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INFRARED EMISSIONS OF H_3^+ IN THE ATMOSPHERE OF JUPITER IN THE 2.1 AND 4.0 MICRON REGION

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ABSTRACT

Infrared spectra of the Jovian atmosphere around 2.1 and 4.0 μm, measured using the NASA Infrared Telescope Facility at Mauna Kea Hawaii, are presented. The observations were made between 1990 February 6 and 8. In both spectral regions, features attributable to H_3^+ were visible. The intensity ratio of lines in the 2 and 4 μm regions measured from the northern auroral "hot spot" during the same night leads to a rovibrational temperature of 1100 ± 100 K for this molecular ion, close to a previous measurement of the rotational temperature of 1099 ± 100 K. This indicates that the upper energy levels are being populated by purely thermal processes, rather than by resonant energy exchange. The para-H_3^+ fractional abundance of 0.58 determined by previous workers is found to be consistent with this study. The time dependency of the H_3^+ emission phenomena is confirmed.

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

I. INTRODUCTION

There has been considerable interest in the study of the molecular ion H_3^+ in the atmosphere of Jupiter since its detection in the auroral "hot spots" in 1988 by Drossart *et al.* (1989) and Trafton, Lester, and Thompson (1989). Both these groups reported emissions in the *K* window (2 μm) region of the infrared spectrum. In both cases, the intensities of the lines measured were comparable to—if not greater than—the 2.122 μm *S*(1) quadrupole transition of neutral H_2.

These new features were identified as transitions from $2\nu_2$ ($l = 2$) vibrational overtone levels of H_3^+ to the ground vibrational state, ν_0, from the *ab initio*–first principles calculations of Miller and Tennyson (1987, 1988*a*, 1989) and the laboratory spectra of Majewski *et al.* (1989) and Bawendi, Rehfuss, and Oka (1989).

In their paper, Drossart *et al.* proposed that the formation of H_3^+ in the Jovian atmosphere was due to the ionization of neutral H_2 molecules by electron impact to form H_2^+, followed by the (highly exothermic) reaction:

$$H_2^+ + H_2 \rightarrow H_3^+ + H . \quad (1)$$

Drossart *et al.* proposed that this process occurred in the upper atmosphere of Jupiter, so that H_3^+ emissions would not be obscured by the planet's atmosphere.

Using *ab initio* Einstein *A*-coefficients (published in Majewski *et al.* 1989), Drossart *et al.* were able to determine a rotational temperature of 1099 ± 100 K for H_3^+ and a para-H_3^+ fractional abundance of $f_p = 0.58 \pm 0.03$. They came to the conclusion that the upper levels of H_3^+ could be populated either thermally or by nonthermal mechanisms such as a resonant exchange of vibrational energy with molecular H_2.

Trafton, Lester, and Thompson (1989) reported measurements of the Jovian spectrum around 2.1 μm taken between 1987 September and 1988 November. They observed a number of features—many of which were later identified as belonging to H_3^+—in spectra taken mainly from the north limb of Jupiter. Trafton *et al.* reported that the intensities of the features they observed varied with time.

This time dependence has been confirmed recently by Oka and Geballe (1990). They used a Fabry-Perot interferometer in conjunction with the cooled grating spectrometer, CGS2, mounted on the United Kingdom Infrared Telescope at Mauna Kea (UKIRT), to investigate both the *L′* and *K* window spectra of Jupiter. With this equipment (resolving power 12,000), Oka and Geballe were able to identify the *Q*(1) transition of the H_3^+ ν_2 fundamental band at 3.953 μm (2530 cm^{-1}). They were also able to resolve the *Q*(5) feature at 4.041 μm (2473 cm^{-1}) into its four strongest constituent lines. From this they were able to derive a rotational temperature of 670 ± 100 K, considerably lower than that deduced previously by Drossart *et al.* Oka and Geballe obtained a value of $f_p = 0.5$.

In addition, they detected the *Q*(1) ν_2 transition over a greater range of longitudes than had been reported for the $2\nu_2(l = 2)$ lines. The latitude range of the fundamental lines, however, did not vary greatly from that of the overtone transitions. Oka and Geballe reported that they could not clearly identify any H_3^+ lines at the lower resolution of around 450 that they achieved using the cooled grating spectrometer alone. Nor could they observe any H_3^+ emissions from vibrational energy levels above ν_2, either at low or high resolution.

From these studies it is clear that there are a number of

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issues which need to be addressed, concerning the observation of H_3^+ emissions from the Jovian atmosphere:

1. What is the mechanism by which the upper levels, from which emission takes place, are populated?

2. On what time scale are the observed emission features varying?

3. What is the spatial extent of the H_3^+ emissions over the surface of Jupiter?

II. OBSERVATIONS

Studies of H_3^+ in the Jovian atmosphere were made using the cooled grating spectrometer CGAS attached to the 3 m NASA Infrared Telescope Facility at Mauna Kea (IRTF), during the mornings of 1990 February 6 and 8 (Universal Time). Detailed data are presented only for the February 8 observations.

It was our intention to observe the *K* and *L*′ window emissions of H_3^+, in order to obtain information concerning the relative populations of the $2\nu_2(l = 2)$ overtone and ν_2 fundamental levels, and to monitor the spatial distribution of the emissions over the planet's surface. The instrumental field of view during the sessions concerned was 3″, while Jupiter's diameter subtended 40″.

Spectral scans from to 2.07 to 2.13 μm in the *K* window and 3.94 to 4.06 μm in the *L*′ window were made. These ranges were covered by the 30 detectors of CGAS. In several spectra, oversampling was obtained by shifting the central grating position by half a detector. All Jovian spectra were divided by the spectrum of a nearby G5 star, SAO 093785, to cancel the effects of telluric absorption lines.

During the February 6 session, data were obtained from a wide range of Jovian latitudes and longitudes, including the northern and southern auroral zones (System III latitudes ±60°, longitudes 180° and 60°, respectively) and the equator, between 06:45 UT and 11:20 UT. On February 8, 4.0 μm measurements of the northern auroral hot spot were made as it was tracked for 1 hr until 09:20 UT, the time at which the hot spot was "directly overhead." Measurements at 2.1 μm, tracking the hot spot, were then made for the subsequent hour.

The resolving power of CGAS is 1100 at 2.1 μm and 1000 at 4.0 μm. Our data are therefore at lower resolution than either the Drossart *et al.* Fourier transform infrared spectrometer measurements or the Fabry-Perot/CGS2 data of Oka and Geballe. They are, however, at higher resolution than the low-resolution measurements of Oka and Geballe, and comparable with those of Trafton *et al.* (resolution 1200), obtained using the McDonald Observatory Infrared Grating Spectrometer.

III. RESULTS

In Figures 1 and 2 we present the 4.0 and 2.1 μm spectra, respectively, recorded for the northern auroral hot spot during the February 8 session. Similar spectra were observed on February 6, but are not presented here.

The 4.0 μm data consist of the average of seven spectra divided by the spectroscopic standard to remove instrument and atmospheric effects. The 2.1 μm data consist of four spectra, similarly ratioed. All spectra were doubly oversampled by shifting the grating central wavelength by one-half a detector position. The 4.0 μm spectrum is shown oversampled to give an effective resolution of $\lambda/\Delta\lambda = 2000$. This has not been done for the 2.1 μm spectrum since fewer individual spectra were taken at this wavelength. In the figures, the (averaged) detector readings (*filled circles*) have been fitted with a low-order polynomial (*dashed curve*). Peak wavelengths and the identifications made as a result of the following deliberations are listed in Table 1.

Figure 1 shows five main peak regions occurring at 3.952, 3.970, 3.984, 4.012–4.028, and 4.042–4.058 μm. The continuum around 4.0 μm is almost zero, and the detector readings presented in the figure have not been subjected to any background subtraction.

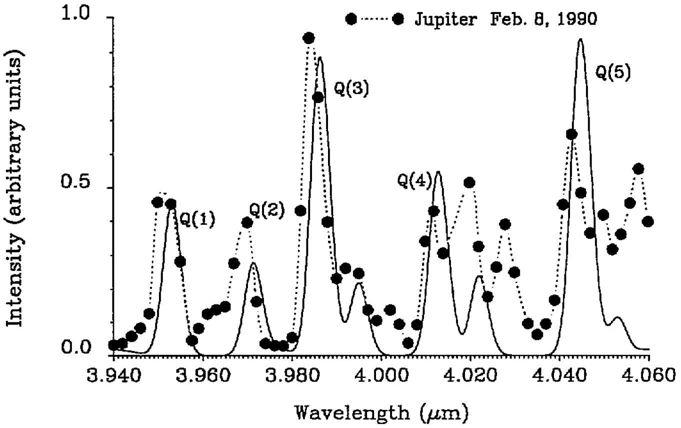

FIG. 1.—Comparison of the measured spectrum of Jupiter's northern auroral hot spot around 4.0 μm (System III latitude 60°N, longitude 180°) with that calculated *ab initio*. Temperature = 1100 K; $f_p = 0.58$. The integrated line intensity of the *ab initio* *Q*(1) peak is 2.78×10^{-22} W per molecule.

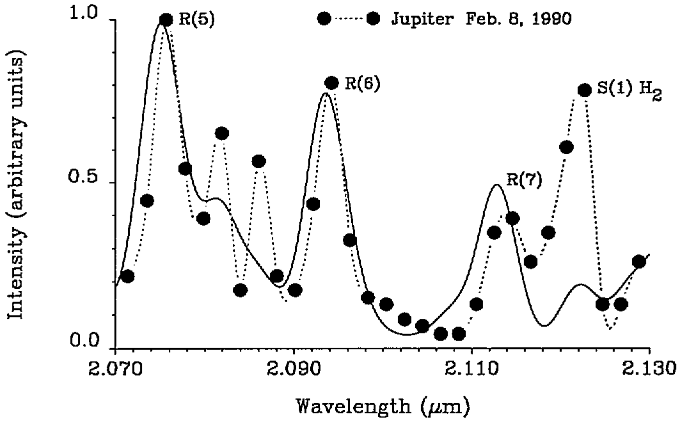

FIG. 2.—Comparison of the measured spectrum of Jupiter's northern auroral hot spot around 2.1 μm (System III latitude 60°N, longitude 180°) with that calculated *ab initio*. Temperature = 1100 K; $f_p = 0.58$. The integrated line intensity of the *ab initio* *R*(6) peak is 2.46×10^{-26} W per molecule.

TABLE 1

JOVIAN NORTHERN AURORAL HOT SPOT EMISSION PEAKS

Vibrational Assignment	Rotational Assignment	Observed Wavelength (μm)	Calculated Wavelength (μm)
H_3^+ $2\nu_2(l = 2)$–ν_0	*R*(5)	2.075	2.074
H_3^+ $2\nu_2(l = 2)$–ν_0	*Q*(3) + *P*(4)	2.082	2.081
H_3^+ $2\nu_2(l = 2)$–ν_0	*Q*(2)	2.086	2.086
H_3^+ $2\nu_2(l = 2)$–ν_0	*R*(6)	2.094	2.093
H_3^+ $2\nu_2(l = 2)$–ν_0	*R*(7)	2.113	2.113
H_2 $v = 1$–0	*S*(1)	2.122	2.122
H_3^+ ν_2–ν_0	*Q*(1)	3.952	3.953
H_3^+ ν_2–ν_0	*Q*(2)	3.970	3.972
H_3^+ ν_2–ν_0	*Q*(3)	3.984	3.986
H_3^+ ν_2–ν_0	*Q*(4)	4.014	4.014
H_3^+ ν_2–ν_0	*Q*(5)	4.042	4.044

As well as the $Q(1)$ ν_2–ν_0 transition at 3.953 μm, Oka and Geballe also found a broader feature at around 3.948 μm. Otherwise, they reported that around this wavelength the background radiation was totally absorbed and concluded that the $Q(1)$ line would be useful for monitoring H_3^+ emissions. We therefore ascribe the feature observed at 3.952 μm to the $Q(1)$ line of H_3^+, which is expected to occur at 3.953 μm—within the accuracy of our spectral resolution. The slight shift in peak position, however, could result from blending with a weak 3.948 μm feature, although the separation between this wavelength and the peak we observe is within the limit of the resolving power of CGAS.

The spectrum of Jupiter around 2.1 μm consists of a number of peaks superposed on a concave continuum (Trafton *et al.* 1989). In Figure 2, these features are shown with the background continuum subtracted as described below. The strongest of these are at 2.075, 2.094, 2.113, and 2.122 μm. The first three of these are due to the $R(5)$, $R(6)$, and $R(7)$ transitions of the $2\nu_2(l = 2)$–ν_0 overtone band of H_3^+ (Drossart *et al.* 1989; Trafton *et al.* 1989); the last is the $S(1)$ quadrupole transition of the H_2 fundamental vibration.

The rovibrational temperature of H_3^+ in the northern hot spot may be calculated to a good approximation from the ratio of peak heights of the $[\nu_2$–$\nu_0]$ $Q(1)$ and $[2\nu_2(l = 2)$–$\nu_0]$ $R(6)$ (2.094 μm) lines, using the *ab initio* Einstein A-coefficients and upper energy levels (Miller and Tennyson 1988*b*, 1989).[2] Both of these lines are due to ortho-H_3^+, so there is no need to assume a value of the ortho/para ratio.

This calculation gives a rovibrational temperature of 1100 K, for an assumed Boltzmann population of both rotational and vibrational levels. Errors arising from fixing the background radiation level in the 2.1 μm region are the main source of uncertainty in this calculation. Together with statistical errors from the measurements themsleves, we consider an uncertainty of ±100 K should be attached to our value 1100 K. This is very close to the rotational temperature of 1099 ± 100 K obtained by Drossart *et al.* from their K window spectra.

This temperature may then be used, along with the para-H_3^+ fraction of 0.58 deduced by Drossart *et al.*, to simulate an *ab initio* 4.0 μm spectrum at the spectral resolution available on CGAS in this wavelength range. The result of this simulation is shown in Figure 1 (*full curve*). In order to compare the calculated and measured spectra, the intensities at 3.953 μm have been set to be equal, in accordance with the assumption that the measured peak may be assigned to the $Q(1)$ transition of H_3^+.

The *ab initio* spectrum shows peaks at 3.953, 3.972, 3.986, 4.013, and 4.044 μm (Table 1), representing a series of lines or blends of lines, $Q(n)$, of the ν_2–ν_0 band, where $n = 1$–5. Additional side peaks are produced at 3.995, 4.023, and 4.054 μm due to weaker lines in the $Q(3)$, $Q(4)$, and $Q(5)$ group.

The H_3^+ transitions clearly reproduce a significant portion of the observed spectrum from the northern auroral hot spot. In particular, the main $Q(1)$ and $Q(3)$ peaks fit the Jovian spectrum very well. Around the wavelengths at which the *ab initio* spectrum produces the $Q(2)$, $Q(4)$, and $Q(5)$ peaks, however, emissions due either to other species or to background radiation are apparent. The agreement between the computed and observed spectra indicates that our data is consistent with the Drossart *et al.* value of f_p.

In order to fix the level of the concave continuum in the 2.1 μm measurements, we calculated the spectrum due to H_3^+ at 1100 K. This is shown in Figure 2 (*full curve*). The computed curve does not reach zero intensity anywhere but shows a number of minima in between the main spectral features. We used this residual intensity to estimate the position of the Jovian continuum at these points and then fitted a smooth curve to get the background emission across the spectral range from 2.070 μm to 2.130 μm.

Intensities at the individual detector positions (Fig. 2, *filled circles*) were then measured from this background and fitted with a low-order polynomial (*dashed curve*). The resulting spectrum is in good agreement, once more, with that calculated, showing, in addition, the $S(1)$ quadrupole transition of H_2.

IV. DISCUSSION AND CONCLUSIONS

1. The detailed study of the northern auroral hot spot conducted on February 8 gives an important insight into the physical processes governing the excitation of H_3^+. Our derived rovibrational temperature is in good agreement with that of Drossart *et al.* for the rotational temperature of the $2\nu_2(l = 2)$ upper levels, indicating that both the rotational and the vibrational temperatures are around 1100 K. This would support the conclusion that both the ν_2 and $2\nu_2(l = 2)$ levels are populated thermally and rule out a resonant exchange of vibrational energy between the H_3^+ ions and neutral H_2 which would preferentially populate the $2\nu_2(l = 2)$ levels. Our data are also consistent with Drossart *et al.*'s value of f_p.

With these parameters we compute a 4.0 μm spectrum which is very similar to that observed. This would indicate that the five main features measured in this region are attributable to H_3^+. At first sight, this might appear to be at odds with the result of the low-resolution spectra of Oka and Geballe (1990). They concluded that none of their CGS2 spectra could meaningfully be ascribed to this molecular ion.

However, their Fabry-Perot measurement of the resolved $Q(5)$ transitions indicated a rotational temperature of only 670 ± 100 K. We compute that this would have resulted in intensities of the 4.0 μm features being only 25% of those for a temperature of 1100 K. In addition, the resolution of GCS2 is roughly half that CGAS (assuming no oversampling) in this spectral region. Thus their expected peak intensities would have been only about one-eighth of those we measured, probably too low to be clearly noticeable.

The failure of Oka and Geballe to observe any $2\nu_2(l = 2)$–ν_0 transitions may be taken as further support for the conclusion that the upper emitting levels of H_3^+ are being populated thermally. We compute that the populations of the $2\nu_2(l = 2)$ levels at 670 K would be less than 3% of those at 1100 K, resulting in emission intensities probably too low to be measured.

2. Our study also confirms that the intensity of the H_3^+ emissions and the hot spot temperatures are time-dependent when viewed at intervals of a few months. Our data are consistent with those of Drossart *et al.*, recorded in 1988 September, but not with the spectra of Oka and Geballe, taken a year later.

Oka and Geballe's observations were made during several periods in 1989 September, each separated by a few days. They reported no time variations with a periodicity of a few days. Similarly, we measured almost identical spectra on 1990 February 6 as on February 8. It would thus appear that the phenomena observed are stable when observed at intervals of a few days.

The 4.0 and 2.1 μm spectra observed during the February 8 session were all measured within a period of 2 hr. The averaged

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[2] Note that the Einstein A-coefficients of Miller and Tennyson (1988*b*) must be divided by $(2J_{\mathrm{upper}} + 1)$ to be used correctly.

spectra at both wavelengths can be reasonably fitted with the same temperature and f_p, nor are there any striking differences in absolute or relative intensities of the individual spectra taken at each wavelength. We feel that this rules out variability over a period shorter than a few hours.

3. We have not attempted to investigate the extent of the spatial distribution of H_3^+ emissions in this paper. Further studies are planned to augment our existing data and examine this question in detail.

Nor have we attempted to simulate the features observed in the 4 μm spectrum additional to those ascribed to H_3^+. Suggestions that they are due to blackbody radiation from the core of Jupiter "leaking" through the middle atmosphere are currently under investigation.

4. Although greater resolving power is always desirable, we consider that we have demonstrated the use that can be made of moderate-resolution ($\lambda/\Delta\lambda = 1000$) grating spectra to probe the physical conditions of the Jovian atmosphere. The advantage of such measurements is that they can be made in relatively quick succession, so that short-term (of order 1 or 2 hr) atmospheric fluctuations may be eliminated.

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