THE ASTROPHYSICAL JOURNAL, 351: L53–L56, 1990 March 10

OBSERVATIONS OF THE 4 MICRON FUNDAMENTAL BAND OF H_3^+ IN JUPITER

T. OKA
Department of Astronomy and Astrophysics and Department of Chemistry, University of Chicago
AND
T. R. GEBALLE
Joint Astronomy Centre, Hilo

Received 1989 October 24; accepted 1989 December 14

ABSTRACT

Emission lines of the ν_2 fundamental vibration-rotation band of H_3^+ have been detected in the northern and southern polar ionospheres of Jupiter. The recently discovered 2 μm overtone band of H_3^+ is currently absent from the spectra of Jupiter's poles, as are lines of several other "hot bands" of H_3^+ and 2 μm lines of H_2, implying that physical conditions in Jupiter's auroral regions have changed considerably within a period of ~1 yr. The present observations provide added evidence for a large abundance of H_3^+ in localized zones of the Jovian atmosphere.

Subject headings: infrared: spectra — line identifications — molecular processes — planets: Jupiter

I. INTRODUCTION

The recent detection of the molecule H_3^+ in the Jovian auroral regions (Maillard and Drossart 1989; Trafton, Lester, and Thompson 1989; Drossart *et al.* 1989), via its 2 μm ν_2 overtone ($v_2 = 2 \rightarrow 0$) band, is the first instance in which this hydrogenic species, which is thought to be basic to the production of many complex molecules in the interstellar medium, has been detected by astronomical observations. Previously, some searches for H_3^+ in dense molecular clouds have been made (e.g., Geballe and Oka 1989). The above measurements of H_3^+ have provided definitive evidence for high ion concentration, high temperature, and localization of the ionized regions near the poles of Jupiter.

In this *Letter* we report the detection of the 4 μm fundamental ν_2 band of H_3^+ in Jupiter. The relation between the overtone band, the fundamental band, and some of the hot bands which are discussed in this *Letter* is shown in Figure 1. The detailed rotational structure of the fundamental ν_2 band has been well characterized in the laboratory (Oka 1980, 1981; Watson *et al.* 1984; Majewski *et al.* 1987), based on the *ab initio* calculations of Carney and Porter (1976, 1980). The rotational structure of the hot bands, $2\nu_2(2) \rightarrow \nu_2$, $2\nu_2(0) \rightarrow \nu_2$, $\nu_1 + \nu_2 \rightarrow \nu_1$ (Bawendi, Rehfuss, and Oka 1989), and overtone band, $2\nu_2 \rightarrow 0$ (Majewski *et al.* 1989; Xu, Gabrys, and Oka 1989) have been determined by recent laboratory spectroscopy aided by the first principle calculations of Miller and Tennyson (1987, 1988, 1989).

The vibrational Einstein spontaneous emission rates calculated by Carney and Porter (1976) are shown in Figure 1. These rates imply that if spontaneous emission of the overtone band is detectable, as it was in Jupiter during 1987–1988, then there are four vibrational transitions which should produce detectable and comparable numbers of photons in the 4 μm region.

II. OBSERVATIONS

Spectra of Jupiter were obtained at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea in two sessions in 1989, during the mornings of September 6 and 9–10 and during September 14–19. UKIRT's cooled grating spectrometer (CGS2) was used to obtain medium-resolution spectra in the 1.95–2.55 μm ($600 < R < 900$) and 2.85–4.15 μm ($350 < R < 550$) intervals during the first session. During the second session, CGS2 was employed in series with Fabry-Perot interferometers to obtain spectra of resolving power ~12,000 near 2,093 μm and 2.31 μm and ~8000 in various spectral intervals near 4 μm. The field of view was a 5″ circular aperture, used with a chopper throw and nods of 45″ EW. On each morning the seeing was better than 1″ until about 8:00 A.M., when it degraded to several arcseconds; pointing was accurate to ±1″ until that time and 2″–3″ thereafter. Flux calibration was achieved through observations of BS 2088, BS 1708, and BS 1713. Wavelength calibration was obtained from absorption lines of telluric N_2O and lines of Ar in a discharge lamp.

As far as the spectrum of H_3^+ is concerned, all meaningful detections were obtained from the higher resolution spectroscopy used in the second session. In addition to providing some significant upper limits to 2 μm lines of H_3^+ and H_2, the lower resolution spectroscopy has produced interesting overview 2–4 μm spectra of Jupiter in various locations. These will be reported in a separate paper.

III. RESULTS

The frequencies, intensities, and identifications of 10 H_3^+ lines from the ν_2 fundamental band, which were detected in Jupiter, are listed in Table 1. All of these lines have been measured in the laboratory. Examples of observed lines are shown in Figures 2–4; note that the Jovian spectrum near 4 μm was Doppler-shifted by $+0.25$ cm^{-1} during these observations. In Jupiter the H_3^+ emission spectrum near 4 μm is superposed on a continuum with strong and broad absorption features. The $(1, 0, -1) \rightarrow (1, 0)$ transition shown in Figure 2 is the strongest line of H_3^+ that we detected and is very useful for mapping. The continuum from Jupiter near this line is totally absorbed, except at ~2533 cm^{-1}, clearly demonstrating that the emitting H_3^+ exists at high altitude. Figure 3 shows a quartet of H_3^+ lines corresponding to the $(5, K, -1) \rightarrow (5, K)$ transitions with $K = 0, 1, 2, 3$. The greater intensities of the $K = 0$ and $K = 3$ lines reflect the ratio of ortho ($I = 3/2$) to para ($I = 1/2$) spin

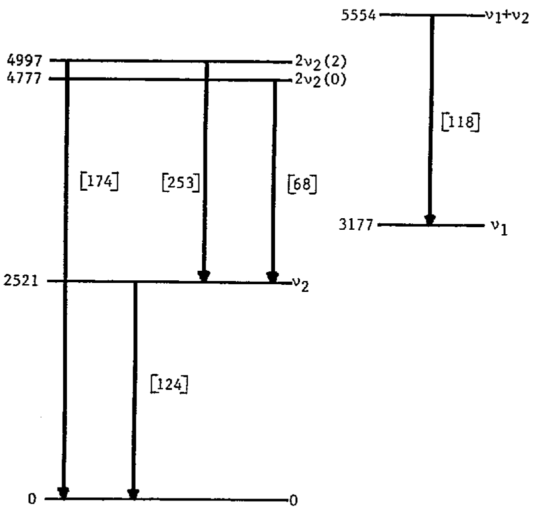

FIG. 1.—Diagram of the lower vibrational levels of H_3^+ showing allowed vibrational transitions. Energies of levels are in cm^{-1}; numbers in brackets are Einstein *A*-coefficients in s^{-1}.

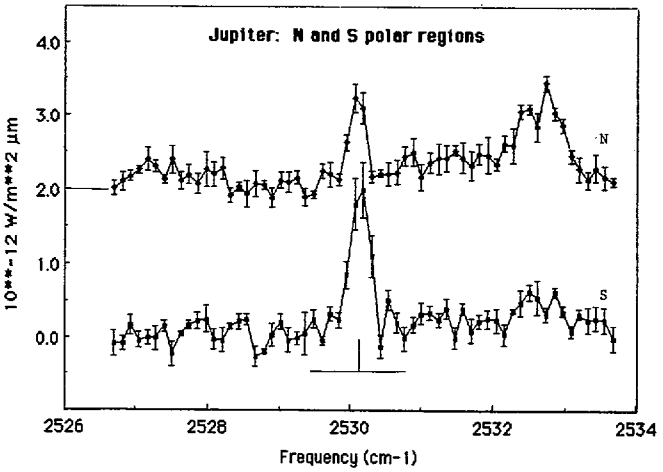

FIG. 2.—Spectra of the 1, 0, −1 → 1, 0 line of H_3^+ at 2530 cm^{-1} in the polar regions of Jupiter, observed at longitudes of 160° and 181°. Refer to Table 1 for details. The bump at 2533 cm^{-1} is believed to be continuum radiation in a gap between strong Jovian absorption lines.

statistical weights of 4 to 2. The weak feature at 2468.0 cm^{-1} coincides with H_3^+ (5, 4, −1) → (5, 4); however, the Doppler-shifted position of H I Brα (rest frequency of 2467.76 cm^{-1}) also is close. The somewhat larger width of this feature may be due to a blend of these two lines; further spectroscopy at higher resolution is required to settle this question. Figure 4 shows the doublet (3, *K*, −1) → (3, *K*) with *K* = 0, 1, which is superposed on the shoulder of a strong absorption feature.

The most remarkable outcome of these observations is the complete absence of emission lines starting from excited vibrational states above $v_2 = 1$. In particular, we did not detect the strongest overtone emission line, (7, 9, +2) → (6, 6) at 4777.226 cm^{-1}, seen by Trafton, Lester, and Thompson (1989) and Drossart *et al.* (1989). We estimate that the surface brightness in this line was at least 10 times lower than at the times of the above observations. Other overtone lines detected by the above observers were also not detected in the present observations. The absence of lines from highly excited vibrational states is further confirmed by the failure to detect hot band spectral lines in the 4 μm region. In addition, the H_2 *S*(1) line at 2.12 μm was also searched for at a number of locations and not detected; our limiting surface brightnesses for this line are typically 3 times less than those seen by Trafton, Lester, and Thompson (1989) and Drossart *et al.* (1989). Thus, the present

TABLE 1

OBSERVED $\nu_2 \rightarrow 0$ LINES OF H_3^+ DURING 1989 SEPTEMBER 17–19

Transition *J′*, *G′*, *U′* → *J*, *K*	Frequency (cm^{-1} laboratory)	Intensity (10^{-16} W m^{-2}, 5″ beam)	Location	Longitude (System III)
5, 4, −1 → 5, 4 (+ Brα?)	2467.553	3.0 ± 1.0	3″N of S limb	338°
5, 0, −1 → 5, 0	2471.923	14. ± 2.	3″S of N limb	12
		9.1 ± 1.5	S limb	35
5, 1, −1 → 5, 1	2472.325	5.5 ± 1.5	3″S of N limb	12
		4.0 ± 1.5	S limb	35
5, 3, −1 → 5, 3	2472.846	12. ± 2.	3″S of N limb	12
		8.0 ± 1.5	S limb	35
5, 2, −1 → 5, 2	2473.238	6.5 ± 1.5	3″S of N limb	12
		4.0 ± 1.5	S limb	35
3, 1, −1 → 3, 1	2508.131	4.2 ± 1.0	3″N of S limb	15
		3.2 ± 1.0	3″N of S limb	118
3, 0, −1 → 3, 0	2509.075	6.0 ± 1.0	3″N of S limb	15
		4.8 ± 1.0	3″N of S limb	118
2, 1, −1 → 2, 1	2518.207	3.5 ± 1.0	3″N of S limb	118
		3.8 ± 1.0	3″N of S limb	136
1, 0, −1 → 1, 0	2529.724	9.3 ± 1.0	3″N of S limb	160
		4.7 ± 1.0	3″S of N limb	181
		18. ± 2.	S limb	283
		22. ± 2.	S limb	299
		8.1 ± 1.	3″S of S limb	303
		6.0 ± 1.	3″N of S limb	305
		3.5 ± 1.	6″N of S limb	308
		6.5 ± 1.	N limb	312
		40. ± 4.	3″S of N limb	314
		6.1 ± 1.	6″S of N limb	317
1, 1, +1 → 1, 1	2545.418	4.0 ± 1.0	S limb	339
		9.3 ± 1.0	3″S of N limb	342

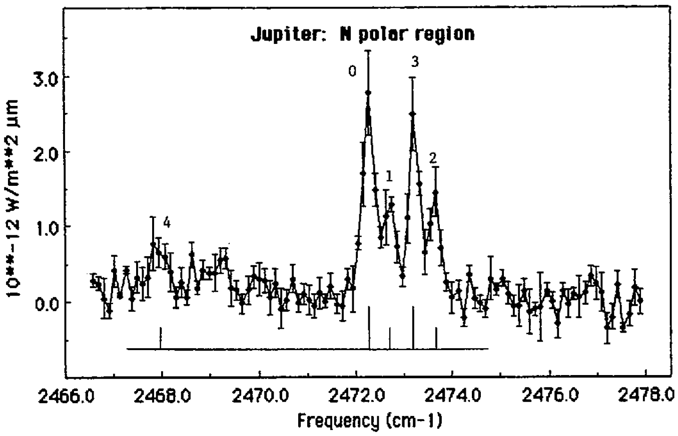

FIG. 3.—A quartet of lines in Jupiter connecting $J = 5$ levels in the ν_2 band of H_3^+. See Table 1 for identifications. The weak feature at 2468 cm^{-1} may be a blend of an H_3^+ line with H I Brα.

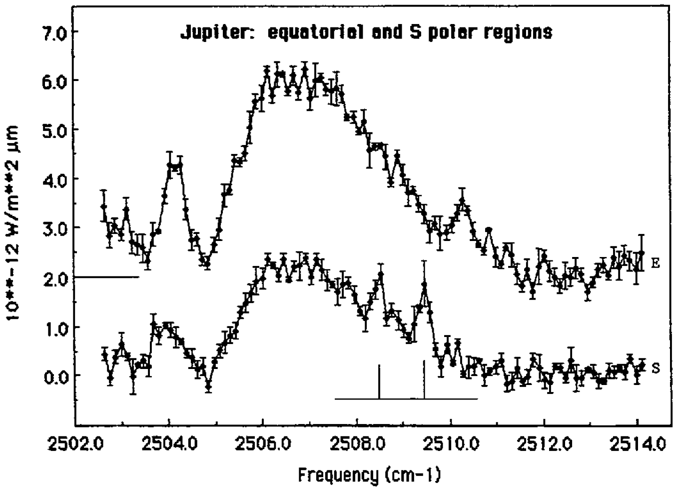

FIG. 4.—Two spectra of Jupiter, on the equator and near the south pole; the latter contains an H_3^+ $J = 3$ doublet near 2509 cm^{-1}, superposed on continuum emission with strong absorption lines.

data provide convincing evidence for large time variations of the physical conditions in Jupiter's auroral plasma. Our negative results are summarized in Table 2. Note that lines of HeH^+ (Bernath and Amano 1982) and H_2D^+ (Foster *et al.* 1986) fell in some of the observed spectral intervals near 4 μm and were absent.

A second interesting difference with some of the previous observations is the presence of H_3^+ lines from the ν_2 fundamental band at much wider variety of longitudes than that reported for the overtone band by Drossart *et al.* (1989). During 1989 September 17–19 we detected the $(1, 0, -1) \rightarrow (1, 0)$ line over widely spaced longitudes, within a few arcseconds of both poles. Taken as a whole, our data set suggests that emission in the fundamental band was present at all longitudes within several arcseconds of each pole. The difference between our result and that of Drossart *et al.*, who found that overtone line emission near the south pole occurred only within a limited range of longitudes, may be related to the heightened sensitivity of the $v_2 = 2$ level to excitation conditions. The latitude dependence that we found for the $v_2 = 1 \rightarrow 0$ band, on the other hand, is quite similar to that reported by Trafton, Lester, and Thompson (1989); we found no H_3^+ line emission further than ~6″ from either pole. The brightest $v_2 = 1 \rightarrow 0$ lines we found were at the south limb at a System III longitude of ~299° and 3″ south of the north limb at a longitude of ~314°; however, we emphasize that complete coverage of either polar region was not achieved on any single morning.

IV. DISCUSSION

The detection of the 4 μm band of H_3^+, together with measurements of the 2 μm band reported earlier, provide a number of significant pieces of information concerning the auroral regions of Jupiter. The present observations of the fundamental band confirm and extend the evidence that H_3^+ is abundant in the auroral regions (McConnell and Majeed 1987). Using the observed line intensities, we estimate rotational temperatures generally to be within 100 K of 670 K and derive column densities in the range 0.1–1.0 × 10^{11} cm^{-2} in the $v_2 = 1$ level near the poles. These column densities are factors of 7–70 times larger than that estimated by Drossart *et al.* (1989)

TABLE 2

NEGATIVE RESULTS FOR NORTH AND SOUTH POLAR REGIONS

Species	Transition	Frequency (cm^{-1} laboratory)	2 σ Limit (10^{-16} W m^{-2}, 5″ beam)	Pole, Longitude (System III)
H_3^+	$2\nu_2 \rightarrow 0\ (6, 3, 2) \rightarrow (7, 0)$	4319.0[a]	0.4	S 65°, N 80°
	$2\nu_2 \rightarrow 0\ (3, 1, 2) \rightarrow (4, 4)$	4325.893	0.4	S 65, N 80
	$2\nu_2 \rightarrow 0\ (7, 9, 2) \rightarrow (6, 6)$	4777.226	0.4	S 30–90, 220–280
	$2\nu_2 \rightarrow 0\ (7, 9, 2) \rightarrow (6, 6)$	4777.226	0.4	N 0–90, 220–280
	$2\nu_2(2) \rightarrow \nu_2\ (2, 0, -2) \rightarrow (2, 0, -1)$	2474.054	1.5	N 12, S 35
	$2\nu_2(2) \rightarrow \nu_2\ (4, 1, 2) \rightarrow (4, 1, 1)$	2508.757	2.0	S 15, S 118
	$2\nu_2(2) \rightarrow \nu_2\ (3, 1, 2) \rightarrow (3, 1, 1)$	2510.291	2.0	S 15, S 118
	$2\nu_2(2) \rightarrow \nu_2\ (1, 1, 2) \rightarrow (1, 1, 1)$	2515.755	2.0	S 118, S 136
	$2\nu_2(0) \rightarrow \nu_2\ (4, 4, 0) \rightarrow (3, 4, 1)$	2532.253	2.0	S 160, N 180
H_2	$v = 1 \rightarrow 0, J = 3 \rightarrow 1$	4712.91	0.7	S 30–90, 220–280
	$v = 1 \rightarrow 0, J = 3 \rightarrow 1$	4712.91	0.7	N 0–90, 220–280
HeH^+	$v = 1 \rightarrow 0, J = 4 \rightarrow 5$	2529.134	2.0	S 160, N 180
H_2D^+	$\nu_3 \rightarrow 0, 4_{13} \rightarrow 3_{22}$	2505.693	2.0	S 15, S 118
	$\nu_3 \rightarrow 0, 2_{20} \rightarrow 1_{11}$	2509.541	2.0	S 15, S 118
	$\nu_2 \rightarrow 0, 3_{31} \rightarrow 2_{12}$	2512.598	2.0	S 15, S 118

[a] Theoretical value by Miller and Tennyson 1989.

to be present in the $v_2 = 2$ level when the 2 μm lines were detected.

A time variation in the excitation conditions for H_3^+ is apparent from the present rotational temperature, which is much lower than the value of 1100 ± 100 K found by Drossart in 1988 September. Assuming that the vibrational temperature is also ~670 K (see below) and the above $v_2 = 1$ column densities, we estimate the current polar column densities in $v_2 = 2$ are 3–30 times less than in 1988 September, which is consistent with our upper limits to lines from that level.

The H_3^+ ions are produced through the well-known ion-molecule reaction,

$$H_2 + H_2^+ \rightarrow H_3^+ + H\ ,$$

which has an exothermicity of 1.8 eV (see Oka 1983). Some of the excess energy is translational, but most remains within H_3^+ as internal excitation (Bowers, Chesnavich, and Huntress 1973). Thus newly formed H_3^+ must contain several quanta of vibrational energy. The observed absence of doubly excited states indicates that the observed line emission is not from freshly formed H_3^+, but from the mass of H_3^+ which was in the ground vibrational state, but was excited to $v_2 = 1$ by collisions with H_2 or He (all other prominent Jovian gases, such as CH_4, NH_3, and H_2O, have higher proton affinity than H_2 and destroy H_3^+). Excitation by H_2 is more efficient than by He, because it is a proton-hopping process with a Langevin rate.

Regarding the ortho to para ratio of H_3^+, we note that the value of ~2 found for Jupiter indicates that the abundances are thermalized at a relatively high temperature. This is not surprising given the likelihood of proton-hopping collisions for a rotational (kinetic) temperature of ~700 K. Since the proton-hopping rate is comparable to the rotational relaxation rate, it is probably reasonable to assume a vibrational temperature of ~670 K. We then obtain total H_3^+ column densities of 0.11–1.1 × 10^{13} cm^{-2}, comparable to the estimate of McConnell and Majeed (1987).

V. CONCLUSION

It is likely that the 4 μm bands of H_3^+ are uniquely suitable monitors of Jovian auroral activity. The present observations demonstrate the temporal nature of Jupiter's aurorae and point out the need for frequent monitoring in order to better correlate Jovian polar phenomena with solar and other activity.

We wish to thank the staff of UKIRT for its support. We also thank L. Kao for assistance with some of the observations. T. O. is supported by NSF grant PHY 87-07025 and Air Force contract FO4611-86-K0069.

REFERENCES

Bawendi, M., Rehfuss, B. D., and Oka, T. 1989, unpublished.
Bernath, P., and Amano, T. 1982, *Phys. Rev. Letters*, **48**, 20.
Bowers, M. T., Chesnavich, W. J., and Huntress, W. T., Jr. 1973, *Internat. J. Mass Spectrometry Ion. Phys.*, **12**, 357.
Carney, G. D., and Porter, R. N. 1976, *J. Chem. Phys.*, **65**, 3547.
———. 1980, *Phys. Rev. Letters*, **45**, 537.
Drossart, P., *et al.* 1989, *Nature*, **340**, 539.
Foster, S. C., McKellar, A. R. W., Peterkis, I. R., Watson, J. K. G., Pan, F. S., Crofton, M. W., Altman, R. S., and Oka, T. 1986, *J. Chem. Phys.*, **84**, 91.
Geballe, T. R., and Oka, T. 1989, *Ap. J.*, **342**, 855.
Maillard, J.-P., and Drossart, P. 1989, *California-France-Hawaii Telescope Bull.*, **20**, 13.
Majewski, W. A., Feldman, P. A., Watson, J. K. G., Miller, S., and Tennyson, J. 1989, *Ap. J.* (*Letters*), **347**, L51.
Majewski, W. A., Marshall, M. D., McKellar, A. R. W., Johns, J. W. C., and Watson, J. K. G. 1987, *J. Molec. Spectrosc.*, **122**, 341.
McConnell, J. C., and Majeed, T. 1987, *J. Geophys. Res.*, **92**, 8570.
Miller, S., and Tennyson, J. 1987, *J. Molec. Spectrosc.*, **216**, 183.
———. 1988, *J. Molec. Spectrosc.*, **128**, 530.
———. 1989, private communication.
Oka, T. 1980, *Phys. Rev. Letters*, **45**, 531.
———. 1981, *Phil. Trans. Roy. Soc. London*, **A303**, 543.
———. 1983, in *Molecular Ions: Spectroscopy, Structure, and Chemistry*, ed. T. A. Miller and V. E. Bondybey (Amsterdam: North-Holland), p. 73.
Trafton, L., Lester, D. F., and Thompson, K. L. 1989, *Ap. J.* (*Letters*), **343**, L73.
Watson, J. K. G., *et al.* 1984, *Canadian J. Phys.*, **62**, 1875.
Xu, L.-W., Gabrys, C., and Oka, T. 1989, unpublished.

T. R. GEBALLE: Joint Astronomy Centre, 665 Komohana Street, Hilo, HI 96720

T. OKA: Department of Chemistry, The University of Chicago, 5735 South Ellis Avenue, Chicago, IL 60637