as CO, HCN and its isotopes, CH_4 and H_2O) exhibit rotational lines that allow us to probe lower altitudes. The higher resolutions (in the Fabry-Pérot mode) were not achieved in any useful spectrum either. The shortcomings of ISO will be compensated in the future thanks to the advent of new space missions which can observe Titan, like Cassini and perhaps FIRST.

3. Titan's far-IR and submm spectrum

Thanks to the Voyager and the ISO data, we have a good coverage of Titan's infrared range. But its sub-mm region remains unobserved from space.

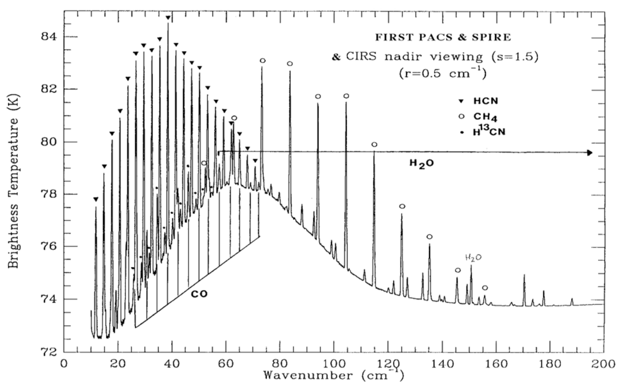

Figure 2. Titan's brightness temperature in the 50-200 cm^{-1} region at moderate resolution (0.5 cm^{-1}) as will be observed by CIRS/Cassini and as it could be observed by FIRST/SPIRE (and PACS but at higher resolution). The spectral signatures of the molecules expected to be present here are identified.

Indeed, Titan is expected to have a rich far-IR and submm spectrum (Coustenis et al. 1993). Pressure-induced N_2-N_2 and N_2-CH_4 absorptions are the dominant source of continuum opacity in this spectral region. Superimposed on this continuum are pure rotational lines of CH_4 (second most abundant atmospheric gas), HCN (a prebiotic molecule) and two oxygen-bearing compounds: CO (whose atmospheric abundance remains uncertain) and H_2O (Fig. 2). Some of these signatures are the only ones available for a given species in Titan's sub-mm and infrared spectrum (this is the case for CO, $H^{13}CN$ and H_2O). The latter was discovered in a number of planetary objects thanks to ISO/SWS observations (Coustenis et al. 1998, Feuchtgruber et al. 1997). The contribution function for N_2-N_2 opacity in this region indicates that the 40-70 km altitude range is sounded, whereas the emission observed in the gas lines originates mainly from the 70-150 km range.

Many of the rotational lines present in this region have never been observed, with the exception of CO and HCN recorded from ground-based heterodyne spectroscopy (Hidayat et al. 1997, Hidayat et al. 1998). The observation of these lines at high resolution (Fig. 3) provides information on their vertical profiles and isotopic ratios.

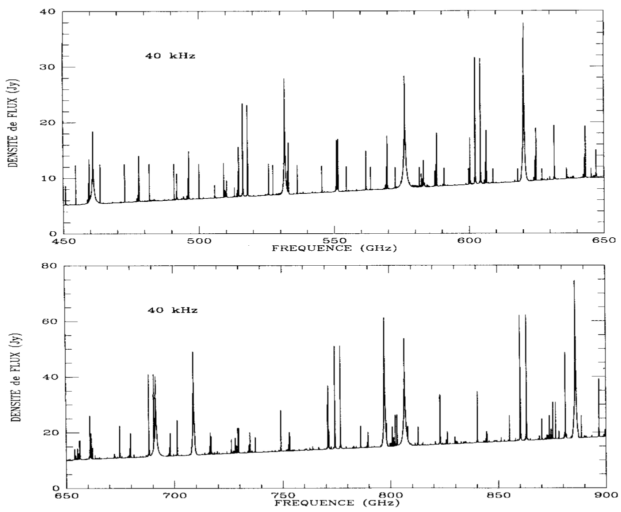

Figure 3. The 450-900 GHz region of Titan is calculated at high spectral resolution (40 kHz : corresponding to IRAM and possibly HIFI observations). The gaseous species identified on Fig. 2 are also shown here. The antenna temperatures are on the order of 0.5 K for IRAM, and 10 times less for FIRST.

Methane contributes to the emission in this part of the spectrum with about ten detectable rotational lines, which correspond to forbidden transitions. Although intrinsically weak in intensity, they should be detectable on Titan due to the large CH_4 stratospheric abundance ($\sim$ 2%). These lines are diagnostic of atmospheric levels from 70 to 150 km, thus complementing the information from the ν_4 methane band at 7.7 μm representative of the 150 to 400 km range (Coustenis & Bézard 1995). However, the contrast of the CH_4 rotational lines is more sensitive to the CH_4 mixing ratio because they are weaker than the allowed transitions in the ν_4 band. Combining the analysis of the two methane bands will simultaneously yield both the CH_4 mixing ratio and the temperature structure in the stratosphere.

4. Future missions

Complementing the Voyager and the ISO observations, the Cassini mission, carrying several instruments – of which the spectrometer CIRS – and destined to arrive around Saturn in 2004 for a 4-year nominal mission, will unveil many of the mysteries remaining about Titan, mainly by *in situ* measurements. The FIRST observatory, to be launched in 2007 (Fig. 4), may offer an additional subsequent opportunity to investigate this remote and outstanding object of our Solar System.

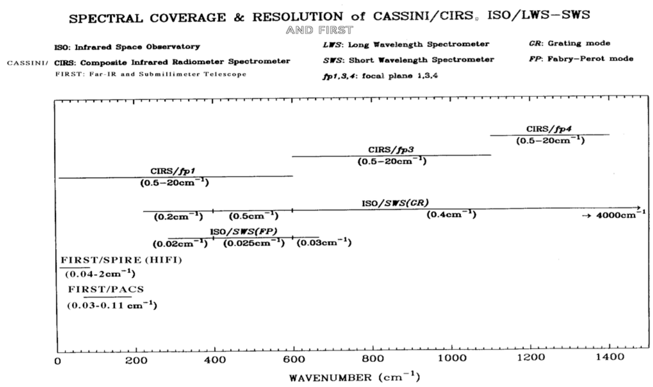

Figure 4. Spectral coverage and resolution of space missions related to Titan observations. ISO has efficiently explored Titan's spectrum in the major part of the 7-45 micron (200-1400 cm^{-1}) range with the SWS in the grating mode. In the future, the Cassini/CIRS instrument will observe Titan in situ in the 7-1000 μm (10-1500 cm^{-1}) range with moderate resolution. The FIRST instruments can offer valuable observations in the far-IR and the submm range, at high spectral resolutions.

4.1. Cassini/CIRS

The Cassini/CIRS instrument will make disk-resolved measurements of Titan's atmospheric composition and temperature above 70 km of altitude at moderate resolutions (Fig. 2). Observations of Titan by CIRS in the sub-mm and far-IR spectral region will allow a mapping of the atmospheric temperature and aerosol properties in the tropopause region and above. In particular, with focal plane 1 (*fp1*) the CIRS instrument will perform observations in the nadir mode and in the far-infrared, in order to map the stratospheric CH_4, HCN and CO from their rotational lines in this region (Fig. 2). CIRS will also search for new compounds. For the expected Titan observations with the CIRS instrument see Coustenis et al. (1993).

At a mean resolution of about 0.5 cm^{-1}, both CIRS and SPIRE may acquire data (as did ISO in the past), we are therefore considering together their capacities (Fig. 5). However, we do not compare them because their characteristics and objectives are different. Notably, for CIRS, one should bear in mind that the information obtained will be spatially resolved, as compared to ISO or FIRST where the spectrum is averaged over the disk (Titan's angular size being 0.8 arcsec). With FIRST/ PACS and HIFI, however, higher resolving powers are offered that might give access to additional information regarding Titan.

4.2. FIRST

Combining the SPIRE and PACS instruments one cover the 50-175 cm^{-1} region on Titan at moderate resolutions. Synthetic spectra in the associated conditions are shown in Figs 5 and 6. HIFI can reach higher resolving powers.

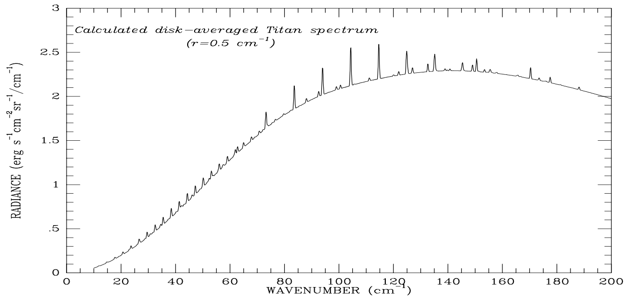

Figure 5. Titan's radiance in the 10-200 cm^{-1} region at moderate resolution (0.5 cm^{-1}) as could be observed by CIRS and by FIRST / PACS or SPIRE. The spectral signatures of the molecules expected to be present here are identified in Fig. 2.

a) PACS

The PACS spectrometer's detection limits in the 50-175 cm^{-1} range are 10 times better than ISO's and thus it should have a better chance with Titan's low flux. At resolving powers of 100-250 km/s, the point source detection limit of PACS (5σ, 1 hr) varies in the 2.5-4 $\times 10^{-18}$ Wm^{-2} range, with a spectral coverage of 0.575-1.15 cm^{-1} (Poglitsch et al. (2000)). At a resolution of 0.03 cm^{-1} (Fig. 6), the whole range could be covered in about 2.5 hrs with S/N ratios as given hereafter.

- **CH_4**: Both weak and strong methane lines appear in the 55-200 μm range, with fluxes from 20 to about 90 Jy over a continuum of 50-90 Jy (Fig. 6). With a sensitivity limit of about 2.6 $\times 10^{-18}$ Wm^{-2}, the weak line at $\sim$ 52 cm^{-1} (192 μm) will require 3 mns to be fully covered (3 spectral elements) with quite high S/N. The stronger lines, at $\sim$ 84, 104, 114 and 135 cm^{-1} (119, 96.2, 87 and 74 μm) can be covered (line + continuum) in about 1 mn each (+ overheads) with even higher S/N ratios. Intermediate lines exist at 73, 94 and 125 cm^{-1}.
- **H_2O**: Similarly to methane, the weak H_2O line (of 20 Jy) at 88 cm^{-1} (113 μm) will require about 3 mns to be covered with an excellent signal-to-noise ratio. The stronger lines, like the one near 150.5 cm^{-1} (66.5 μm), with fluxes of about 90 Jy will achieve even higher S/N in 1 mn.
- **CO**: The CO lines in this region are quite weak and should be observed at as high resolution as possible (Fig. 6). For the 15 Jy CO line at 57.5 cm^{-1} (173 μm) PACS will achieve a quite high S/N in 1 mn (2 spectral elements).
- **HCN**: On one of the strongest HCN lines, of 50 Jy, at 56 cm^{-1} (178 μm) PACS will achieve an excellent S/N in 1 mn (2 spectral elements), whereas its isotope $H^{13}CN$ at 55.5 cm^{-1}, with only 10 Jy, will reach a S/N of more than 1000 at the same time.

b) SPIRE

SPIRE is also more sensitive than ISO or CIRS and could allow the detection of new spectral signatures in the 15-50 cm^{-1} range. The adjustable spectral resolution varies from 0.04-2 cm^{-1} (Griffin et al. 2000).

- In spectroscopy, the 15-50 cm^{-1} region could be covered by the FTS with a resolution of ~ 0.04 cm^{-1} and S/N of 700 or higher in 1 hr (+ overheads).
- In spectrophotometry, the weak HCN and CO lines (of 1-2 Jy at 0.5 cm^{-1} resolution, Fig. 5) in the same region, can be covered in 1 hr with S/N of 30-100.

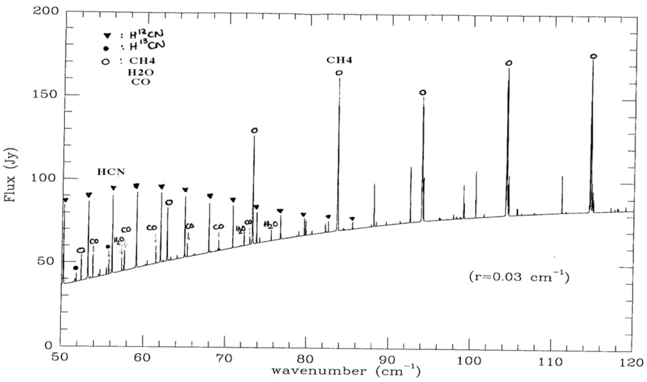

Figure 6. The 50-120 cm^{-1} region of Titan is calculated at high resolution as could be observed by FIRST/ PACS or SPIRE.

c) HIFI

The Heterodyne Instrument for FIRST will cover the 492 to 1113 GHz spectral range with resolving powers of 5×10^5 to 1.2×10^7 (Whyborn 1997). Titan has been observed from the ground from various telescopes and in particular with the 30-m IRAM radiotelescope at Grenada, Spain in the 80-270 GHz range and with the JCMT in Hawaii at frequencies longer than 300 GHz. These Titan observations have yielded precious information on the abundances and distributions of HCN and CO (Hidayat et al. 1997, Hidayat et al. 1998) with, in addition, the detection for the first time of acetonitrile (CH_3CN) on Titan (Bézard et al. 1993). The spectrum of Titan as could be observed with HIFI in the 450-900 GHz range at a resolution corresponding to the HIFI higher capability of 1.2 $\times10^7$ is shown in Fig. 3 (from Hidayat, 1997).

With respect to IRAM, FIRST will have the advantage of covering frequencies not available from the ground due to the Earth's atmospheric interference. On the other hand, the FIRST telescope being smaller (by a factor of about 10 with respect to IRAM), the antenna temperature will be 10 times lower than as observed with IRAM, where about 0.5 K were reported at 220 GHz (Bézard et al. 1993). A temperature of 0.05 seems to be under the 0.1 K noise level at 500 GHz (Table 3 of Whyborn (1997)). Thus, it may be that HIFI will not be able to observe the weak lines in Titan's submm spectrum.

5. Perspectives for Titan

It is obvious that in the case of Titan, the Cassini mission will produce a great amount of new results that will significantly enhance our knowledge of the satellite. The advantage of CIRS is the spatial resolution and also the possible correlation with measurements from the Huygens probe. However, CIRS will operate at a resolution of 0.5 cm^{-1} at best. It may be the case that this is not sufficient to extract precise and extended vertical distributions of CO and HCN because they have very weak lines (Fig. 5). The CO distribution is currently uncertain, while it brings clues to the satellite's origin. The methane distribution was to have been attemped with the ISO LWS Fabry-Pérot, but was not succesful.

The water lines on Titan (two of which were discovered by ISO/SWS at a resolution of 0.12 cm^{-1}), may not be resolved by CIRS. They could be monitored with PACS and new information on the spatial distribution of H_2O, as well as on its influx at Titan could then be recovered. This information is important, when compared with the Saturn influx also derived by ISO (Feuchtgruber et al. 1999), because it yields insights on the production rate of dust in the Saturnian system. The current measurements from ISO are still not precise enought to allow us to distinguish between the various possible sources of the water in the vicinity of Titan. A few rotational lines of CH_4 could be detected with PACS or HIFI (Fig. 6).

Hence, since higher resolutions are required, even if the CIRS measurements are succesful, the FIRST instruments are well adapted for Titan and could offer the possibility to significantly complement the outcoming of the Cassini mission.

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