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LETTER

Letter to the Editor

First results of ISO-SWS observations of Saturn: detection of CO_2, CH_3C_2H, C_4H_2 and tropospheric $H_2O^{\star}$

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Abstract. The spectrum of Saturn has been recorded between 4.5 and 16.0 μm with the grating mode of the Short-Wavelength Spectrometer (SWS) of ISO. The resolving power is 1500. The main results of this observation are (1) the detection of CO_2, CH_3C_2H and C_4H_2 in the stratosphere and (2) the detection of H_2O in the troposphere. In the 4.5–5.5 μm range, information is retrieved on the tropospheric composition (NH_3, PH_3, AsH_3, GeH_4, CH_3D and H_2O) down to pressure levels of several bars. Above 7 μm, the Saturn spectrum probes the upper troposphere and the lower stratosphere, at pressure levels ranging from 0.5 bar to 0.4 mbar. The CH_4 emission band at 7.7 μm and the H_2-He continuum longward of 11 μm are used to retrieve the thermal profile, which is then used to derive the vertical distributions of minor species: NH_3, PH_3, CH_3D in the troposphere, and C_2H_2 and C_2H_6 in the stratosphere. Estimates of the CO_2, CH_3C_2H and C_4H_2 mean mixing ratios (above the 10-mbar level) are $3\ 10^{-10}$, $6\ 10^{-10}$ and $9\ 10^{-11}$ respectively. The retrieved disk-averaged thermal profile is found to be colder in the stratosphere than the Voyager 1 ingress radio-occultation profile by about 7 K at P = 0.5 mbar, and slightly warmer in the troposphere (about 5 K at 400 mbar and 3 K at 150 mb).

Key words: Planets - Saturn - infrared: solar system

1. Introduction

The spectrum of Saturn is characterized by a solar reflected component and a thermal component, corresponding to the internal heat source and to the absorbed part of the solar energy. At $\lambda > 4$ μm, thermal radiation prevails, with some contribution from the reflected component up to about 7 μm. In the thermal range, spectral signatures strongly depend upon the thermal profile, which shows a temperature inversion at the tropopause, at a pressure level of about 0.1 bar. Depending upon the region where they are formed, below or above the tropopause (troposphere or stratosphere), molecular signatures appear in absorption or in emission respectively.

Previous spectra of Saturn have been recorded in the 4.5–5.2 μm window, from the ground (Noll and Larson, 1990) and from the KAO (Larson et al., 1980). The IRIS-Voyager infrared spectrometer recorded the spectrum of Saturn between 5 and 50 μm (Hanel et al., 1981). The Voyager observations were limited to a spectral resolution of 4.3 cm^{-1} (resolving power ranging from 50 to 500) and a sensitivity of about 1000 Jy per spectrum. The ISO SWS spectrum offers for the first time a continuous spectral coverage from 2.3 to 45 μm, a resolving power of 1500

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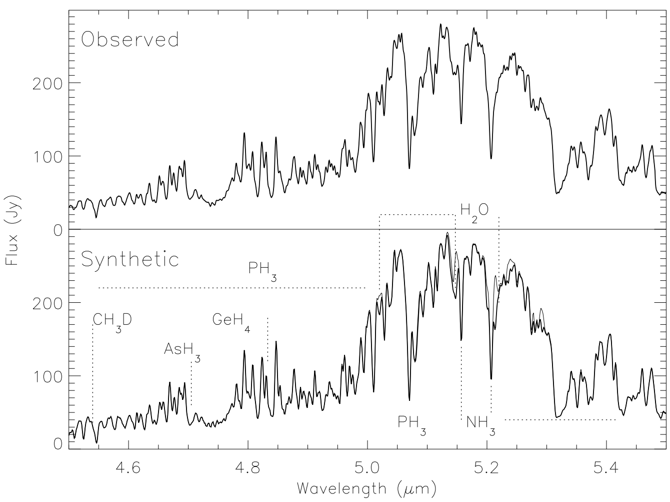

Fig. 1. Observed ISO-SWS spectrum (upper curve) and synthetic spectrum of Saturn (lower curve) in the 5-μm region. Spectral absorptions are due to NH_3, PH_3, AsH_3, GeH_4, CH_3D and H_2O. In the lower curve, the narrow line corresponds to a calculation without H_2O.

and a sensitivity limit better than 1 Jy. We report here on the observed spectrum between 4.5 μm and 16.0 μm.

2. Observations

The SWS grating spectrum of Saturn was recorded on June 15, 1996. Descriptions of the ISO satellite and the SWS instrument can be found in Kessler et al. (1996) and de Graauw et al. (1996) respectively. The SWS flux and wavelength calibrations are described in Schaeidt et al. (1996) and Valentijn et al. (1996). The aperture (14”x20” below 12.5 μm, 14”x27” above) was centered on the center of Saturn’s disk, with the long axis aligned perpendicular to the ecliptic, and thus roughly aligned with the central meridian (polar angle = 3.6 deg.). The exposure time was 110 minutes. The resolving power is about 1500, and the estimated accuracy of the flux scale is about 20 percent. In addition to the standard reduction, the 14–16 μm region was subsequently FFT filtered in order to minimize the distortions by the instrumental fringing.

3. Interpretation

3.1. The 4.5–5.5 μm region

As for Jupiter, the 5–μm window of Saturn’s spectrum probes the troposphere, in the 2–5 bar pressure range. The 5–μm Saturn window has been studied from the KAO by Fink and Larson (1978) and Larson et al. (1980), at a slightly higher resolution (R = 2500), but lower sensitivity than the ISO data. The 4.5–5.0 μm region was also studied from the ground at high spectral resolution (above 20000) by Noll et al. (1986, 1988, 1989), Noll and Larson (1990) and Bézard et al. (1989), leading to the detection of CO, GeH_4 and AsH_3 in Saturn’s troposphere.

As pointed out by Bézard et al. (1989), a major difference between the Jupiter and Saturn spectra in the 5–μm window is the presence, in the case of Saturn, of a significant contribution coming from reflected sunlight. This is a consequence of the lower temperature of the tropospheric region of Saturn probed at 5 μm, which gives a much lower thermal emission at this wavelength as compared to Jupiter. Another difference between the Jupiter and Saturn spectra lies in the lower abundance, in Saturn’s upper troposphere, of NH_3 and H_2O, and the much larger abundance of PH_3.

Figure 1 shows a comparison between the Saturn spectrum and a synthetic calculation. A cloud layer at 0.55 bar, with a transmission of 0.9, reflects the sunlight. Another deeper cloud, around 1.55 bar, with a transmission of 0.2, acts as a grey absorbing layer for the thermal emission coming from lower tropospheric levels. Calculations show that the synthetic spectrum is not strongly sensitive to the altitudes of these clouds. In the calculations of the thermal component, contributions due to AsH_3, GeH_4, NH_3, PH_3, CO, CH_3D and H_2O were included with the following mixing ratios: $AsH_3/H_2 = 2.0\ 10^{-9}$, $GeH_4/H_2 = 2.0\ 10^{-9}$, $NH_3/H_2 = 1.0\ 10^{-4}$, $PH_3/H_2 = 4.4\ 10^{-6}$, $CO/H_2 = 1.8\ 10^{-9}$, $CH_3D/H_2 = 3.2\ 10^{-7}$ and $H_2O/H_2 = 2.0\ 10^{-7}$. CO is only very marginally detected. The GeH_4 and CH_3D abundances bear a large uncertainty. The abundances of PH_3, GeH_4 and AsH_3 in the upper troposphere, affecting the solar reflected component, have to be lowered to fit the spectrum, as first discussed by Noll et al. (1989), Noll and Larson (1990) and Bézard et al. (1989), and a vertical profile decreasing with height was introduced for these molecules. The ISO-SWS spectrum shows the first evidence for tropospheric H_2O on Saturn. An acceptable overall fit of the H_2O lines is obtained with a constant mixing ratio of 2 10^{-7} below the 3–bar level, and a cutoff at higher altitudes. Saturated profiles give too large absorption features for H_2O, which implies tropospheric water undersaturation; a similar result was recently found in the case of a Jovian hot spot by the Galileo probe (Niemann et al., 1996), confirming previous ground-based measurements (Bjoraker et al, 1986). The NH_3 vertical abundance is also strongly depleted above the 1.2–bar level in the model, to account for saturation. The synthetic and observed spectra agree within 2.5% between 4.5 and 5 μm. Our determinations of the AsH_3 and PH_3 mixing ratios are in good agreement with the results of Bézard et al. (1989) and Noll and Larson (1990), while our value of the GeH_4 mixing ratio is 1.6 to 2 times higher than their values; our NH_3 value is consistent with the upper limit (3 10^{-4}) set by Noll and Larson (1990). The ISO spectrum confirms the oversolar abundance of phosphorus in the deep atmosphere of Saturn. In contrast, the abundance of NH_3 at 5 μm corresponds to a N/H ratio closer to the solar value. It should be mentioned that all these measurements are still preliminary.

3.2. The 7–15 μm region

The atmospheric region probed by the 7–15 μm spectrum is the upper troposphere and the lower stratosphere of Saturn. The corresponding pressure levels range from about 0.5 bar at 9 μm to about 0.4 mb in the Q–branch of the ν_4 CH_4 band at 7.7 μm. Figures 2 and 3 show a comparison between the ISO data and

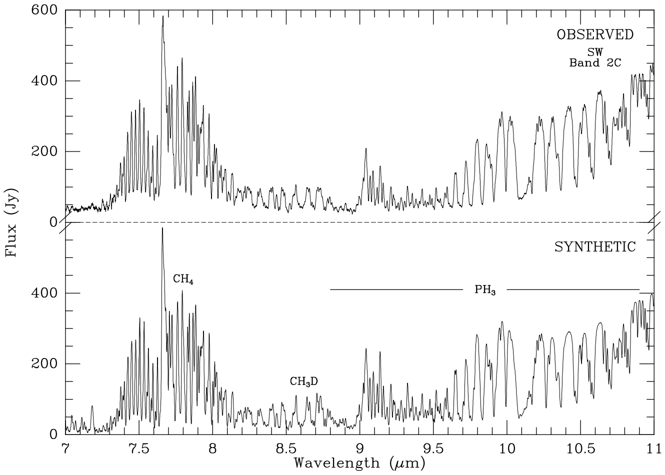

Fig. 2. Comparison between the Saturn ISO-SWS data (above) and a synthetic model (below) in the 7–11 μm range. The spectrum shows stratospheric emission features due to CH_4, and tropospheric absorption features due to CH_3D, PH_3 and NH_3.

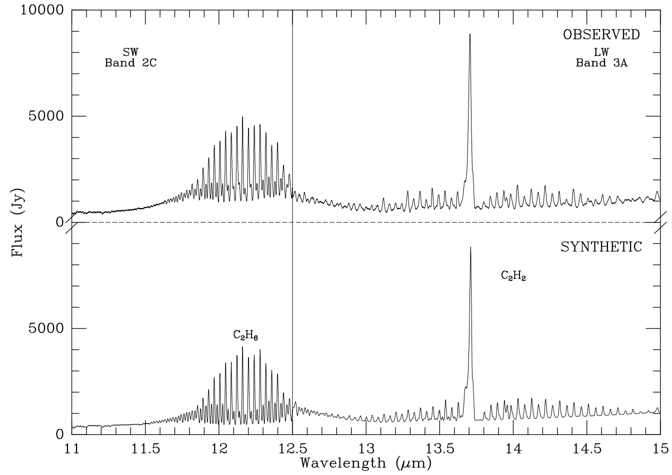

Fig. 3. Observed ISO-SWS spectrum of Saturn (upper curve) and synthetic spectrum (lower curve) between 11 and 15 μm. Molecular emissions are due to C_2H_6 and C_2H_2.

a nominal synthetic spectrum in the 7 –11 μm and 11 – 15 μm range respectively. Between 7 and 11 μm, the observed spectrum exhibits stratospheric emission features due to CH_4 (ν_4 band), and tropospheric absorption features from CH_3D (ν_6), PH_3 (ν_4 and ν_2) and NH_3 (ν_2). The 11 – 15 μm range shows emissions by C_2H_6 (ν_9) and C_2H_2 (ν_5).

We present here a first attempt to model the ISO spectrum. Our fit is quite satisfactory, except in the 7.0-7.2–μm region where the observed spectrum shows more flux than the model. We first determined a temperature profile which allowed us to reproduce the H_2–He continuum between the molecular features, and the 7.7–μm methane band assuming a mixing ratio of 4.4×10^{-3} in the lower stratosphere and troposphere (Courtin et al., 1984). In the stratosphere, this profile is colder (by $\sim$7 K at 0.5 mbar) than the Voyager radio–occultation profile recorded at 36°N in 1981, whereas the tropospheric part is warmer (by $\sim$5 K at 400 mbar and $\sim$3 K at 150 mbar). Spatial or temporal variations might be responsible for the differences observed between the Voyager profile, measured in a single point, and the present disk-averaged profile, retrieved 15 years later.

We used a CH_3D mixing ratio of 3.2×10^{-7}, as derived from previous 5–μm investigations (Bézard et al., 1989; Noll and Larson, 1990) and in agreement with our 5–μm model. A PH_3 profile with a mole fraction of $\sim4.5\times10^{-6}$ below 600 mbar (as derived from the 5–μm spectrum), decreasing to $\sim2.5\times10^{-6}$ at 300 mbar, and sharply depleted above, allowed us to reproduce the various absorption features observed between 8.8 and 11.1 μm. No emission was observed in the core of the strong Q–branches from the ν_2 (10.1 μm) and ν_4 (8.95 μm) bands, indicating that the stratospheric abundance of PH_3 is negligible in contradiction with the analysis of Voyager spectra by Courtin et al. (1984). The cutoff of the PH_3 vertical distribution in Saturn's atmosphere around the 300–mbar level is quite consistent with the analysis of PH_3 rotational multiplets detected in the ISO-LWS spectrum of Saturn (Davis et al., 1996). The C_2H_6 mixing ratio in our model is held constant at 4×10^{-6} above the 10–mbar level, in agreement with Courtin et al. (1984). We infer a C_2H_2 mixing ratio of $\sim3.5\times10^{-6}$ at 0.1 mbar decreasing to $\sim2.5\times10^{-7}$ at 1 mbar. This abundance is slightly higher than the Voyager determination (Courtin et al., 1984). The decrease with depth, expected from photochemical models, is needed to reproduce the relative strengths of the fundamental ν_5 and the associated hot band $2\nu_5 - \nu_5$. A few weak absorption features from NH_3 are detected and can be reproduced with a mixing ratio profile having a $\sim$50% humidity.

3.3. Detection of CO_2, CH_3C_2H, and C_4H_2

Figure 4 shows the Saturn spectrum observed between 14 and 16 μm. As mentioned above (Section 2), a procedure was applied to these data to remove some of the instrumental fringes that affect observations in Band 3A. This treatment also modified the intensities of the lines from the C_2H_2 P–branch, which are then fitted with a mixing ratio profile 30% lower than before. This illustrates that the present uncertainty on the C_2H_2 mixing ratio derived from ISO cannot be better than 30%.

Besides the components of the C_2H_2 P–branch, the spectrum clearly shows an emission peak at 14.98 μm, a position where no C_2H_2 line is expected. We attribute this emission to the strong Q–branch of the CO_2 ν_2 band. A possible fit of this feature is obtained with a CO_2 mixing ratio of about 3×10^{-10} above the 10–mbar pressure level, assuming that this ratio is constant with height. The corresponding column density is 9×10^{14} molecule cm^{-2}. Smaller amounts are still consistent with the data if CO_2 is located higher in the stratosphere. We note that the CO_2 emission feature is not sensitive to the CO_2 abundance below the 10–mbar level. Carbon dioxide may indirectly originate from the infall of oxygen bearing material. The recent detection of H_2O emission lines in the ISO–SWS spectra of Saturn, Uranus, and Neptune (Feuchtgruber et al., 1996) gives evidence for such an exogenic source of material, which may originate from Saturn's

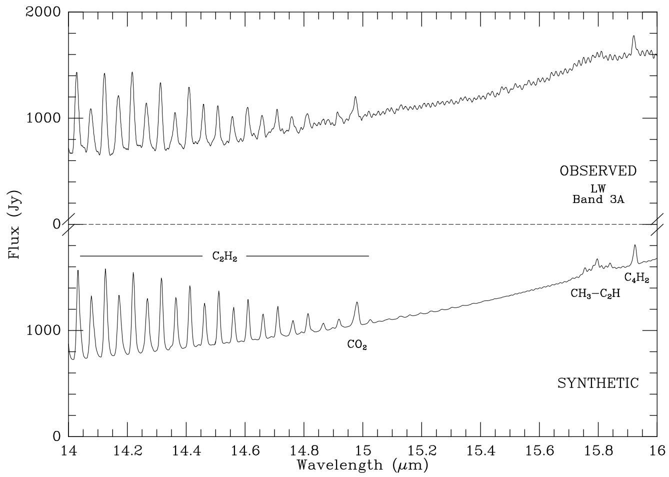

Fig. 4. Observed ISO-SWS spectrum of Saturn (upper curve) and synthetic spectrum (lower curve) between 14 and 16 μm. The 14.98 μm emission feature is attributed to CO_2. Emission from C_4H_2 (15.92 μm) and CH_3–C_2H (around 15.8 μm) are also detected. Below 15 μm, lines from the P–branch of the ν_5 band of C_2H_2 dominate the spectrum.

rings, moons, or interplanetary particles (Connerney and Waite, 1984). Reaction of CO with the OH radical, formed through photolysis of H_2O molecules, appears as a possible mechanism for the production of CO_2. Detailed modelling of the Saturn CO_2 emission feature and investigation of its production through photochemical processes will be presented in a forthcoming publication.

The spectrum also shows an emission peak from the ν_8 band of diacetylene (C_4H_2) at 15.92 μm, and a broad emission feature centered at 15.8 μm due to the ν_9 band of propyne (or methylacetylene, CH_3C_2H). These two species are produced by methane photodissociation. The observed features can be reproduced with constant mixing ratios of 9×10^{-11} (C_4H_2) and 6×10^{-10} (CH_3C_2H) above the 10–mbar level. The corresponding column densities are about 3×10^{14} and 2×10^{15} molecule cm^{-2} respectively. No constraints on the actual vertical distribution of these species in the stratosphere are available from the data. These two gases are produced by photochemistry of methane occuring in the upper atmosphere of Saturn. Comparison of the ISO observations with predictions from photochemical models is deferred to a subsequent publication.

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