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Letter to the Editor

ISO observations of Uranus: The stratospheric distribution of C_2H_2 and the eddy diffusion coefficient

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Abstract. The infrared spectrum of Uranus has been recorded between 7 and 16.5 μm with the grating mode of the Short-Wavelength Spectrometer of ISO, with a resolving power of 1500. The 6–12 μm spectrum of Uranus has also been recorded at lower resolution (R=90) by the PHOT instrument in spectroscopic mode. The spectra show no signatures other than the C_2H_2 band centered at 13.7 μm. From the absence of emission in the region of the CH_4 7.7 μm band, and by fitting the C_2H_2 data on the basis of a photochemical model, the eddy diffusion coefficient is retrieved (in the range 5 10^3–10^4 cm^2 s^{-1} at the homopause). This result is consistent with the values previously derived from the Voyager UV occultation experiments.

Key words: planets and satellites – Uranus – infrared: solar system

1. Introduction

The stratosphere of Uranus is characterized by a very low value of the eddy diffusion coefficient. The mean stratospheric temperature was first retrieved in the pressure range 0.3–30 μbar from ground-based stellar occultation measurements (Dunham et al., 1980; French et al., 1983; Sicardy et al., 1985). C_2H_2 was detected from UV spectroscopy using IUE (Caldwell et al., 1984; Encrenaz et al., 1986), and from low-resolution IR ground-based data (Orton et al., 1987). The most precise measurements of Uranus stratospheric parameters have been obtained from the Voyager ultraviolet solar occultation data (Herbert et al., 1987) which provide the opacity of the stratosphere as a function of wavelength and altitude between 1 μbar and 500 μbar. Atmospheric thermal profiles and hydrocarbon vertical distributions were derived. Subsequent analyses yielded an eddy mixing coefficient at the homopause between 3 10^3 cm^2 s^{-1} and 10^4 cm^2 s^{-1} (Herbert et al., 1987; Summers and Strobel, 1989; Bishop et al., 1990; Atreya et al., 1991), significantly lower than the currently accepted values of 10^6 cm^2 s^{-1} for Jupiter (Atreya et al., 1981), 10^7-10^8 cm^2 s^{-1} for Saturn (Atreya, 1981; Sandel et al., 1982; Parkinson et al., 1997) and 10^7 cm^2 s^{-1} for Neptune (Bishop et al., 1998).

Infrared spectroscopy offers a powerful tool for sounding the stratospheres of the giant planets, through the study of the emission bands of methane and its photochemical products. Infrared spectroscopy with ISO (Infrared Space Observatory), launched in November 1995, has provided a major improvement in this research field. In the present paper, the ISO thermal spectrum of Uranus is compared to synthetic spectra using a new set of theoretical vertical distributions of CH_4 and C_2H_2, calculated for various values of the eddy diffusion coefficient. A new determination of this coefficient is thus derived.

2. Observations

The 7–16.5 μm spectrum of Uranus was first recorded in October 1996 with ISO, using the grating mode of the SWS. The resolving power is about 1500. 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 7–12 μm spectrum was recorded on October 4, 1996, with an aperture of 14x20 arcsec and an integration time of 45 min. The 12–16.5 μm part was recorded on October 28, 1996, with an aperture of 14x27 arcsec and an integration time of 53 min. In both cases, the aperture includes the full disk of Uranus (3.5 arcsec diameter).

In the 7–11 μm range, no spectral signature is exceeding the noise level (1 σ = 0.1 Jy); in particular, the CH_4 ν_4 band at 7.7 μm is not detected. Beyond 11 μm, the noise level increases

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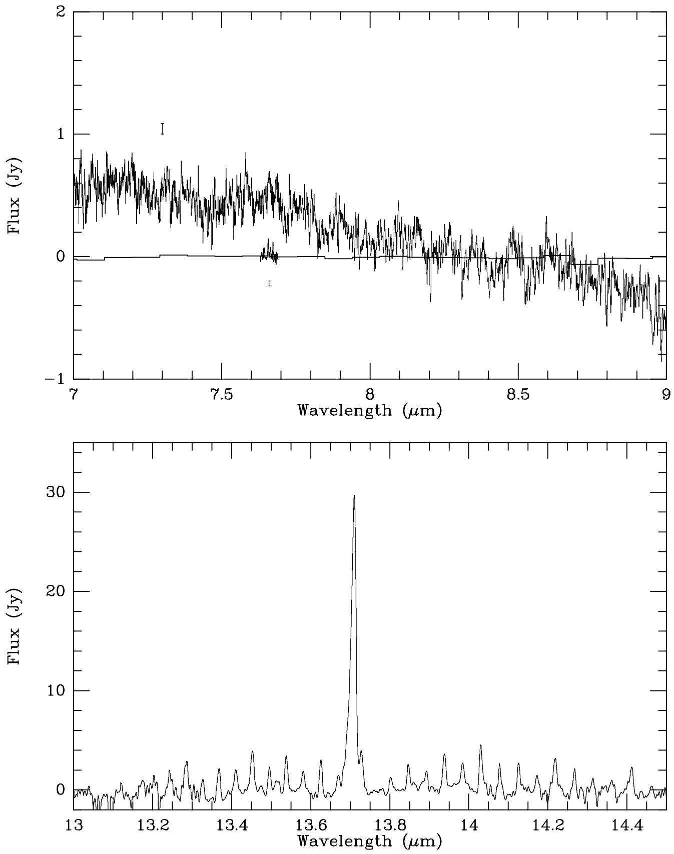

Fig. 1a and b Top **a**: ISO SWS grating (light line) and PHT-S spectra (histograms) of Uranus in the 7–9 μm region. The upper error bar corresponds to the 1-σ noise level of the SWS spectrum; for the PHT-S data, this noise level is 0.01 Jy. The data at 7.63–7.69 μm, centered on the Q-branch of the CH_4 ν_4 band, correspond to the second SWS grating spectrum (see text); the lower error bar is the 1-σ noise level. Bottom **b**: ISO SWS grating spectrum of Uranus in the C_2H_2 ν_5 band. The 1-σ noise level is 0.3 Jy.

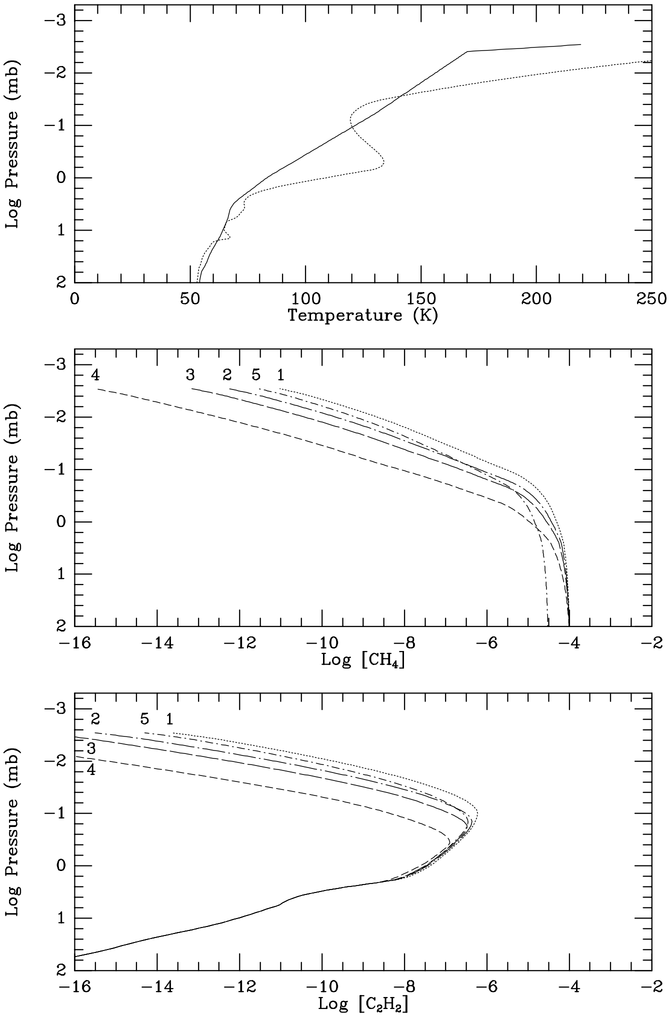

Fig. 2a–c Top **a**: Vertical temperature profile used in our calculations (solid line) compared to the profile of Bishop et al. (1990) (dashed line). Middle **b**: vertical distributions of CH_4 for Models 1 to 5 (see text). Bottom **c**: vertical C_2H_2 distributions for Models 1 to 5 (see text).

(1 σ = 0.3 Jy); the only detected signal is the ν_5 band of C_2H_2 at 13.7 μm.

In order to improve the upper limit on the CH_4 emission, other ISO data were recorded, both with the SWS grating and with the spectroscopic mode of the photometer (PHT-S). The region of the CH_4 ν_4 Q-branch (7.63–7.69 μm) was scanned by the SWS on May 13, 1997, with an integration time of 29 min. In addition, the complete spectrum of Uranus between 6 and 12 μm has been recorded by PHT-S on May 7, 1997 with an integration time of 90 min. The PHT-S spectral resolving power (R = 90) is lower than the SWS one, but its sensitivity is higher. A description of the photometer can be found in Lemke et al. (1996). As shown in Fig. 1a, there is no detectable emission at the position of the CH_4 ν_4 Q-branch. The 1-σ noise level is 0.04 Jy in the SWS data and 0.01 Jy in the PHT-S data.

Fig. 1b shows the spectrum of Uranus in the C_2H_2 ν_5 emission band between 13 and 14.5 μm. The spectral resolution is 0.0094 μm (R = 1450). The S/N ratio in the Q-branch is about 100. Ten years after a first tentative detection by low resolution ground-based spectro-photometry (Orton et al., 1987), this is the first unambiguous infrared detection of C_2H_2 in Uranus.

3. Modelling and interpretation

For an object of Uranus' size, a flux of 1 Jy corresponds to a blackbody temperature of 72 K at 13.7 μm,; at 7.7 μm, a flux of 0.1 Jy corresponds to a temperature of about 100 K. This shows that the C_2H_2 and CH_4 emission bands in the Uranus spectrum can provide information upon the stratospheric regions which are warmer than these temperatures. Assuming the composite temperature profile based upon Voyager UVS and radio data (Atreya et al., 1991), these regions correspond to pressure levels lower than 3 mbar in the C_2H_2 band and 0.3 mbar in the CH_4 band. On the other hand, both CH_4 and C_2H_2 mixing ratios drop around the homopause level, believed to be at a pressure in the range 10–100 μbar, depending upon the value of the eddy diffusion coefficient (Bishop et al., 1990; Atreya et al., 1991).

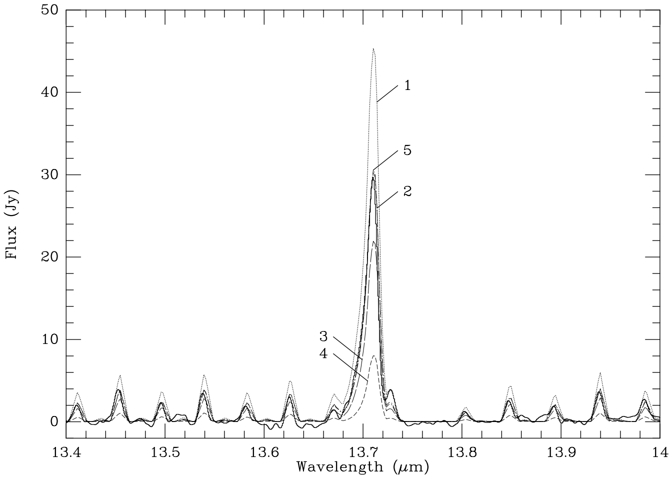

Fig. 3. The ISO spectrum of Uranus in the C_2H_2 band compared to synthetic profiles. Both Models 2 ($Q = 10^{-4}$, $K = 5\ 10^3$ cm^2 s^{-1}) and 5 ($Q = 3\ 10^{-5}$, $K = 10^4$ cm^2 s^{-1}) provide a very good fit to the data.

The atmospheric region probed by our study thus covers the pressure range 3 mbar–10 μbar.

Fig. 2 shows the atmospheric parameters used in our model. We adopted the composite, smoothed thermal profile of Atreya et al. (1991); this profile was preferred to the thermal profile retrieved by Bishop et al. (1990) from the radio occultation profile. Indeed, the warm region shown in Bishop et al.'s profile (Fig. 2a), possibly the result of breaking gravity waves (Hinson and Magalhaes, 1991), may be restricted to equatorial latitudes, and should not be included in global-average models. The CH_4 and C_2H_2 distributions (Fig. 2b and 2c) were derived from a new analysis including photochemistry (Bishop et al., 1998) and taking into account the solar fluxes at the time of the observations. Five models are considered, generated with different values of the CH_4 mixing ratio at the tropopause (Q) and the eddy diffusion coefficient at the homopause (K): (1) $Q = 10^{-4}$, $K = 10^4$ cm^2 s^{-1}; (2) $Q = 10^{-4}$, $K = 5\ 10^3$ cm^2 s^{-1}; (3) $Q = 10^{-4}$, $K = 3\ 10^3$ cm^2 s^{-1}; (4) $Q = 10^{-4}$, $K = 10^3$ cm^2 s^{-1}; (5) $Q = 3\ 10^{-5}$, $K = 10^4$ cm^2 s^{-1}. Models 1 to 4 correspond to methane condensation at the tropopause level (P = 100 mbar, T = 52.5 K), while Model 5 assumes methane condensation at a temperature level of 49.5 K. Our radiative transfer model, previously used for Jupiter and Saturn atmospheric modelling (Encrenaz et al., 1996; de Graauw et al., 1997) includes the GEISA spectroscopic parameters for CH_4 and C_2H_2 (Husson et al., 1986); the Lorentz linewidths of C_2H_2 and CH_4 are taken from Varanasi (1992) and Varanasi and Tejwani (1972) respectively.

3.1. The C_2H_2 ν_5 emission band

Fig. 3 shows the ISO-SWS spectrum of Uranus in the C_2H_2 ν_5 band, compared to the synthetic spectra generated with the five above-mentioned models at the SWS resolution (0.0094 μm). It can be seen that both Models 2 and 5 provide an excellent fit to the data. They correspond to a C_2H_2 mixing ratio close to $4\ 10^{-7}$ at a pressure level of about 100 μbar. We conclude that, for all reasonable values of the methane mixing ratio at the tropopause, the eddy diffusion coefficient ranges between $5\ 10^3$ and 10^4 cm^2 s^{-1}. For these two K-values, the homopause altitudes above the 1-bar pressure level are 354 km (P = 0.037 mbar) and 390 km (P = 0.020 mbar) respectively. Our calculations show that the C_2H_2 spectrum of Uranus does not strongly differ for the two T(P) profiles shown in Fig. 2, simply because the temperatures are roughly the same at the level of maximum C_2H_2 abundance.

It can be noted that Models 2 and 5 predict a maximum C_2H_6 mixing ratio of 3–4 10^{-7} at a pressure level of about 0.1 mbar. This C_2H_6 abundance corresponds to a maximum flux of 0.08–0.12 Jy in the strongest multiplet of the ν_9 band, at 12.16 μm. The absence of detection of this band is thus not surprising. Taking into account our 1-σ error bar of 0.3 Jy, we derive a 3-σ upper limit of $3\ 10^{-6}$ for the maximum C_2H_6 mixing ratio (P = 0.1 mbar).

3.2. The CH_4 ν_4 emission band

Synthetic models of Uranus in the CH_4 ν_4 band have been calculated and convolved to the spectral resolution of the ISO data for comparison (0.0052 μm in the case of SWS and 0.084 μm in the case of PHT-S). Results are shown in Fig. 4. Taking into account the noise level in the SWS and PHT-S data, only Model 1 can be ruled out at a 3-σ confidence level. This implies that the CH_4 mixing ratio at the 100–μbar level has to be less than $3\ 10^{-6}$. In this case, the synthetic spectrum is more sensitive to the temperature profile: calculations show that, if the temperature profile of Bishop et al. (1990) is used, the CH_4 emission spectrum is enhanced by a factor of about 4; this is due to the temperature increase of Bishop et al.'s profile at the level of 1 mbar (Fig. 2a). In the same way, if the temperature is decreased by about 10 K in the 0.1–1 mbar pressure region, the CH_4 emission is decreased by a factor of 2 while the C_2H_2 emission is decreased by less than 10%.

4. Conclusions

Our preferred models of the C_2H_2 vertical profile have a mixing ratio of 2–4 10^{-7} in the pressure range 0.1–0.3 mbar, and a total column density of 4–5 10^{16} cm^{-2}. This result is consistent with the early estimate of Encrenaz et al. (1986) based on IUE observations. However, it is significantly larger than the Voyager UVS determinations, based either on solar occultation equatorial measurements (Herbert et al., 1987; Bishop et al., 1990; Atreya et al., 1991) or on the solar reflection spectrum recorded at the pole (Yelle et al., 1989). On the other hand, the ISO results are consistent with the low-resolution ground-based observations of Orton et al. (1990).

It can be seen that the comparison of the ISO Uranus data sets with synthetic models all favor a value of the eddy mixing coefficient between $5\ 10^3$ and 10^4 cm^2 s^{-1} at the homopause. From the Voyager UV solar occultation data, typical equatorial values of $3\ 10^3$–10^4 cm^2 s^{-1} were retrieved at the homopause (Herbert et al., 1987; Summers and Strobel, 1989; Bishop et

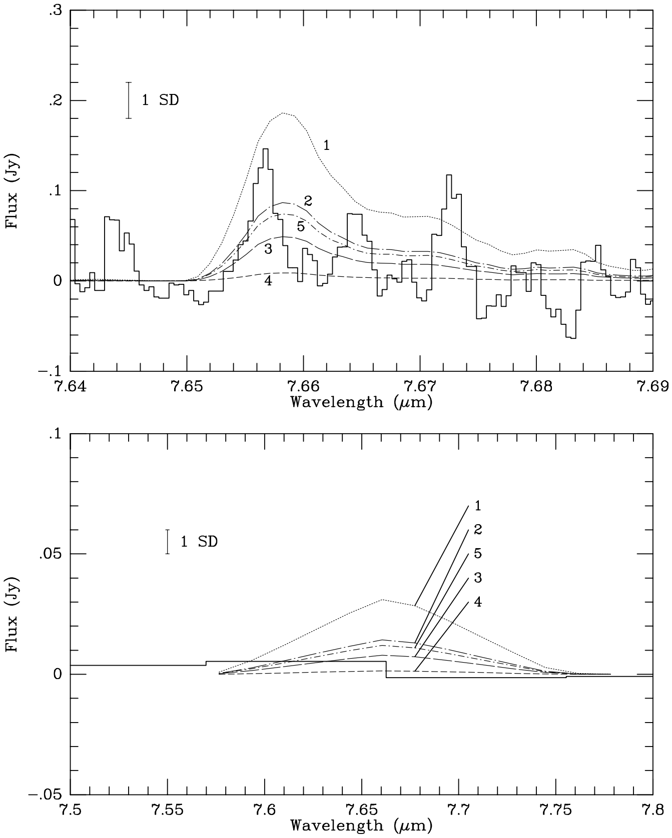

Fig. 4a and b Synthetic CH_4 emission spectra of Uranus for Models 1 to 5 compared with the ISO spectra of Uranus. Top **a**: SWS data (spectral resolution: 0.0052 μm); bottom **b**: PHT-S data (spectral resolution: 0.084 μm).

al., 1990; Atreya et al., 1991), while lower values were derived from the analysis of the UVS solar reflection spectrum (1.5 10^3 cm^2 s^{-1} for overhead insolation conditions (Summers and Strobel, 1989), and less than/equal to 100 cm^2 s^{-1} for globally averaged conditions (Yelle et al., 1989)). Ten years later, our derived value of K, corresponding to the whole disk, rather favours the solar occultation results which refer to equatorial latitudes, near terminator at the Voyager epoch.

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References

Atreya S.K., 1981, Adv. Space Res 1, 127
Atreya S.K., Donahue T.M. and Festou M.C., 1981, ApJ 247, L43
Atreya S.K., Sandel B.R. and Romani P., 1991, in: Uranus, eds. J.T. Bergstrahl, E.D. Miner and M.S. Matthews, Un. of Arizona Press, p. 110
Bishop J., Atreya S.K., Herbert F. and Romani P., 1990, Icarus 88, 448
Bishop J., Romani P. and Atreya S.K., 1998, Plan Space Sci, in press
Caldwell J., Wagener R., Owen T., Combes M. and Encrenaz T., 1984, in: Uranus and Neptune, ed. J.T. Bergstrahl, NASA CP-2330, 157
de Graauw Th. et al., 1996, A&A 315, L49
de Graauw Th. et al., 1997, A&A 321, L13
Dunham E., Elliot J.L. and Gierasch P.J., 1980, ApJ 235 274
Encrenaz Th. et al., 1986, A&A 163, 317
Encrenaz Th. et al., 1996, A&A 315, L397
French R.G., Elliott J.L., Dunham E.W., Allen D.A., Elias J.H., Frogel J.A. and Liller W., 1983, Icarus 53, 399
Herbert F.L., Sabdel B.R., Broadfoot A.L., Shemansky D.E., Holberg J.B., Yelle R.V., Atreya S.K. and Romani P.N., 1987, J. Geophys. Res. 92, 15093
Hinson D.P. and Magalhaes J.A., 1991, Icarus 94, 64
Husson N. et al., 1986, Ann. Geophys. 4, 185
Kessler M.F. et al., 1996 A&A 315, L27
Lemke D. et al., 1996 A&A 315, L64
Orton G.S., Aitken D.K., Smith C., Roche P.F., Caldwell J. and Snyder R., 1987, Icarus 70, 1
Orton G.S., Baines K.H., Caldwell J., Romani P., Tokunaga A.T. and West R.A., 1990, Icarus 85, 257
Parkinson C.D., Griffioen E., Mc Connell J.C., Gladstone G.R. and Sandel B.R., 1997, B.A.A.S. 29, 995
Sandel B.R., Mc Connel J.C. and Strobel D.F., 1982, Geophys. Res. Lett. 9 1077
Sicardy B. et al., 1985, Icarus 64, 88
Summers M.E. and Strobel D.F., 1989, ApJ 346, 495
Varanasi P., 1992, J. Quant. Spectr. Rad. Transfer 47, 263
Varanasi P. and Tejwani G.D. T., 1972, J. Quant. Spectr. Rad. Transfer 12, 849
Yelle R.V., Mc Connell J.C., Strobel D.F. and Doose, L.R., 1989, Icarus 77, 439