On the Dynamics of the Jovian Ionosphere and Thermosphere II: the Measurement of H$_3^+$ Vibrational Temperature, Column Density and Total Emission

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September 4, 2001

Pages: 48

Figures: 13

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Abstract

We present the first reported measurements of the intensity of a “hotband” transition for the H$_3^+$ molecular ion in the northern auroral/polar region of Jupiter. This transition is identified as the R(3,4') line of the (2v$_2$(l=0)$\rightarrow$ v$_2$) hotband, with a wavelength of 3.94895 microns. This is the first time such a transition has been measured outside of the laboratory, and the wavelength as measured on Jupiter is within the experimental accuracy of the lab measurement. This detection makes it possible investigate H$_3^+$ transitions that simultaneously originate from different vibrational levels. We use the intensity ratio between this line and the Q(1,0') fundamental transition to derive effective vibrational temperatures, column densities and total emission parameters as a function of position across the auroral/polar region. Effective temperatures range from ~900K to ~1250K; an increase in average temperature during our observing run of ~100K is noted. The derived temperatures are towards the high end, or in excess of, the auroral temperature range that has been reported in the literature to date. The relationship between emission intensity and temperature, and density, is shown to be complex. This may reflect the non-thermalisation of the vibrational levels at the gas densities prevailing in the jovian thermosphere. An alternative analysis allowing for this effect is presented. But this approach requires thermospheric temperatures to be ~1500K at the level that the majority of H$_3^+$ is being produced, higher than has previously been proposed.
Keywords

AURORAE
INFRARED OBSERVATIONS
IONOSPHERES
JUPITER, ATMOSPHERE
SPECTROSCOPY
Introduction

This paper is the second in a series looking at the dynamic conditions prevailing in the jovian upper atmosphere - the coupled thermosphere and ionosphere. For the sake of brevity, therefore, readers are referred to our first contribution - Stallard et al. (2001), henceforth Paper I - for much of the general discussion relevant to this area of active investigation. In particular, in Paper I we draw attention to considerable interest currently being shown in the relationship between the auroral/polar regions of Jupiter and the dynamics of the middle magnetosphere - interest which is likely to increase with the ongoing publication of results from the Galileo mission. This paper presents a spatially detailed analysis of $\text{H}_3^+$ temperatures, column densities and emission rates across the auroral/polar regions of Jupiter, enabling us to investigate the extent to which assumptions about the physical conditions of the upper atmosphere are justified.

Our initial analysis assumes that a form of local thermal equilibrium (LTE) prevails, such that vibrational temperatures are representative of the neutral thermosphere as well as the ionosphere (e.g. Lam et al., 1997; Miller et al., 1997). At the pressure levels where $\text{H}_3^+$ peak auroral production is located, ~0.3 microbars (Achilleos et al., 1998), neutral $\text{H}_2$ molecules make up the bulk of the thermosphere, and thus control the typical time between collisions (~$10^{-10}$s). The typical time before emission from neutral $\text{H}_2$ and rotational lines of $\text{H}_3^+$ ($10^7$s and $10^3$s respectively; Miller and Tennyson (1988)) is thus much longer than the time between collisions. This means that LTE clearly holds...
within the H$_2$ thermosphere and that the rotational sub-levels within any particular H$_3^+$ vibrational band are also thermalised in the ionosphere.

However, typical ro-vibrational radiation times, $\tau_{rv}$, are of the order of $10^{-2}$s for H$_3^+$. Given that vibrational excitation may be highly inefficient, the effective collisional vibration excitation time, $\tau_{v,\text{col}}$, may not be much shorter than $\tau_{rv}$. Only one study has so far tried to determine whether H$_3^+$ vibrational levels are thermally populated. Miller et al. (1990) used the ratio between $(2\nu_2(l=2)\rightarrow 0)$ overtone line intensities and those of the $(\nu_2\rightarrow 0)$ fundamental to determine a ro-vibrational temperature of ~1000K, in reasonable agreement with the rotational temperatures deduced from ratioing lines with in the same vibrational band. Miller et al. (1997) called this situation “quasi-local thermal equilibrium” (QTE). (QTE can be considered to be equivalent to the notion of “effective thermal equilibrium” discussed by Spitzer (1998a) with regard to the interstellar medium.)

Knowing the extent to which vibrational levels are thermalised is important for determining the overall emission levels and, hence, the thermal balance of the jovian upper atmosphere, since H$_3^+$ is the principal coolant of this atmospheric region. To do this means, ideally, measuring transitions from different vibrational levels simultaneously. In this paper, we present the detection of emission from an H$_3^+$ hotband, along with emission from the fundamental band. Whilst making measurements of the $\nu_2$ Q(1,0') line at 3.9530 microns, for the purposes of determining ionospheric wind velocities,
we also detected the $R(3,4^+)$ line of the $(2\nu_2(l=0)\rightarrow\nu_2)$ band at 3.9499$\mu$m. This is the first time a hotband line has been reported detected outside of the laboratory, and our simultaneous measurement of two vibrational lines presented us with the opportunity of determining “vibrational temperatures”.

**Observations**

All the observations reported here were carried out using the CSHELL facility infrared echelle spectrometer on the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. Our observations were made on the nights of September 7 to 11 (UT), 1998. The echelle was set up to measure the $Q(1,0^-)$ line in the fundamental $\nu_2(v_2=1\rightarrow0)$ vibrational band of the $H_3^+$ molecular ion, at 3.9530$\mu$m, and the slit was set to 0.5”, giving a nominal resolving power of 40,000. This was orientated parallel to the jovian equator, moving the slit from the polar limb equatorwards in 1” steps across the jovian auroral/polar regions. Details of the observations and their reduction are given in Paper I.

Figure 1a presents a single exposure (50s) spectral image of the northern auroral/polar region, taken on the night of September 11, 1998, at a jovian central meridian longitude (CML) of 166°. As well as the $Q(1,0^-)$ line at the centre of the array, a secondary line is clearly visible at a shorter wavelength. For comparison, in Fig. 1b we show the sum of 20 spectral images taken in a previous observing run in September 1997. Only the slightest hint of the secondary line is visible in that spectral image.
The secondary line showed very clearly in the array for almost all of the spectral images obtained, with its intensity, with respect to the \(Q(1,0')\) line, increasing from September 7 to 11. We first considered that this previously unobserved line might be a “ghost” - an internal reflection of \(Q(1,0')\). But we rejected this after discussions with the instrument designers (private communication, J. Rayner) for the following reasons:

- Internal reflections in CSHELL should be symmetric about the centre of the array. Since the \(Q(1,0')\) line had been centred on the array, its ghost should have been (nearly) coincident with it. But, as Fig. 1a shows, this secondary line was near the edge of the array;
- The wavelength displacement between the secondary line and \(Q(1,0')\) was constant throughout our observing run, although the exact position of \(Q(1,0')\) varied slightly from night to night as a result of moving the array between nightly observations. A “ghost” would be expected to change in relative displacement, as a result of differing reflectance angles due to changes in the exact array positioning;
- Although the intensity of the secondary line and \(Q(1,0')\) were generally well correlated across the array, as would be expected from a “ghost”, the relative intensity varied from \(~1\%\) to \(>3\%\) along the slit, for any particular spectral image, indicating that the secondary line was behaving somewhat independently of \(Q(1,0')\).

These factors, taken together with the non-detection of the secondary line in the previous year’s data, led to the conclusion that it was a genuine jovian emission and not an instrumental artifact.
In order to determine the exact wavelength of this line, rows across one of the spectral images where the line was observed clearly were co-added along the slit, and the resulting secondary line peak compared with arc lines - similarly co-added along the slit - measured earlier the same night. Figure 2 shows the result of this comparison (allowing for the relative motion between the Earth and Jupiter). The secondary line appears almost centrally between the Argon arc lines that have an apparent wavelength of 3.94783\(\mu\)m and 3.94989\(\mu\)m. Its wavelength was best fitted with a gaussian peak of central wavelength 3.94895\(\mu\)m, corresponding to a wavenumber of 2532.319\(\text{cm}^{-1}\). This is within the experimental error of the laboratory frequency of the \((2\nu_3(l=0)\rightarrow\nu_2)\ R(3,4^+)^\) line of \(H_3^+\) given as 2352.253\(\text{cm}^{-1}\) (Kao et al., 1991), and - since the line had a similar intensity profile to the \(Q(1,0^-)\) - we felt this compelling evidence that our secondary line was indeed the \(R(3,4^+)\), observed in the jovian northern auroral/polar region for the first time.

Temperature determination

In LTE, the intensity of an \(H_3^+\) line may be calculated from the usual equation, assuming the emission is optically thin (Lam et al. 1997):

\[ I(\omega_f) = N(H_3^+) \times [g_{ns}(2J'_+1) h c \omega_f A_{if} \exp(-E'/kT)] / 4\pi Q(T) \]  

(1)

where \(I(\omega_f)\) is the line intensity for the \((if)\) transition; \(N(H_3^+)\) is the column density along the line of sight; \(g_{ns}\) is the nuclear spin weight (4 for ortho...
transitions, 2 for para); $J'$ is the rotational quantum number of the upper level of the transition; $\omega_i$ is the frequency in wavenumbers; $A_{ii}$ is the Einstein A-coefficient for spontaneous emission; $E'$ is the energy of the upper level; $Q(T)$ is the partition function at a thermospheric temperature $T$. In what follows, we assume a single temperature may be derived from our data. In reality, the parameters we deduce are local-density-weighted averages along the line of sight. For the auroral regions, however, $H_3^+$ concentrations peak in a relatively narrow altitude range (Achilleos et al., 1998; Grodent et al., 2001), so this approximation is fairly good.

In the QTE approximation, where it is assumed that the ratio of vibrationally excited levels should approximate to a Boltzmann distribution, this equation may be used to derive vibrational temperatures, $T_{\text{vib}}$, by ratioing lines from different vibrational manifolds. The relevant parameters are given in Table I (from Kao et al. 1991); for our lines, Eq. 1 then gives:

$$T_{\text{vib}} = \frac{hc}{k} \cdot \frac{[E'_{HB} - E'_{\text{FUND}}]}{[\ln(\beta) - \ln(I(\omega_{HB})/I(\omega_{\text{FUND}}))]}$$

$$= \frac{3783.3}{[-0.2637 - \ln(I(\omega_{HB})/I(\omega_{\text{FUND}}))]}$$

where $\beta$ is given by the ratio of the pre-exponential terms in Eq.1, and the subscripts HB and FUND refer to $R(3,4^+)$ hotband and $Q(1,0^+)$, respectively.

Figure 3 shows the intensity profiles for the $Q(1,0^+)$ transition (dark line) and the $R(3,4^+)$ transition (light line) corresponding to Fig 1a, the 11N4#166 spectral image. The intensities were obtained by fitting a gaussian profile to both the fundamental and hotband lines (see Paper I) and were corrected for
array distortions using star spectra. The intensity profiles of both lines show the Rising Auroral Oval (RAO) peak (East on the sky, left on Fig. 3), the Dark Polar Region (DPR), the Bright Polar Region (BPR) and the Setting Auroral Oval (SAO) discussed in Paper I.

Figure 4 shows the values of $T_{\text{vib}}$ derived for the range of values of $I(\omega_{\text{HB}})/I(\omega_{\text{FUND}})$ typically found in our data. In the auroral/polar regions, errors in the fundamental intensity measurement for our high signal-to-noise (S/N ~20 to 100) lines were typically less than 5%. But the weaker hotband intensities could usually be measured only to between +/-10% and 15%. This gave $I(\omega_{\text{HB}})/I(\omega_{\text{FUND}})$ errors typically of +/-11% to 16%, with some individual pixels slightly higher. Figure 4 shows the potential range for our temperatures assuming an error of +/-17.5% (in auroral regions) and +/-35% (for peri-auroral regions), although some of this error is offset in practice because of the greater intensity of R(3,4’) with increasing temperature.

Figure 5 shows vibrational temperature profiles derived from Eq. 2, calculated using a rolling average of $I(\omega_{\text{HB}})/I(\omega_{\text{FUND}})$ smoothed over nine pixels along the slit, for the northern auroral/polar region, covering the nights of September 8, 10 and 11. Also shown are the corresponding intensity profiles of Q(1,0’). The profiles have been selected to show both “typical” behaviour (e.g. left hand panels) and departures from this (e.g. right hand panels). The Q(1,0’) profiles reflect the way the CSHELL slit cut east-west across the auroral/polar region at the time of observation. Values of $T_{\text{vib}}$ range between 900K and 1150K, although local maxima and minima outside of this range are also apparent.
The higher temperature values are at the upper end of the range so far reported (see review by Miller, et al., 2000). The profiles show there are considerable pixel-to-pixel variations. In part these reflect the difficulty of accurately measuring the hotband intensity. In what follows, therefore, trends in temperature profiles, rather than individual location results, are discussed.

In general in our overall dataset, the rising side of the planet (east on the sky) is hotter than the centre and the setting side of the planet by about 50K-100K. Looking at the four regions identified in Paper I, in the majority of our $T_{\text{vib}}$ profiles, the RAO and BPR are regions of higher temperature and the DPR and SAO regions of lower temperature. In Fig. 6, we present the $T_{\text{vib}}$ profiles for the 11N4 dataset, referred to in detail in Paper I. These generally show the behaviour described above. But there are clear exceptions to this: the profile obtained at a CML of $\lambda_{\text{III}}=159^\circ$ on September 11 (11N4#166) has the highest temperatures on the SAO, which is about 50K warmer than the RAO, although the profile obtained 1” equatorward of this (11N4#168, $\lambda_{\text{III}}=160^\circ$), as well as those obtained at similar locations on September 8 ($\lambda_{\text{III}}=153^\circ$) and September 10 ($\lambda_{\text{III}}=151^\circ$), have the RAO as the warmest region. From these data, it is clear that derived $T_{\text{vib}}$ values do not correlate particularly well with the $Q(1,0)$ intensity; this is especially the case for the SAO, which generally represents an intensity maximum but a temperature minimum.

Figure 7 shows the temperatures derived from averaging $T_{\text{vib}}$ across individual profiles as a function of time. Table II gives nightly averages of the
profile-averaged temperatures. (To indicate relatively reliability, the integrated hotband signal-to-noise is also given.) Two trends emerge:

- The scatter on profile-averaged temperatures decreases from ~400K on September 8 (the first day for which more than 10 profiles were obtained) to ~100K on September 11;
- The nightly averaged temperature increases from 955K (weighted average of September 7 and 8) to 1065K (September 11). In addition, for September 10 - the night for which most data were obtained - there is a rise of ~50K during the night.

We take this as evidence that the auroral/polar region was generally warming during the course of our observations (see further in Discussion section), since the nightly averaged values of $T_{\text{ vib}}$ have associated errors of just +/- 15K. Figure 8 shows the profile-averaged values of $T_{\text{ vib}}$ as a function of the CML at which the profile was obtained. The nightly scatter is apparent in the figure, but there is also a trend to maximum temperatures centred around CML $\lambda_{\text{III}}$=190°-200°, an orientation where the northern auroral/polar region is most exposed to sunlight (and - possibly - the solar wind).

**Column density and total emission**

In the QTE approximation, we can derive values for the column density, $N(H_3^+)$, from Eq. 1, although these may underestimate the real total $H_3^+$ column density if there is a relative overpopulation of the Ground State, as has been suggested by Kim *et al.* (1992). We can also derive values for the
total emission, \( E(\text{H}_3^+) \), determined by calculating the total emission per molecule at a given temperature, assuming LTE, and multiplying it by the number of emitters in the line of sight (Lam et al., 1997). This parameter is stable to within +/-10% for the extremes of the range of \( T/N(\text{H}_3^+) \) values which could be expected within the auroral region. Additionally, at temperatures around 1000K, more than 90% of the emission is due to \( \nu_2 \) transitions, so \( E(\text{H}_3^+) \) is affected little by QTE, or by even greater departures from LTE. (Since \( \text{H}_3^+ \) has no permanent dipole there is no Ground State rotational spectrum, to first order, and so \( E(\text{H}_3^+) \) is not affected by any overpopulation of this level (Lam et al., 1997).)

The data is presented in the form of line-of-sight (l.o.s.) corrected values, using a secant correction, with an additional factor on the limb to account for the high altitude of \( \text{H}_3^+ \) and the pixel filling factor. (*) denotes l.o.s. corrected values. Figure 9 shows these for the 11N4 dataset. \( N^*(\text{H}_3^+) \) values vary between \( 3 \times 10^{15} \text{ m}^{-2} \) in the DPR to \( 1.4 \times 10^{16} \text{ m}^{-2} \) in the SAO. Figure 10 shows the corresponding values of the total emission, \( E^*(\text{H}_3^+) \), ranging from 0.6milliWatts \text{ m}^2 in the DPR to 3.1mW \text{ m}^2 in the SAO. These values are typical of those reported previously (Lam et al., 1997; Satoh and Connerney, 1999; Rego et al. 2000), but even using a 9-pixel rolling average these results show much more structure across the auroral/polar region than has previously been derived. These values confirm the importance of \( \text{H}_3^+ \) as a thermospheric cooling agent.
Both $N^*(H_3^+)$ and $E^*(H_3^+)$ correlate strongly with the l.o.s. corrected $Q(1,0')$ intensity profiles, unlike $T_{\text{vib}}$. This is an important result, since mapping $H_3^+$ emission in just one (Rego et al., 2000) or a few (Satoh and Connerney, 1999) line(s) assumes that a limited spectral range will be representative of overall $H_3^+$ behaviour and distribution. It is also important because such studies relate emission levels directly to ion density. Since auroral/polar $H_3^+$ densities are dependent on the flux of energetic particles - although not necessarily linearly (Millward et al., work in progress) - the close correspondence between $N^*(H_3^+)$ and/or $E^*(H_3^+)$ and the $Q(1,0')$ intensity validates using this ion as a quantitative tracer of energy inputs.

Table III gives the nightly averaged values of $N^*(H_3^+)$ and $E^*(H_3^+)$. These are more problematic to interpret than $<T_{\text{vib}}>$, since the value of these parameters depends critically on the viewing geometry of ionospheric structures. Nightly averaged values range from $0.62 \times 10^{16} \, \text{m}^{-2}$ on Sept. 8 to $1.10 \times 10^{16} \, \text{m}^{-2}$ on Sept. 11, and from $0.60 \, \text{mW} \, \text{m}^{-2}$ on Sept. 8 to $1.24 \, \text{mW} \, \text{m}^{-2}$ on Sept. 7 for the two averages. Neither $<N^*(H_3^+)>$ nor $<E^*(H_3^+)>$ show a smooth trend of the period of the observation run. Part of this is due to the fact that on September 7 and 9, the northern aurora was displayed high on the polar limb, where the line-of-sight correction is most difficult to apply. These are also the nights when fewest spectral images for the northern hemisphere were obtained. However, the Table III does show a distinct increase in both $<N^*(H_3^+)>$ and $<E^*(H_3^+)>$ for Sept. 11, when the northern auroral region was well displayed on the planet, over Sept. 8 and Sept. 10, the other two days for similar auroral/polar viewing geometry was available.
Departure from QTE/LTE

In the foregoing data analysis we have made use of the QTE approximation as formulated by Miller et al. (1990), where relative populations of excited vibrational levels approximate to a Boltzmann distribution and that the temperatures derived from H$_3^+$ therefore represent the true thermospheric temperatures. However, Kim et al. (1992) question whether vibrationally excited states of H$_3^+$ would be thermally populated in the jovian ionosphere. Their conclusion was that vibrationally excited levels would be relatively underpopulated with respect to the Ground State. They also proposed that the overtone (v$_2$=2) level might be additionally populated by the resonant excitation mechanism:

$$\text{H}_2(\text{v}=1) + \text{H}_3^+(v_1,v_2=0) \rightarrow \text{H}_2(\text{v}=0) + \text{H}_3^+(v_1=0,v_2=2)$$  \hspace{1cm} (3)

since the vibrational energies of H$_2$(v=1) and H$_3^+(v_1=0,v_2=2)$ are nearly equal.

Overall, Kim et al.’s 1992 model produced populations for the lower (E$_{\text{vib}} < 0.8$eV) vibrational levels of H$_3^+$ which were 50%-60% of those expected from a Boltzmann distribution, including the effect of Eq. 3.

If the vibrational excited levels of H$_3^+$ are not thermally populated, then the intensity ratio between the two lines observed must be dependent on the collisional excitation rate and, thus, on the local H$_2$ density. Following Kim et al. (1992) and Schultz et al. (1997), we assume the most effective way of producing vibrational excitation in H$_3^+$ is by the “proton hopping” reaction:
\[ \text{H}_3^+ + \text{H}_2^+ \rightarrow \text{H}_2 + \text{H}_3^{+*} \]  

(4)

where the asterix denotes the colliding molecule. The value of the vibrational collision rate for a particular level \((\tau_{v=n,\text{col}})\) is then given by:

\[
\tau_{v=n,\text{col}} = \{k_{\text{PH}} \times [\text{H}_2] \times \exp(-E_{v=n}/kT)\}^{-1} = \tau_{v=0,\text{col}} \exp(E_{v=n}/kT) \tag{5}
\]

where we have explicitly included reference to the particular \(v=n\) \((n=1(1)\) or \(n=2(0)\)) vibrational level, and used \(\tau_{v=0,\text{col}}\) (henceforth \(\tau_{v,\text{col}}\))\(= \{k_{\text{PH}} \times [\text{H}_2]\}^{-1}\). \(T\) is the true kinetic temperature of the neutral thermosphere, and determines the proportion of collisions sufficiently energetic to cause a change in \(\text{H}_3^+\) vibrational level. \(k_{\text{PH}}\) can be calculated for a given temperature using the typical ion-molecule reaction rate favoured by Schultz et al. (1997):

\[
k_{\text{PH}}(T) = k_{\text{PH}}(T=1000) \times [T/1000.0]^{1/2} \text{ (m}^3\text{ s}^{-1}) \tag{6}
\]

We set \(k_{\text{PH}}(T=1000K) = 10^{-15}\text{ m}^3\text{ s}^{-1}\). The distribution of radiative decay from any given ro-vibrational level can be modelled by a factor, \(b\), which weights the collision time, \(\tau_{v,\text{col}}\), using the following function:

\[
b = \sum_{i} A_{ig}/A_{if} \tag{7}
\]
where the sum is over all the possible radiative decays from the upper level.

In order to assess the influence of non-thermal conditions on the intensity of individual lines, we use a simple modification of the normal equation governing spontaneous line emission (Rego et al., 2000):

$$I(\omega) \propto \left[ g_{ns}(2J' + 1) \frac{hc\omega_{if} \exp(-E'/kT)}{4\pi Q(T)b_{\tau_{v=\text{col}} + \tau_{if})} \right]$$

(8)

where \(\tau_{if}\) is the reciprocal of the Einstein A-coefficient for the transition.

For the Q(1,0') line, \(b_{\text{FUND}}=1\), since the 1,0' rotational sub-level of the \((v_2=1,l=1)\) vibrational level can only radiatively decay to the (1,0) Ground State level. \((v_2=2,l=0)\) is of higher energy than the \((v_2=1,l=1)\) and \((v_1=1,l=0)\) levels, as well as the Ground State, but it can only decay into the first of these three lower levels, since \((l=0)\rightarrow(l=0)\) transitions are forbidden. The 4,4 level of \((v_2=2,l=0)\) can radiate into \((v_2=1,l=1)\) 5,4' (P-branch) and 4,4' (Q-branch), as well as the 3,4' level which gives the R-branch transition of interest here. The latest transition strengths available (Neale et al., 1996) then give \(b_{\text{HB}}=1.8\) from Eq. 7, for the R(3,4') line. For the two levels we are discussing, Eq. 5 and Eq 8 lead to:

$$I(\omega_{\text{HB}})/I(\omega_{\text{FUND}}) = \frac{1.502 \exp(-3783.3/T) \times [\tau_{v=\text{col}} \exp(3625.6/T + 0.00775)]}{[1.8 \times \tau_{v=\text{col}} \exp(6869.5/T + 0.01515)]}$$

(9)
where we have specifically included the values of \((E'_{R(3,4+)} - E'_{Q(1,0-)})\), \(E_{v=2(0)}\) and \(E_{v=1}\) in kelvin, as well as the reciprocals of \(A_{if}(=1/\tau_{if})\) for the two transitions. Equation 9 is equivalent to that deduced by Spitzer (1998b) for a three level system, with the exception of the inclusion of the b-parameters.

Since both \(T\) and \(\tau_{v,\text{col}}\) are unknowns (and only two lines are available) the use of Eq. 9 is effectively limited either to determining values of \(T\), for a given \([H_2]\) and \textit{vice versa}, or to determining pairs of linked parameters which give valid solutions to the equation. (Eq. 1 and Eq. 8 are equivalent when \(\tau_{v,\text{col}} \ll \tau_{if}(=1/a_{if})\) for both vibrational levels of interest.) Equation 8 and 9 also show that, under the conditions of relatively small departures from LTE for which they are valid, any values of \(T_{\text{vib}}\) obtained by assuming that Eq. 1 is valid will \textit{underestimate} the true thermospheric temperature.

Figure 11 shows values of \([H_2]\) obtained from the ratio of \(I(\omega_{\text{HB}})/I(\omega_{\text{FUND}})\), for a variety of assumed thermospheric temperatures, \(T\), and for the value of \(k_{PH}\) given by Eq. 6. Typically our measured values of \(I(\omega_{\text{HB}})/I(\omega_{\text{FUND}})\) varied from ~0.01 to 0.03. In the lower thermosphere, \([H_2]\) is generally of the order of \(10^{19}\) m\(^{-3}\) at the 1\(\mu\)bar pressure level, a level which is already somewhat lower in altitude than the main \(H_3^+\) production peak at 0.3\(\mu\)bar (Achilleos \textit{et al.}, 1998). (The production peak may be lower than 0.3\(\mu\)bar if more energetic particles than those used in this paper are invoked. Nonetheless, the \(H_3^+\) production peak cannot be below the homopause, since reactions with hydrocarbons destroy this ion.) Figure 11 shows that the 1\(\mu\)bar density is
exceeded for values of $I(\omega_{HB})/I(\omega_{FUND}) > 0.017$ for $T=1300K$, and for all values of $I(\omega_{HB})/I(\omega_{FUND})$ for the lower temperatures shown. Not until $T~1500K$ do $[H_2]$ levels remain within the limits of those normally assumed for the thermosphere for all measured values of $I(\omega_{HB})/I(\omega_{FUND})$.

The foregoing discussion shows, therefore, that another way of interpreting the observed variations in $I(\omega_{HB})/I(\omega_{FUND})$ is to take a constant value of $T$ and assume that the intensity variations derive from changes in thermospheric density - either due to pressure fluctuations at a constant altitude, or due to our data probing different $H_3^+$ formation altitudes. But, for a realistic thermospheric $H_2$ density (see Atreya, 1986), we require $T~1500K$, higher than has generally been proposed for the auroral/polar regions by several hundred kelvin. (The value of $[H_2]$ computed from any $I(\omega_{HB})/I(\omega_{FUND})$ ratio is inversely dependent on $k_{PH}$: a value of $k_{PH}(T=1000)$ greater than $10^{-15} m^3 s^{-1}$, produces lower $H_2$ densities than shown in Fig. 11, and vice versa.)

Figure 12 shows the 11N4 dataset interpreted in terms of $[H_2]$ variations. These range from a low of $8 \times 10^{17} m^{-3}$ in the DPR to $8 \times 10^{18} m^{-3}$ in the RAO, but the difficulty in measuring $I(\omega_{HB})/I(\omega_{FUND})$ precisely causes significant pixel-to-pixel variations. One interesting feature is that on the SAO, where $T_{vib}$ changes from 980K to 1120K in moving 1" poleward (data obtained at $\lambda_{III}=160^\circ$ and $\lambda_{III}=159^\circ$), the change in $[H_2]$ required to account for the corresponding change in $I(\omega_{HB})/I(\omega_{FUND})$ is from $2.0 \times 10^{18} m^{-3}$ to $7.0 \times 10^{18} m^{-3}$. This could be interpreted either as a density fluctuation along the auroral oval
at constant altitude. In Hubble Space Telescope ultraviolet images, longitudinal brightness variations along the auroral oval are well known (Ballester et al., 1996; Clarke et al., 1998). As well as variations in jovian azimuthal magnetic field, these features might be explained by density fluctuations. This explanation would fit our data in this region: the I.o.s. corrected intensity of Q(1,0') increases from 3.0x10^{-13} W m^{-2} \mu m^{-1} to 4.8x10^{-3} W m^{-2} \mu m^{-1} alongside the increase in [H_2]. But the explanation might also be that the precipitating particles are locally more energetic, and thus penetrate further into the atmosphere (e.g. Rego et al., 1994), from 0.4μbar down to 1.4μbar. Similar explanations are possible within our model to account for variations in derived [H_2] values in other localities.

If we take these results as demonstrating density fluctuations at a constant altitude of auroral ion production, we should also allow for local density variations to be accompanied by local fluctuations in the temperature of the neutral thermosphere. If the thermosphere behaves adiabatically, we have $T \propto P^{(\gamma-1)\gamma}$. For the mixture of H and H_2 prevailing at the 0.3μbar level (Atreya, 1986; Achilleos et al., 1998), this gives $T \propto P^{0.3}$. It is then possible to solve Eq. 9 iteratively, starting from paired thermospheric baseline pressure and temperature values, $P_{\text{baseline}}$ and $T_{\text{baseline}}$, to produce P/T pair profiles: these are not unique solutions to the determination of the physical conditions in the thermosphere; instead, they may be considered as adiabatic P/T paired values consistent with the $I(\omega_{HB})/I(\omega_{FUND})$ profile. Figure 13a shows the effect on the thermospheric pressure, allowing for adiabatic effects in interpreting
the $I(\omega_{IB})/I(\omega_{FUND})$ profile of the 11N4#166 spectral image, using $T_{\text{baseline}}=1500\text{K}$. Figure 13b shows the corresponding effect on the temperature. In both figures we display the results for values of $P_{\text{baseline}}$ of 0.3$\mu$bar (broken line) and 0.6$\mu$bar (solid line). Figure 13 shows that a higher average value of $T$, $\sim1550\text{K}$, is associated with the lower baseline pressure, while for $P_{\text{baseline}}=0.6\mu\text{bar}$, the average thermospheric temperature is $\sim1480\text{K}$. Comparison of Fig. 13a with Fig. 12 shows that the data can be fitted with much smaller pressure fluctuations, if adiabatic effects are considered.

**Discussion**

In presenting our results, we have examined two interpretations that fit what was observed - QTE and small departures from this, with or without allowances for adiabatic changes to the thermospheric baseline temperature. Neither of these interpretations is without its problems. Presenting the data in terms of QTE is the most straightforward and is consistent with the approaches of previous studies. We have generally discussed our results in terms of regional temperatures, but within our designated regions - RAO, DPR, BPR and SAO - there are considerable pixel-to-pixel variations that we have so far not tried to examine in detail. This is the first study, however, to examine the temperature structure of the jovian upper atmosphere at such high spatial resolution. At the rarified pressures of the jovian thermosphere, small variations in local energy inputs - due either to particle precipitation or Joule heating - may produce quite large temperature variations, and it is
perhaps not surprising that our data show such fluctuations. Within this locally varying temperature behaviour, values of $N(H_3^+)$ and $E(H_3^+)$ show far less variation, as might be expected from an atmosphere in which chemical equilibrium is reached rapidly.

Taking the observed temperature variability as evidence of the need to go beyond QTE - as suggested by Kim et al. (1992) - also produces results which are consistent with the observed data. However, the need for high baseline thermospheric temperatures, and the large $[H_2]$ variations derived from $\tau_{v,\text{col}}$ values, introduces interpretative problems. The one attempt to derive the kinetic temperature of the thermosphere from the collisional broadening of $H_3^+$ lines did produce a temperature of $\sim 1150K$ (Drossart et al. 1993), larger than those usually derived from ratioing rotational lines within a vibrational manifold; in this instance, Drossart et al. also obtained a rotational temperature of $1250K$. This study, however, indicates that a baseline thermospheric temperature of $1500K$ is necessary to fit the data, considerably in excess of previous studies and the results of the Galileo probe (Seiff et al., 1996). (N.B. the Galileo probe entered the jovian atmosphere at a location close to the equator, rather than in the auroral/polar region studied here.) The need for large $[H_2]$ fluctuations to explain the data can be partially offset by assuming that the variability in the $I(\omega_{\text{HB}})/I(\omega_{\text{FUND}})$ profile is due to pressure fluctuations that vary adiabatically. A fuller treatment of the data presented here would need detailed balance calculations - difficult in absence of reliable ro-vibrational excitation cross-sections.
In this study, we have not considered whether the effect of the resonant excitation mechanism (Eq. 3), proposed by Kim et al. (1992) to produce high populations in the \((v_2=2)\) levels, could play an additional role. If this mechanism were even more efficient than Kim et al. (1992) model, it might explain the values of \(I(\omega_{HB})/I(\omega_{FUND})\) found in our data, in the “beyond QTE” situation, without the need to invoke high thermospheric baseline temperatures. Our reason for not dealing with this mechanism in detail is the lack of any prior observational evidence to support the relative overpopulation of \((v_2=2)\). Additionally, the large uncertainty in the rate constant associated with Eq. 3, compared with the “normal” collisional excitation rate constant, makes this effect difficult to compute reliably. Our rejection of resonant excitation is in line with recent detailed 1-D modelling of the jovian auroral regions by Grodent et al. (2001).

During the course of the observing run, night-to-night variations were observed in the averaged values of the parameters presented here. In particular, \(\langle T_{vib} \rangle\) increased by \(-100K\) between September 7 and 11, and Sept. 11 also had the highest values of \(\langle N^*(\text{H}_3^+) \rangle\) and \(\langle E^*(\text{H}_3^+) \rangle\) for the nights when the northern auroral/polar region was best displayed. Paper I showed that this period was also marked by an increase in the velocity of the auroral electrojet. Southwood and Kivelson (2001) and Cowley and Bunce (2001) have both proposed that increasing auroral activity can be triggered by an expansion of the middle jovian magnetosphere, which itself could be due to decreased solar wind pressure: precipitation and electrojet velocities would increase, leading to the sort of heating observed in our data. This
mechanism could certainly account for changes to the auroral oval itself; corresponding changes in those regions of the magnetosphere that couple to the polar ionosphere would also produce heating there.

Conclusions

This is the first spectroscopic study of the dynamic physical properties of the jovian auroral/polar ionosphere to be carried out at high (<1") spatial resolution, using a newly observed hotband line of H_3^+ simultaneously measured with a fundamental line on the same array. It is clear from our observations that the parameters usually reported - temperature, ion density and emission - vary over distances much smaller than the extent of the auroral region, revealing fine-scale detail not previously considered. This result has consequences for future imaging and spectral studies, as well as attempts to model Jupiter's upper atmosphere, although we conclude that studies using H_3^+ imaging or spectroscopy of limited spectral ranges to derive total emission/cooling values are justified in their approach.

We have also stepped beyond this approach to provide evidence for an alternative non-thermal explanation for the variation in the intensity ratio between the two lines measured. We conclude that a non-thermal explanation requires thermospheric temperatures greatly in excess of those previously recorded, a strong argument against any significant departure from LTE. New studies are underway which attempt to measure large numbers of ro-vibrational lines in different vibrational manifolds simultaneously, thus
making it possible to derive rotational and vibrational temperatures for the same location and the same time. The increased auroral activity noted during the period of our observations now needs to be compared with the data from spacecraft observations over the same period to see if mechanisms recently proposed can account for it.

Acknowledgments

It is a pleasure to acknowledge the expert assistance of the staff of the IRTF in obtaining the data discussed here. TS would like to thank the UK Particle Physics and Astronomy Research Council (PPARC) for a research studentship, during which the bulk of the analysis for this article was accomplished. This current paper has drawn on the helpful advice given by Prof. Fred Taylor and Dr. Michele Dougherty, thesis examiners for TS. SM would like to thank the University of Hawaii Institute for Astronomy for granting him the status of Visiting Research Scientist during January to June, 2001, when work on drafting this article took place, and their helpful discussions. JIM calculations referred to in this article were carried out on the Miracle supercomputer at the HiPerSPACE centre at University College London, supported by PPARC.
References


Atreya S., 1986. Atmospheres and ionospheres of the outer planets and their satellites. (Springer Verlag, Heidelberg), 139-143.


Table I: Spectroscopic parameters for the fundamental and hotband lines

<table>
<thead>
<tr>
<th></th>
<th>Fundamental $(\nu_2 \rightarrow 0) \text{ Q}(1,0')$</th>
<th>Hot band $(2\nu_2(0) \rightarrow \nu_2) \text{ R}(3,4')$</th>
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<tbody>
<tr>
<td>$E'$ (cm$^{-1}$)</td>
<td>2616.5</td>
<td>5250.2</td>
</tr>
<tr>
<td>$A_{\text{nf}}$ (s$^{-1}$)</td>
<td>129</td>
<td>66</td>
</tr>
<tr>
<td>$g_{\text{ns}}$</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>$(2J' + 1)$</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>$\omega_{\text{nf}}$ (cm$^{-1}$)</td>
<td>2529.5</td>
<td>2532.3</td>
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<tr>
<td>Band origin (cm$^{-1}$)</td>
<td>2521.3</td>
<td>4777.1</td>
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</table>
Table II: Nightly averaged vibrational temperatures

<table>
<thead>
<tr>
<th>U.T.</th>
<th>(&lt;T_{\text{vib}}&gt;)</th>
<th>Integrated Hotband S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>07 Sept. 1998</td>
<td>981</td>
<td>38</td>
</tr>
<tr>
<td>08 Sept. 1998</td>
<td>940</td>
<td>65</td>
</tr>
<tr>
<td>09 Sept. 1998</td>
<td>973</td>
<td>45</td>
</tr>
<tr>
<td>10 Sept. 1998</td>
<td>1021</td>
<td>102</td>
</tr>
<tr>
<td>11 Sept. 1998</td>
<td>1065</td>
<td>78</td>
</tr>
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</table>
### Table III: Nightly averaged column density and total emission

<table>
<thead>
<tr>
<th>U.T.</th>
<th>(&lt;N^*(H_3^+)&gt; (\text{m}^{-2}))</th>
<th>(&lt;E^*(H_3^+)&gt; (\text{mW m}^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>07 Sept. 1998</td>
<td>0.70 x 10^{16}</td>
<td>1.24</td>
</tr>
<tr>
<td>08 Sept. 1998</td>
<td>0.62 x 10^{16}</td>
<td>0.60</td>
</tr>
<tr>
<td>09 Sept. 1998</td>
<td>1.10 x 10^{16}</td>
<td>1.21</td>
</tr>
<tr>
<td>10 Sept. 1998</td>
<td>0.58 x 10^{16}</td>
<td>0.78</td>
</tr>
<tr>
<td>11 Sept. 1998</td>
<td>0.72 x 10^{16}</td>
<td>1.22</td>
</tr>
</tbody>
</table>
Figure Captions

1) Spectral images of the region around 3.953\(\mu\)m taken (bottom) on September 11, 1998, and (top) co-added data from 1997. The hotband line is clearly seen in the 1998 individual spectral image, but is not visible in the co-added 1997 data.

2) Fundamental and hotband transition wavelengths superimposed on Argon and Krypton arc lines used to calibrate the CSHELL array. The Krypton lines at 3.95197\(\mu\)m and 3.95333\(\mu\)m bracket the \(H_3^+\) Q(1,0) line at 3.9530\(\mu\)m (shown with intensity truncated). The R(3,4) hotband line is bracketed by Argon lines at 3.94783\(\mu\)m and 3.94989\(\mu\)m.

3) East-west intensity profiles for the Q(1,0) (solid, dark line) and R(3,4) (dotted, light line) lines taken on September 11, at a CML of \(\lambda_{III}=159^\circ\) (11N4#166 spectral image). Note that array effects (discussed in the text) cause a slight displacement of the hotband profile to higher pixel numbers.

4) Values of \(T_{vib}: I(\omega_{HB})/I(\omega_{FUND})\) ratio based on Eq. 2. The error limits for 17.5% and 33% in \(I(\omega_{HB})/I(\omega_{FUND})\) ratio are also shown.

5) Selection of \(T_{vib}\) profiles (broken line) from the dataset. The Q(1,0) intensity profile is shown to help visualisation (full line). “Typical” profiles are shown in the left panels; “atypical” profiles on the right.
6) \( T_{\text{vib}} \) profiles (broken line) for the 11N4 sequence of spectral images. The \( Q(1,0^-) \) intensity profile is shown to help visualisation (full line).

7) \( <T_{\text{vib}}>_T \) values as a function of time during the observing run. The time origin is set at 0:00hrs on September 7 (U.T.).

8) As Fig. 7, as a function of CML at the time the data was taken.

9) As Fig. 6 for \( N^*(H_3^+)^{-} \) profiles for the 11N4 dataset.

10) As Fig. 9, for \( E^*(H_3^+) \).

11) \( \log_{10}[H_2]: \frac{I(\omega_{H_2})}{I(\omega_{\text{FUND}})} \) ratio for appropriate thermospheric temperatures.

12) As Fig. 9, for \([H_2]\).

13) Adiabatic profiles of thermospheric pressure (a, bottom) and temperature (b, top) for the 11N4#166 spectral image assuming \( P_{\text{baseline}} = 0.3\mu\text{bar} \) and \( T_{\text{baseline}}=1500\text{K} \) (broken line); and \( P_{\text{baseline}} = 0.6\mu\text{bar} \) and \( T_{\text{baseline}}=1500\text{K} \) (full line). The l.o.s. corrected \( Q(1,0^-) \) intensity profile is shown to help visualisation (dotted line).
Figure 2
Figure 3
Figure 5
Figure 6
Figure 7
Figure 9
Figure 10
Figure 12
Figure 13a+b