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The rotational temperature and column density of H_3^+ in Uranus

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Abstract

H_3^+ emission from Uranus has been observed repeatedly for over a decade. However, the details of the emission mechanisms are still poorly understood. In this paper, we discuss our findings from the observations we made in September 2000 and September 2001. The spectrum of Uranus was recorded at the NASA Infrared Telescope Facility using the SpeX instrument between 3 and 5 μm, with a resolving power of 1000. The 3.4–4.1 μm range permits a determination of both the H_3^+ column density and its rotational temperature. The H_3^+ emission, measured at 3.986 μm in the 0.8 × 3.7 arcsec aperture, was 0.031 Jy in September 2000 and 0.053 Jy in September 2001. The rotational temperature was found to be 560 ± 40 K and 640 ± 40 K in 2000 and 2001 respectively, with corresponding column densities of 5.1 (+3.2, −1.4) 10^{11} and 4.0 (+1.8, −1.0) 10^{11} cm^{-2}. These results extend the baseline for the variability study of the H_3^+ emission (Astrophys. J. 524 (1999) 1059). Previous observations between 1992 and 1998 seemed to indicate a correlation between the H_3^+ intensity and the solar cycle. The current data for 2000 and 2001 appear to be consistent with this general tendency.

Keywords: Infrared spectroscopy; Planetary atmospheres; Uranus

1. Introduction

The detection of the H_3^+ ion in the giant planets, first on Jupiter (Drossart et al., 1989), then on Uranus (Trafton et al., 1993) and Saturn (Geballe et al., 1993), offered new opportunities for understanding the physico-chemical processes at work in their ionospheres. Several mechanisms have been proposed to account for the observed emissions. In the case of Jupiter, charged particle precipitation is believed to be the main mechanism in the auroral regions (Drossart et al., 1989) with photoionization contributing mainly to the emission in the equatorial regions (Marten et al., 1994; Miller et al., 1997; Brown et al., 2003). In the case of Uranus, whose magnetospheric power input is smaller by at least a factor of 100 compared to Jupiter (Atreya, 1986), whereas the incoming solar flux is only 16 times lower, the auroral source may be responsible for only a small fraction of the H_3^+ emission (Lam et al., 1997). Spatial mapping of H_3^+ on Uranus (Lam et al., 1997), combined with a study of the temporal variations of the H_3^+ emission since 1992—that show the same general trend as the solar activity—suggested that solar photoionization is the main source of H_3^+ on Uranus (Trafton et al., 1999). More recent disk-averaged measurements with the ISO satellite (Encrenaz et al., 2000) also confirm this tendency.

In the case of Jupiter, H_3^+ was first detected in the $2\nu_2$ overtone vibrational band around 2.1 μm (Drossart et al., 1989). Subsequent studies were mostly made near the center of the ν_2 fundamental band around 3–4 μm, a spectral range which is also observable from the ground. In the case of Uranus, most of the observations were performed in the 3.3–4.1 μm region (Trafton et al., 1993, 1999; Lam et al., 1997; Encrenaz et al., 2000).

We report here new measurements of the H_3^+ emission from Uranus. A preliminary analysis of these data was presented by Encrenaz et al. (2001, 2002). The measurements were done in the 3.5–4.1 μm range. This spectral coverage allows us to retrieve separately the rotational temperature and the column density of H_3^+ in Uranus. The observations

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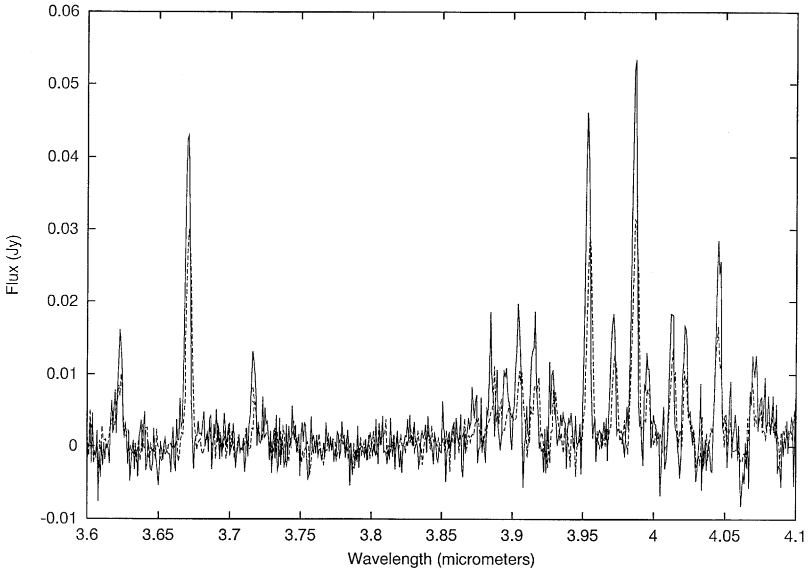

Fig. 1. The spectrum of Uranus between 3.6 and 4.1 μm: (a) September 2000 run; (dashed line) (b) September 2001 run (solid line). The resolving power is 1000. The star ι Cap is used for calibration. All emission lines can be attributed to H_3^+ emissions.

are described in Section 2. The results of analysis are presented in Section 3, followed by their discussion in Section 4.

2. Observations

Observations took place during two observing runs (September 9–10, 2000 and September 1–2, 2001) at the NASA Infrared Telescope Facility (IRTF) using the SpeX instrument. SpeX is a near-infrared spectrograph (Rayner et al., 1998), operating between 0.8 and 5.5 μm with a resolving power ranging between 1000 and 2000, which may be used in different operating modes. We used the 2.4–5.5 μm cross-dispersed mode with a 0.8 × 15 arcsec slit, aligned along the celestial N–S axis, corresponding to a resolving power of 1000. The detector was a Raytheon 1024 × 1024 InSb array, on which six different orders were displayed.

The angular diameter of Uranus was 3.7 arcsec. Uranus was centered alternatively, every 30 s, on two positions of the slit separated by 7.5 arcsec. For each spectral image, the difference between the two positions was recorded in order to perform the sky cancellation. The G8III star ι Cap was used for calibration. The total observing time on Uranus was 4.5 h for each of the two runs.

The 2–5 μm spectrum of Uranus is expected to be comprised largely of reflected sunlight, dominated by strong CH_4 and CH_3D absorptions, except in two spectral windows where the signal is very weak. The first is at 2.75 μm, which was first detected by the ISO satellite (Encrenaz et al., 2000), and the second at 4.7 μm, which was first detected by ground-based spectrophotometry (Orton and Kaminski, 1989). In addition, discrete thermal H_3^+ emission lines are expected between 3 and 5 μm, as mentioned above. At all other wavelengths in the 2–5 μm range, the spectrum of Uranus is expected to be black.

Between 2 and 5 μm, the signal of Uranus was detected with SpeX in the form of narrow emissions between 3.59 and 4.1 μm, and also in the form of a weak continuum between 4.5 and 5.0 μm. No signal from Uranus was detected in the 3 first orders (2.3–3.6 μm). Indeed, the 2.75 μm window observed with ISO in 1997 (at a flux level of 0.03 Jy for the entire disk; Encrenaz et al., 2000) cannot be detected with SpeX because of the large opacity of the Earth's atmosphere in this spectral range.

A weak continuum was observed at Uranus around 4.7 μm, confirming the first tentative detection of Uranus at these wavelengths by Orton and Kaminski (1989). A few H_3^+ emission lines were also superimposed over the continuum, but the signal-to-noise in these lines was much weaker than at 3.6–4.1 μm.

The SpeX raw images were reduced to spectra by fitting the spectral image of the slit on the bidimensional array along a parabolic curve, with a width equivalent to 3.7 arcsec. The spectral calibration was then easily performed from the H_3^+ line positions themselves.

Fig. 1 shows the spectrum of Uranus between 3.6 and 4.1 μm, for the September 2000 run (a) and the September 2001 run (b).

3. Data analysis

Synthetic spectra were calculated for optically thin emissions of H_3^+, with line parameters taken from Kao et al.

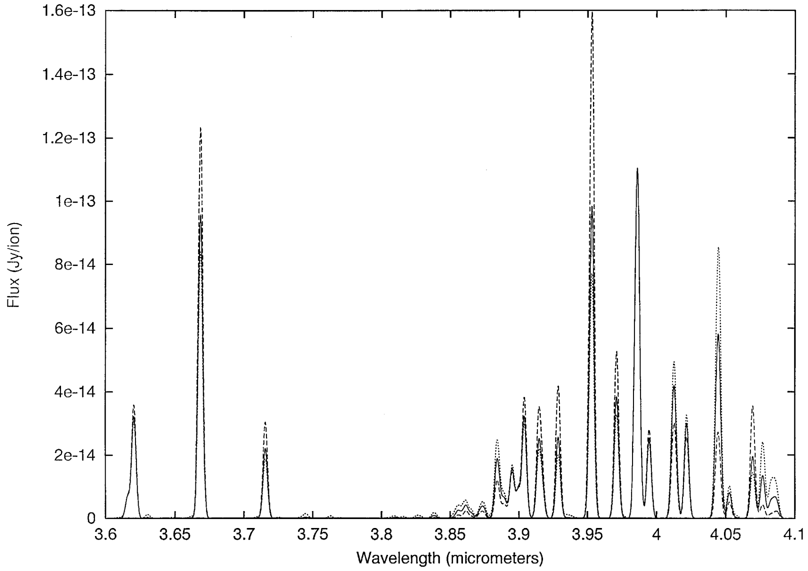

Fig. 2. The emission spectrum of H_3^+ between 3.6 and 4.1 μm, calculated from the data of Kao et al. (1991), for a rotational temperature of 600 K (solid line), 400 K (dashed line) and 800 K (dotted line). All curves have been normalized at 3.986 μm, where the observed H_3^+ emission line is maximum. The ordinate is the flux in Jy per number of ions over the line of sight, in the FOV corresponding to our observation (0.8 × 3.7 arcsec).

(1991). They were convolved to the spectral resolution of SpeX, assuming a gaussian instrument function. An isothermal ionospheric emission was assumed in our modeling, as is commonly done for H_3^+ emissions. More sophisticated models are not warranted at this time in view of the uncertainty in the ionospheric thermal profile of Uranus.

3.1. Rotational temperature

Fig. 2 shows a comparison of the synthetic emission spectra of H_3^+ corresponding to rotational temperatures of 400, 600 and 800 K, normalized to the 600 K scale at 3.953 μm. It can be seen that all the emission features observed in Fig. 1 can be attributed to H_3^+. For both data sets, the comparison shows that the rotational temperature of H_3^+ must be close to 600 K.

The H_3^+ rotational temperature has been retrieved from the relative intensities of the four strongest lines (3.668, 3.986, 3.953 and 4.045 μm). We derive rotational temperatures, T, of 560 ± 40 K for the September 2000 run and 640 ± 40 K for the September 2001 run. The contribution from weaker lines in a least-squares fitting gives negligible improvement to the four line fits presented here.

3.2. H_3^+ column density

The absolute calibration of the data was achieved using the calibration star ι Cap. The spectral type of this star is G8 III and its visual magnitude is 4.28. The absolute flux scale in Fig. 1 was calculated with an ι Cap flux of 37 Jy at 4.0 μm. The uncertainty on the flux scale is estimated to be 25%, mostly due to instrumental calibration and sky-subtraction uncertainties. Assuming an H_3^+ intensity peaked toward the disk center, as observed by Trafton et al. (1999), we infer H_3^+ column densities, N, of 5.1 (+3.2, −1.4) 10^{11} and 4.0 (+1.8, −1.0) 10^{11} cm^{-2} for 2000 and 2001, respectively.

4. Discussion

Table 1 summarizes our results and compares them with previous measurements.

Our determinations of T and N fall within the range of previous measurements for both parameters. However, the uncertainties are too large to permit firm conclusions about their temporal variability. In Table 1, we also show the temporal variations of the frequency-integrated H_3^+ intensity in the strongest transition at 3.986 μm. In the case of the measurements reported by Trafton et al. (1999), we used the $E(H_3^+)$ quantity listed by the authors in their Table 6. The uncertainty on $E(H_3^+)$, directly measured from the observations, is smaller than the uncertainties on the inferred physical parameters T and N.

The solar activity was maximum in 1990–1991 and minimum in 1996–1997 (NOAA National Geophysics Data Center). The last maximum (solar cycle #23) occurred in April 2000, but a secondary maximum also occurred between September 2001 and February 2002 (Coffey, 2000; Coffey and Erwin, 2002). In addition, the solar cycle exhibits numerous strong fluctuations superimposed over the 11-year period. It is thus very difficult to search for a correlation between the H_3^+ intensity on Uranus and the solar activity. However, as pointed out by Lam et al. (1997) and Trafton et al. (1999), the general decrease of the H_3^+ intensity between 1992 and 1995 were in global agreement

Table 1
H_3^+ rotational temperatures, column densities and frequency-integrated H_3^+ intensities at 3.986 μm

Date	$T(H_3^+)$[a] (K)	$N(H_3^+)$ (10^{11} cm^{-2})	$E(H_3^+)$ (m Wm^{-2} sr^{-1})	Reference
1992 Apr 1	757 (25)	2.1	17.1	Trafton et al. (1993, 1999)
1993 May 3	751 (65)	1.7	13.3	Lam et al. (1997) Trafton et al., 1999
1993 May 4	735 (65)	1.7	12.2	Trafton et al., 1999
1993 May 5	660 (65)	2.7	10.4	Trafton et al., 1999
1994 Jul 20	635 (65)	3.8	12.1	Trafton et al., 1999
1994 Jul 23	648 (75)	4.2	14.1	Trafton et al., 1999
1995 Jun 11	717 (70)	1.6	9.37	Trafton et al., 1999
1995 Jun 12	662 (70)	1.9	7.74	Trafton et al., 1999
1995 Jun 13	668 (70)	1.9	7.66	Trafton et al., 1999
1995 Jun 14	717 (70)	1.4	8.60	Trafton et al., 1999
1998 Apr 7[b]	600 (200)	7.0	16.0	Encrenaz et al. (2000)
1998 May 9[b]	600 (200)	7.0	16.0	Encrenaz et al. (2000)
2000 Sep 9–10	560 (40)	5.1	10.7	This work
2001 Sep 1–2	640 (40)	4.0	18.2	This work

[a] The uncertainty is indicated in parentheses.

[b] Due to the large uncertainty on T, the N and E values are very uncertain ($N = 0.1\text{–}40 \times 10^{12}$; Encrenaz et al., 2000).

with the cyclic variations of the solar activity. The 1998 data indicated a new increase of the intensity, also consistent with the 11-year solar cycle, but this result was still uncertain and temperature dependent, as the measurement was performed at a different wavelength (3.3 μm). The 2000 and 2001 measurements of $E(H_3^+)$ also indicate a possible increase with respect to the 1995 values, and are thus also consistent with the global variations of the solar activity.

Measuring separately the rotational temperature and the column density of H_3^+ with a better accuracy should allow one to place more constraints on the nature of the emission mechanisms. These results also indicate the need for spatially resolved observations, such as those performed by Lam et al. (1997) in order to better isolate the emission source.

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