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

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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 (ν_2 = 2 → 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, 2ν_2(2) → ν_2, 2ν_2(0) → ν_2, ν_1 + ν_2 → ν_1 (Bawendi, Rehfuss, and Oka 1989), and overtone band, 2ν_2 → 0 (Majewski et al. 1989; Xue, 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) → (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) → (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 = 5/2) to para (I = 1/2) spin
statistical weights of 4 to 2. The weak feature at 2468.0 cm\(^{-1}\) coincides with \(\text{H}_2^+ (5, 4, -1) \rightarrow (5, 4)\); however, the Doppler-shifted position of \(\text{H} \, \text{I} \, \text{Br} \alpha\) (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 \((3, K, -1) \rightarrow (3, K)\) 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 overture emission line, \((7, 9, +2) \rightarrow (6, 6)\) 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 overtones 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 \(\mu\)m region. In addition, the \(\text{H}_2\) S(1) line at 2.12 \(\mu\)m 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

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Transition & Frequency (cm\(^{-1}\) laboratory) & Intensity (10\(^{-16}\) W m\(^{-2}\) cm\(^{-1}\)) & Location \\
\hline
\(5, 4, -1 \rightarrow 5, 4\) (+ Brα?) & 2467.553 & 30 ± 10 & 3"N of S limb \(338^\circ\) \\
\(5, 0, -1 \rightarrow 5, 0\) & 2471.923 & 14 ± 2 & 3"S of N limb \(12\) \\
\hline
\(5, 1, -1 \rightarrow 5, 1\) & 2472.325 & 91 ± 1.5 & S limb \(35\) \\
\hline
\(5, 3, -1 \rightarrow 5, 3\) & 2472.846 & 55 ± 1.5 & 3"S of N limb \(12\) \\
\hline
\(5, 2, -1 \rightarrow 5, 2\) & 2473.238 & 4.0 ± 1.5 & S limb \(35\) \\
\hline
\(3, 1, -1 \rightarrow 3, 1\) & 2508.131 & 4.0 ± 1.5 & 3"N of S limb \(15\) \\
\hline
\(3, 0, -1 \rightarrow 3, 0\) & 2509.075 & 4.0 ± 1.5 & 3"S of limb \(118\) \\
\hline
\(2, 1, -1 \rightarrow 2, 1\) & 2518.207 & 4.0 ± 1.5 & 3"N of S limb \(118\) \\
\hline
\(1, 0, -1 \rightarrow 1, 0\) & 2529.724 & 4.0 ± 1.5 & 3"S of limb \(136\) \\
\hline
\(1, 1, +1 \rightarrow 1, 1\) & 2545.418 & 4.0 ± 1.5 & 3"S of N limb \(312\) \\
\hline
\end{tabular}
\caption{Observed \(v_2 \rightarrow 0\) lines of \(\text{H}_2^+\) during 1989 September 17-19}
\end{table}
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 \( \text{HeH}^+ \) (Bernath and Amano 1982) and \( \text{H}_2\text{D}^+ \) (Foster et al. 1986) fell in some of the observed spectral intervals near 4 \( \mu \text{m} \) and were absent.

A second interesting difference with some of the previous observations is the presence of \( \text{H}_2^+ \) lines from the \( v_2 \) 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 \( \text{H}_2^+ \) line emission further than \(~6^\circ\) from either pole. The brightest \( v_2 = 1 \rightarrow 0 \) lines we found were at the south limb at a System III longitude of \(~299^\circ\) and \(3^\circ\) south of the north limb at a longitude of \(~314^\circ\); however, we emphasize that complete coverage of either polar region was not achieved on any single morning.

### IV. DISCUSSION

The detection of the 4 \( \mu \text{m} \) band of \( \text{H}_2^+ \), together with measurements of the 2 \( \mu \text{m} \) 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 \( \text{H}_2^+ \) 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 \( \times 10^{13} \text{ cm}^{-2} \) 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

<table>
<thead>
<tr>
<th>Species</th>
<th>Transition</th>
<th>Frequency (cm(^{-1}) laboratory)</th>
<th>2 ( \sigma ) Limit (10(^{-16}) W m(^{-2}) sr(^{-1}), 5° beam)</th>
<th>Pole Longitude (System III)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2^+ )</td>
<td>( 2v_2 \rightarrow 0 (6, 3, 2) \rightarrow (7, 0) )</td>
<td>4319.0*</td>
<td>0.4</td>
<td>S 65°, N 80°</td>
</tr>
<tr>
<td></td>
<td>( 2v_2 \rightarrow 0 (3, 1, 2) \rightarrow (4, 4) )</td>
<td>4325.893</td>
<td>0.4</td>
<td>S 65, N 80</td>
</tr>
<tr>
<td></td>
<td>( 2v_2 \rightarrow 0 (7, 9, 2) \rightarrow (6, 6) )</td>
<td>4777.226</td>
<td>0.4</td>
<td>S 30–90, 220–280</td>
</tr>
<tr>
<td></td>
<td>( 2v_2 \rightarrow 0 (7, 9, 2) \rightarrow (6, 6) )</td>
<td>4777.226</td>
<td>0.4</td>
<td>N 0–90, 220–280</td>
</tr>
<tr>
<td></td>
<td>( 2v_2 \rightarrow v_2 (2, 0, -2) \rightarrow (2, 0, -1) )</td>
<td>2474.054</td>
<td>1.5</td>
<td>N 12, S 35</td>
</tr>
<tr>
<td></td>
<td>( 2v_2 \rightarrow v_2 (4, 1, 2) \rightarrow (4, 1, 1) )</td>
<td>2508.757</td>
<td>2.0</td>
<td>S 15, S 118</td>
</tr>
<tr>
<td></td>
<td>( 2v_2 \rightarrow v_2 (3, 1, 2) \rightarrow (3, 1, 1) )</td>
<td>2510.291</td>
<td>2.0</td>
<td>S 15, S 118</td>
</tr>
<tr>
<td></td>
<td>( 2v_2 \rightarrow v_2 (1, 1, 2) \rightarrow (1, 1, 1) )</td>
<td>2515.755</td>
<td>2.0</td>
<td>S 118, S 136</td>
</tr>
<tr>
<td></td>
<td>( 2v_2 \rightarrow v_2 (4, 0, 0) \rightarrow (3, 4, 1) )</td>
<td>2532.253</td>
<td>2.0</td>
<td>S 160, N 180</td>
</tr>
<tr>
<td>( \text{H}_3 )</td>
<td>( v = 1 \rightarrow 0, J = 3 \rightarrow 1 )</td>
<td>4712.91</td>
<td>0.7</td>
<td>S 30–90, 220–280</td>
</tr>
<tr>
<td></td>
<td>( v = 1 \rightarrow 0, J = 3 \rightarrow 1 )</td>
<td>4712.91</td>
<td>0.7</td>
<td>N 0–90, 220–280</td>
</tr>
<tr>
<td>( \text{HeH}^+ )</td>
<td>( v = 1 \rightarrow 0, J = 4 \rightarrow 5 )</td>
<td>2529.134</td>
<td>2.0</td>
<td>S 160, N 180</td>
</tr>
<tr>
<td>( \text{H}_2\text{D}^+ )</td>
<td>( v_2 \rightarrow 0, J = 3 \rightarrow 1 )</td>
<td>2505.693</td>
<td>2.0</td>
<td>S 15, S 118</td>
</tr>
<tr>
<td></td>
<td>( v_2 \rightarrow 0, J = 3 \rightarrow 1 )</td>
<td>2509.541</td>
<td>2.0</td>
<td>S 15, S 118</td>
</tr>
<tr>
<td></td>
<td>( v_2 \rightarrow 0, J = 3 \rightarrow 1 )</td>
<td>2512.598</td>
<td>2.0</td>
<td>S 15, S 118</td>
</tr>
</tbody>
</table>

* Theoretical value by Miller and Tennyson 1989.
to be present in the $v_2 = 2$ level when the 2 $\mu$m lines were detected.

A time variation in the excitation conditions for $\text{H}_2^+$ is apparent from the present rotational temperature, which is much lower than the value of $1100 \pm 100$ K found by Drossart in 1988 September. Assuming that the vibrational temperature is also $\sim 670$ 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 $\text{H}_3^+$ ions are produced through the well-known ion-molecule reaction,

$$\text{H}_2 + \text{H}_2^+ \rightarrow \text{H}_3^+ + \text{H},$$

which has an exothermicity of 1.8 eV (see Oka 1983). Some of the excess energy is translational, but most remains within $\text{H}_3^+$ as internal excitation (Bowers, Chesnavich, and Huntress 1973). Thus newly formed $\text{H}_3^+$ 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 $\text{H}_3^+$, but from the mass of $\text{H}_3^+$ which was in the ground vibrational state, but was excited to $v_2 = 1$ by collisions with $\text{H}_2$ or $\text{He}$ (all other prominent jovian gases, such as $\text{CH}_4$, $\text{NH}_3$, and $\text{H}_2\text{O}$, have higher proton affinity than $\text{H}_2$ and destroy $\text{H}_3^+$). Excitation by $\text{H}_2$ is more efficient than by $\text{He}$, because it is a proton-hopping process with a Langevin rate.

Regarding the ortho to para ratio of $\text{H}_3^+$, we note that the value of $\sim 2$ 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 $\sim 700$ K. Since the proton-hopping rate is comparable to the rotational relaxation rate, it is probably reasonable to assume a vibrational temperature of $\sim 670$ K. We then obtain total $\text{H}_3^+$ column densities of $0.11 - 1.1 \times 10^{13}$ cm$^{-2}$, comparable to the estimate of McConnell and Majeed (1987).

V. CONCLUSION

It is likely that the 4 $\mu$m bands of $\text{H}_3^+$ 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.

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