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First results of ISO-SWS observations of Jupiter*

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Abstract. The spectrum of Jupiter has been recorded between 2.75 and 14.5 μm with the grating mode of the Short-Wavelength Spectrometer (SWS) of ISO. The resolving power is 1500. The main preliminary results of this observation are (1) at 3 μm, the first spectroscopic signature, probably associated with NH_3 ice, of the Jovian cloud at 0.5 bar and (2) the first detection of a thermal emission at the center of the CH_4-ν_3 band at 3.3 μm, showing evidence for a high temperature in the upper jovian stratosphere (T=800 K at P=0.16 microbar). In addition, the R(2) HD line has been detected for the first time in Jupiter, using the Fabry-Pérot (FP) mode of the SWS, with a resolving power of 31000. A preliminary analysis of the HD line indicates a D/H ratio of about 2.2 10^{-5}.

Key words: planets – Jupiter – infrared: solar system

1. Introduction

The spectrum of Jupiter 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, molecular signatures, dominated by CH_4, NH_3 and H_2, are seen in absorption superposed on the solar continuum. In the thermal range, spectral signatures strongly depend upon the thermal profile. Depending upon the region where they are formed (troposphere or stratosphere), molecular signatures appear in absorption or in emission respectively.

The infrared spectrum of Jupiter extends over a very large dynamical range (from over 1000 Jy at 2.7 μm down to a few Jy around 3.3 μm, and then up to several ten thousand Jy at 15 μm). Previous spectra of Jupiter have been recorded from the ground in a few windows (3.4-3.8 μm, 4.5-5.2 μm, 7-13 μm) and with the IRIS infrared spectrometer of the Voyager spacecrafts between 5 and 50 μm (Hanel et al, 1979). 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 2.4 to 45 μm, a resolving power of 1500 and a sensitivity limit better than a Jy. We report here on the observed spectrum between 2.75 μm and 14.5 μm.

2. Observations

The SWS grating spectrum of Jupiter was recorded on April 12, 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 μm, 14"x27" above) was centered on the center of the Jovian disk, with the long axis aligned perpendicular to the Ecliptic, and thus roughly aligned with the central meridian (polar angle = 352 deg.). The exposure time was 110 minutes. The grating spectrum was convolved to a resolving power of 1500 over the whole spectral range.

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The rotational R(2) line of HD was detected for the first time in Jupiter on March 29, 1996, using the FP mode of SWS, at a wavelength of 37.70 μm. The aperture (17"x40") was also positioned along the North-South axis, and thus roughly aligned with the Jovian polar axis, covering the whole Jovian diameter. The exposure time was 45 minutes. The resolving power was 31000, corresponding to a FWHM of 0.0012 μm.

The calibration data still exhibit some jumps between the different spectral bands, due to uncertainties in the relative spectral response function; the flux scale is thus still preliminary, with an estimated accuracy of 20 percent.

3. Interpretation

3.1. The 2.75-3.2 μm region

The Jovian spectrum shows the NH_3-ν_1 absorption band, observed for the first time, with its Q-branch clearly visible at 3.0 μm, superposed on the solar continuum. This continuum is reflected by a cloud level at 0.55 bar, which has been assumed in the literature to be NH_3 ice, on the basis of thermochemical models. Figure 1a shows the ISO data compared to two synthetic models, calculated with a nominal NH_3 gaseous distribution above the cloud. Model 1, which assumes a constant cloud albedo as a function of wavelength, provides a very poor fit to the data. This demonstrates the need to introduce a cloud effective albedo which varies with wavelength. In order to retrieve the general shape of the albedo curve, the synthetic spectrum with constant albedo was divided by the ISO spectrum and smoothed to a very low spectral resolution. The retrieved effective albedo decreases from 0.19 at 2.75 μm down to 0.05 at 2.85 μm and 0.027 at 2.95 μm, and stays constant up to 3.2 μm. Model 2 of Fig.1a shows the final fit obtained with the retrieved albedo. It can be noted that the general shape of the retrieved effective albedo shows some analogy with the general shape of the reflection spectrum of NH_3 ice (Fink and Sill, 1982). Laboratory measurements of the NH_3 ice absorption coefficient indicate, in particular, a sharp maximum near 3 μm. There is thus some indication that the Jovian spectrum in the 2.75-3.2 μm range shows the spectral signature of the NH_3 ice cloud, either pure or possibly mixed with other species. It can be noticed that, although suspected to be NH_3 ice for a long time, the Jovian cloud at 0.5 bar has never been spectroscopically identified as such. The ISO spectrum provides a first information about its chemical composition.

3.2. The 3.2-3.6 μm region

The 3.2–3.6 μm range clearly shows the CH_4-ν_3 band in emission, at a level of about 10 Jy (Fig.1b). Strong CH_4 emissions have long been observed in Jupiter, but only in the auroral regions. Synthetic calculations with an isothermal profile around 180 K in the upper stratosphere are unable to reproduce the level of emission observed by ISO. As for auroral modeling of infrared emission, a family of thermal profiles are able to reproduce the observed emission, either by a strong heating of the upper, or by a moderate heating in the lower stratosphere

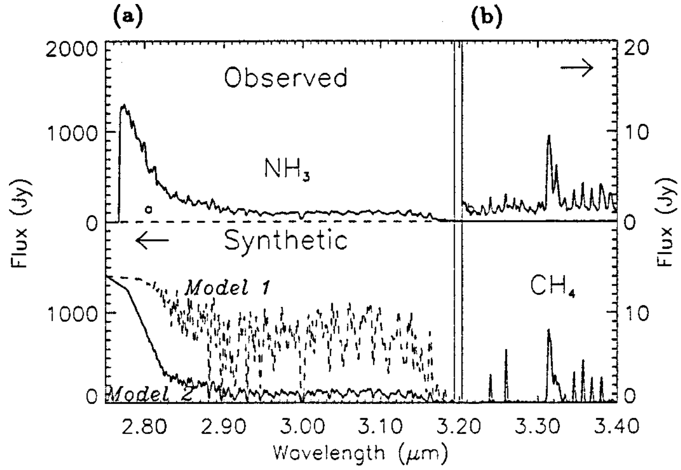

Fig. 1. (a) Observed ISO-SWS spectrum of Jupiter (upper curve) and synthetic spectrum (lower curve) between 2.75 and 3.2 μm. Molecular absorptions are due to NH_3, CH_3D and CH_4. Model 1: constant albedo cloud; Model 2: albedo-varying cloud. (b) ISO-SWS spectrum of Jupiter in the spectral range of the ν_3 band of CH_4 (upper curve), and synthetic spectrum calculated with upper atmospheric heating (lower curve).

(Drossart et al, 1993). A preliminary attempt to fit the ν_3 emission is shown in Figure 1b, with a temperature profile raising from 193 K at a pressure level of 2 μbar, to 800 K at 0.16 μbar. Such thermal profiles imply an increase of the ν_4 emission at 7.7 μm by about 60 percent. This effect can be countered by modifying the thermal profiles by a few degrees in the lower stratosphere at 1 mbar, and can be therefore consistently handled with the long wavelength interpretation of the ISO spectrum (see 3.4). On the other hand, deeper modifications of the thermal profile (P>2 μbar) would modify by a larger amount the ν_4 emission. The thermal profile presented here, although preliminary, is therefore likely to give a better overall agreement with the ISO observations in the whole spectral range. In addition to the CH_4 emission, a small continuum can be seen at a level of 0.8 Jy. This continuum could be due either to CH_4 hot bands, not taken into account in these preliminary calculations, or to a very high altitude component of a reflecting haze. Fluorescence in the CH_4 ν_3 band is expected at a level lower than 1 Jy, using Jupiter non-LTE parameters as in Drossart et al (1993).

There are various observational indications of a significant heating of the jovian upper stratosphere and thermosphere, in particular from H_3^+ observations (Marten et al, 1994) and from the Galileo measurements (Seiff et al, 1996). Several interpretations have been proposed for this heating. The interpretation by precipitating particles is favoured in view of some recent developments in Jupiter upper atmosphere modeling (Waite et al, 1996). Another possible heating source could be associated to gravity waves breaking in the stratosphere (Yelle et al, 1996).

At wavelengths larger than 3.4 μm, the Jovian spectrum shows a superposition of thermal emission lines, due to CH_4 and H_3^+, and reflected solar light showing up in a few windows between the strong CH_4 absorption features. Toward longer wave-

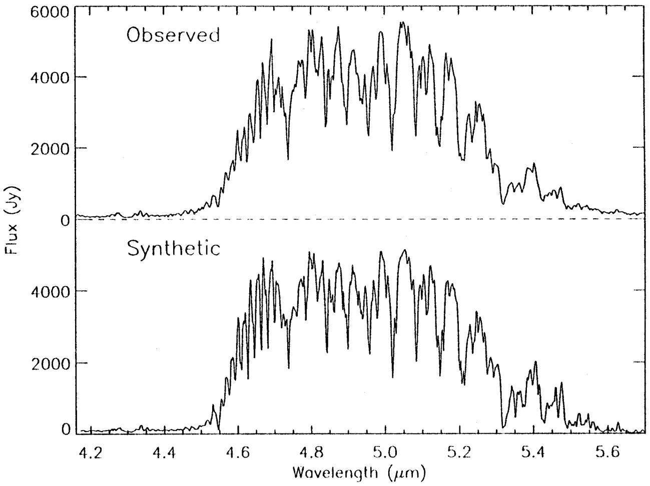

Fig. 2. Observed ISO-SWS spectrum (upper curve) and synthetic spectrum of Jupiter (lower curve) in the 5 micron region. Spectral absorptions are due to NH_3, PH_3, H_2O, GeH_4 and CH_3D.

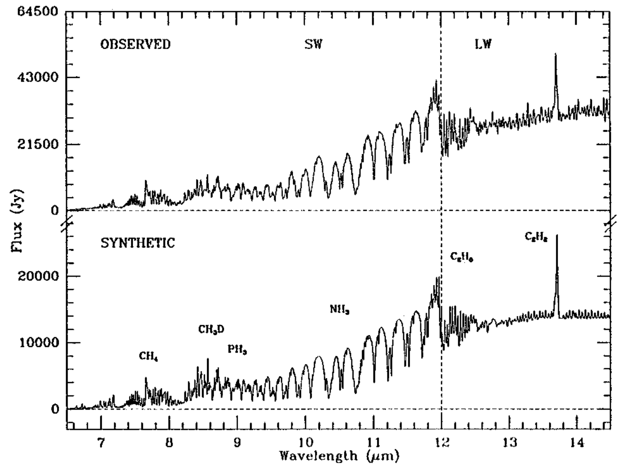

Fig. 3. Comparison between the Jupiter ISO/SWS data (above) and a synthetic model (below) in the 6.5-14.5 micron range. The spectrum shows stratospheric emission features due to CH_4, C_2H_6 and C_2H_2, and tropospheric absorption features due to CH_4, CH_3D, PH_3 and NH_3.

lengths, the reflected component peaks at 3.7 μm and decreases again due to the absorption by the ν_1 and ν_3 bands of PH_3.

3.3. The 4.5-5.5 μm region

The Jovian spectrum in this spectral range probes the deep troposphere of Jupiter at pressure levels between 2 and 5 bar. The size of the window is limited by the PH_3 ν_1 and ν_3 bands on the blue side and by the NH_3 $2\nu_2$ and ν_4 bands on the red side. Absorption signatures due to CH_3D (ν_2 band), CO (1-0), GeH_4 (ν_3 band), and H_2O (ν_2 band) are also clearly visible. The ISO data provide new information in the 4.2-4.5 μm range, where the very low signal allows to probe the Jovian PH_3 distribution in the upper troposphere, and the 5.2-5.5 μm range, dominated by NH_3 and H_2O signatures. Fig.2 shows a comparison between the ISO data and a nominal atmospheric model of Jupiter (mostly derived from Voyager), using the following parameters (q is the tropospheric mole fraction): q(NH_3) =1.75 10^{-4} (Kunde et al, 1992); q(PH_3)=6.0 10^{-7} (Kunde et al, 1982), q(H_2O) =1.38 10^{-5}, i.e. 1 percent of the solar value (Sromovsky et al, 1996); q(GeH_4)= 2.0 10^{-10}; q(CH_4)=2.1 10^{-3}; q(CH_3D)=2.5 10^{-7}, which corresponds to D/H = 2.2 10^{-5} (see 3.5) and a fractionation factor of 1.37 (Beer and Taylor, 1978) . There is a cloud layer at 1.55 bar, consistent with the Galileo probe measurements (Ragent et al, 1996); a transmittance of 0.09 for this layer provides a good fit of the continuum. A low albedo (0.03) of the reflecting cloud at 0.55 bar is needed to fit the 4.3 μm region. It should be pointed out that the ISO data can be fitted with a model including a highly subsolar abundance of H_2O, as suggested by the recent Galileo results.

3.4. The 6.5-14.5 μm region

The atmospheric region probed by the 6.5-14.5 μm spectrum is the upper troposphere and the lower stratosphere. The corresponding pressure levels range from about 0.5 bar at 9 μm to about 1 mb in the Q-branch of the ν_4 CH_4 band at 7.7 μm. Figure 3 shows a comparison between the ISO data and a nominal synthetic spectrum between 6.5 and 14.5 μm. The spectrum exhibits stratospheric emission features due to CH_4 (ν_4 band), C_2H_6 (ν_9) and C_2H_2 (ν_5), and tropospheric absorption features due to CH_4 (ν_4 and ν_2 bands), CH_3D (ν_6), PH_3 (ν_4 and ν_2) and NH_3 (ν_2). The model parameters are as follows: the temperature and NH_3 vertical profiles are from Bézard et al. (1996); the CH_4 profile is from Gladstone et al.'s (1996) standard model while we used their C_2H_2 profile multiplied by a factor of 0.3; the C_2H_6 mixing ratio is 4.0 10^{-6} between 0.3 and 50 mbar and decreases rapidly outward of this pressure range; we used the PH_3 distribution from Kunde et al. (1982); the CH_3D mixing ratio is 2.5 10^{-7}. A grey cloud, presumably NH_3 ice (see 3.1), with τ = 0.6, is included between 0.67 and 0.3 bar. It should be mentioned that the flux scale is still preliminary.

3.5. The HD R(2) line and the D/H ratio

Figure 4 shows the HD R(2) line at 265 cm^{-1} (37.7 μm), detected for the first time in a planetary atmosphere. The line shows up as a 10 percent deep absorption feature at the instrumental resolution. In order to account for the specific observing geometry, the radiative transfer equation must be integrated over very different airmass conditions with proper weights. Furthermore, Doppler shift effects due to Jupiter's differential rotational velocity between the two long sides of the slit are significant at the very high spectral resolution of the observation. We have accounted for these effects in a simplified way. A full 2-D model is necessary for an exact calculation, but for this preliminary interpretation, we simply integrated the radiative transfer equation over the polar axis direction (assumed to be identical to the long side of the slit), assigning a single airmass for all points located on a line parallel to the small side of the aperture. We also neglected cloud opacity effects at this point, although tempera-

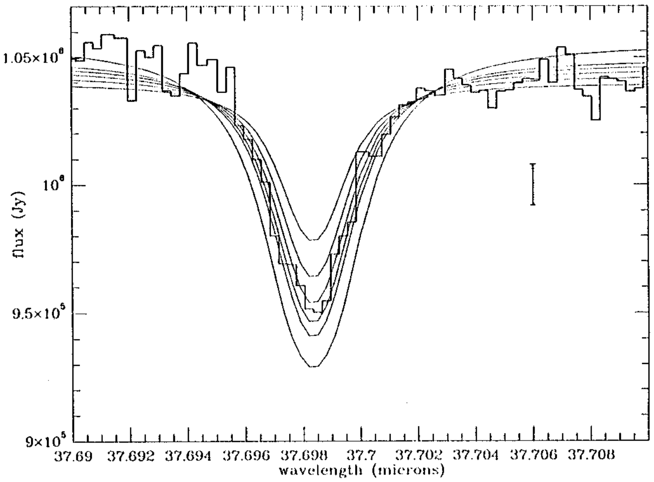

Fig. 4. The SWS/FP spectrum of Jupiter, at a resolution of 31000 (histograms). The 2-σ error bar is indicated. Solid lines show models with various values of HD/H_2. From top to bottom: HD/H_2 = (2, 3, 4, 5, 6, 10) 10^{-5}.

ture maps in the Voyager/IRIS spectra suggest these effects are present (Conrath and Gierasch 1986). Adding a cloud opacity would result in an increase of the D/H ratio. As shown in Fig. 4, the best fit (without cloud opacity) is obtained for HD=4.4 10^{-5}, i.e. D/H=2.2 10^{-5}. The formal error bar on D/H is +/- .5 10^{-5}, but true error bars are certainly larger given the preliminary character of the model. Fig. 4 also illustrates that the Galileo-derived value for D/H (5+/-2 10^{-5}) produces too deep an absorption. On the other hand, a D/H value of about 2.2 10^{-5} is fully consistent with that inferred from 5 μm spectroscopy by Bjoraker et al. (1986) (2.1+/-0.6 10^{-5}) and with estimates of the protosolar value (Geiss, 1993) It also agrees with the preliminary value inferred from ISO/LWS measurements of the HD R(1) line at Saturn (Griffin et al., 1996). Our results, however, should be viewed as preliminary until a more detailed modelling is performed.

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