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On Possible Vibrational Enhancement of N_2^+ First Negative Bands in Auroral Hydrogen Arcs

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Proton aurora fail to show any vibrational enhancement of the N_2^+ first negative bands, as compared to ordinary electron aurora. This is in agreement with laboratory measurements. It is shown that some earlier spectra which have been presented to show such enhancement in the $\Delta v = 2$ sequence are contaminated by OII emission, which is enhanced in proton aurora.

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INTRODUCTION

Relative intensities of band heads in first negative bands of N_2^+ have been measured fairly accurately both in the laboratory and in the aurora, and also predicted theoretically. Certain observations of aurora, however, indicate anomalous intensity distributions (Clark and Belon 1959, Clark 1969) coinciding with the presence of protons among the incident particles.

Reactions giving rise to first negative N_2^+ bands by proton impact is, according to Eather (1967) (the asterisk indicates the $B^2\Sigma^+_u$-state):

$$H^+ + N_2 = N_2^{+*} + H^+ + e, \qquad (1)$$

$$H^+ + N_2 = N_2^{+*} + H. \qquad (2)$$

In addition we have reactions with neutral hydrogen:

$$H + N_2 = N_2^{+*} + H^+ + 2e, \qquad (3)$$

and

$$H + N_2 = N_2^{+*} + H + e. \qquad (4)$$

Reaction (1) is the one most readily produced in the laboratory and for which precise band profiles have been obtained (Carlton et al., Roesler et al. 1958), indicating no rotational or vibrational enhancement.

The other reactions have only been measured indirectly in the laboratory and no band profiles have been obtained. The purpose of this note is to examine the intensities of the band emitted by the sum of all the above reactions, as is the case in aurora (and to determine if and to what extent vibrational enhancement of N_2^+ first negative bands occurs in auroral hydrogen arcs.).

INSTRUMENTATION AND MEASUREMENTS

The instrument used was a Littrow scanning spectrophotometer operated in the spectral range 4150–4300 Å. This region includes the N_2^+ first negative bands at 4278, 4236 and 4199 Å, belonging to the $\Delta v = -1$ sequence.

The field of view was about 8° wide and $< 1°$ high and the resolution was 5 Å. The spectral range was divided into approximately 100 channels and photon counting was applied, recording the numbers from each channel on paper tape. Each scan required one minute and because each spectrum was weak, particularly the proton-induced ones, it was necessary to add counts for about two hours in order to give the displayed spectrum.

With the instrumental resolution used, the rotational structure could not be resolved and the recordings showed only the envelope of the rotational lines. Fig. 1 shows such spectra for two different cases: The spectrum of an electron aurora on 13 Jan. 1969 from 2327 UT to 14 Jan. 0124 UT and of proton-induced aurora on 16 Jan. from 1552 UT to 1632 UT. Together with this the synthetic spectra for temparatures 300 and 500°K are traced. All spectra are normalized to an equal area under the curves.

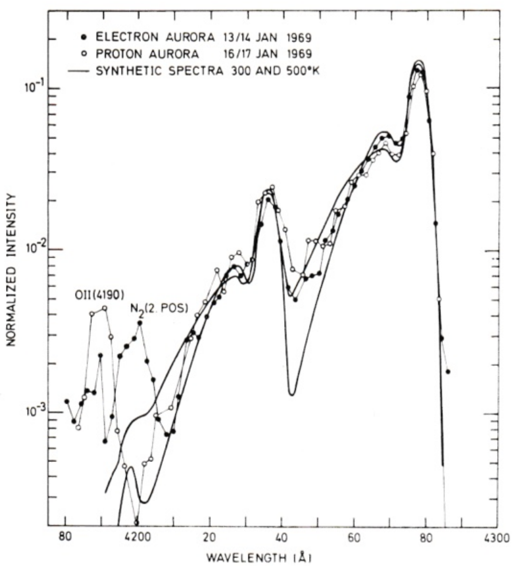

Fig. 1. Spectra of the $\Delta v = 1$ sequence of N_2^+ first negative bands. Points show the average spectrum of an electron aurora on 13 Jan 2327 UT to 14 Jan 0124 UT and open circles show the average spectrum of a proton aurora on 16 Jan from 1552 UT to 1632 UT. Together with these are also traced synthetic spectra with vibrational intensity ratio adjusted to be 100/14/0.2 and rotational temperatures of 300 and 500°K.

Comparing the measured spectra to the synthetic ones, we find that the rotational temperatures were between 400 and 500°K, with the electron aurora being closer to 400°K and the proton aurora with a temperature somewhat below 500°K. This should place the height of the main emissions of the two auroras at around 110 km and 120 km (CIRA 1965).

INTERPRETATION

Proton aurora

From the measured spectra, several points of interest are apparent. The emission line of atomic oxygen ions at 4190 Å ($3p'^2F_{1/2} - 3d'^2G_{9/2}$) is more pronounced in the proton-induced aurora. This may be explained by protons reacting with atmospheric oxygen through the reaction $H^+ + O \rightarrow O^+ + H$, which, according to Eather (1967) is the most effective charge exchange process of protons at high altitudes. The N_2 second positive band head (2–6) is below the threshold of detectivity in the proton-induced spectrum. This is expected, since these bands are excited through an intercombination transition which involves electron exchange. This can only occur by secondary reactions involving neutral hydrogen which are less important, or by secondary electrons.

Electron aurora

Hunten (1959) reports a measured ratio of the second positive band to the first negative band $I_{2P}(0,2)/I_{1N}(0,0) = 0.06$. Using Nicholl's (1963) values for the transition factor for the second positive bands together with Broadfoot & Hunten's (1964) values for relative populations of the $N_2(C^3\pi)$ state, we obtain the ratio $I_{2P}(2,6)/I_{1N}(0,1) = 0.02$. The ratio obtained from the measurements reported here is more than twice as big, but there are large uncertainties in measuring the band area. It is agreed that N_2^+ first negative bands are produced by simultaneous ionization and excitation from the electronic and vibrational ground state of the nitrogen molecule. For electron excitation, the population rate $g_{v'}$ of a vibrational level of an upper electronic excited state of the ion is proportional to the Franck-Condon factor connecting this level and the vibrational levels v''' of the ground state of the neutral nitrogen molecule:

$$g_{v'} \propto \sum_{v'''} N''' \cdot q_{v'v'''} \approx q_{v'0} \,. \tag{5}$$

$g_{v'}$, or more exactly the quantity $\sigma_{v'}$ (ionization cross section into the v'-level), has also been measured in absolute values as a function of electron energy by McConkey & Latimer (1965). The radiation rate is equal to the population rate:

$$g_{v'} = N_{v'} \sum_{v''} A_{v'v''} \,. \tag{6}$$

Substituting $N_{v'}$ from the emission formula: $I_{v'v''} = N_{v'} \cdot A_{v'v''}$ into Eq. (6) and taking Eq. (5) into account, we obtain:

$$I_{v'v''} \propto q_{v'o} \cdot A_{v'v''} / \sum A_{v'v''} \,. \tag{7}$$

The sum ${}_{v''}\Sigma A_{v'v''}$ is a constant for a given v' and the expression (7) may then be written:

$$I_{v'v''} \propto q_{v'o} \cdot A_{v'v''} \,. \tag{8}$$

Franck-Condon factors for this ionization-excitation process giving rise to the first negative system have been computed by Nicholls (1961). In the synthetic spectra the intensity ratio $I_{1N}(1,2)/I_{1N}(0,1)$ has been put equal to 0.14 in order to fit the measured profile to the theoretical one. The $I_{1N}(2,3)$-band is very weak and is blended by the second positive band.

No cases could be found which showed any vibrational enhancement. Laboratory measurements by Philpot & Hughes (1964) using proton impact excitation indicates an intensity ratio $I_{1N}(1,2)/I_{1N}(0,1) = 0.16$ and no enhancement compared to electron excitation. Using impact excitation of several ions, Sheridan & Clark (1965) also report no enhancement of bands with proton excitation. Their value for the ratio $I_{1N}(2,3)/I_{1N}(1,2)$ is 0.2. For heavier ions such as He^+, N^+ and Ne^+ they report enhancement of this ratio up to 0.4.

Vibrational distribution among the N_2^+ bands

The auroral spectra where the anomalous intensity distribution of the N_2^+ ($\Delta v = -2$) sequence was observed by Clark & Belon (1959) also contained several atomic lines not usually observed (Belon & Clark, 1959). The three bandheads at 4710, 4651 and 4600 were recorded with the rather coarse resolution of 8 Å.

Table I
Relative intensities in the N_2^+ bands

Transition (v', v'')	λ(Å)	$A_{v'v''}$ $\times 10^{-6}$	$q_{v'o}$ $\times 10^{+2}$	$g_{v'}(a)$ $\times 10^{+18}$	Relative intensities				
					Theory	a, b	c	d	e
$N_2^+(0,1)$	4278	3.50	89.1	20.7	100	100	100	100	100
$N_2^+(1,2)$	4236	4.27	10.7	1.7	14.6	10	16	20±2	14±2
$N_2^+(2,3)$	4199	3.70	0.175	–	0.2	–	–	–	
$N_2(2,6)$	4200								4.5±1.0(1)
OII	4190								1.8±0.2(2)

a: McConkey & Latimer (1965)
b: Thomas, Bent & Edwards (1968)
c: Philpot & Hughes (1964)
d: Sheridan & Clark (1965)
e: Intensities reported here where (1) is electron aurora and (2) is proton aurora only.

In addition we will use the $A_{v'v''}$ values of Broadfoot (1967). With the help of Eq. (8) we can deduce theoretical ratios for the three bands considered here, and Table I displays the values obtained. The relevant parameter for electron excitation is also listed. Therefore several atomic lines of OII might have contributed to the unusual intensity distribution. Dufay et al. (1966) have measured the cross section for emissions using a 20–600 keV proton beam on an oxygen target. The relative intensities measured are given in Table II.

Table II
Intensities of OII lines and N_2^+ bands

OII lines		N_2^+ first negative bands			
Wavelength	Intensity (a)	Wavelength	Theory	Intensity Clark & Belon (c)	Difference (d)
4690/96 4700/5/10	0	4710	208	208	0
4650 4639/41	220 weak	4651	95	276	181
4591/97 4416	120 100	4600	1.2	120	119
4341 4190	90 45(16(b))	4278 4236	910 134		
1	2	3	4	5	6

a: Intensities taken from Dufay et al. (1966) normalized so that I(4416) = 100.
b: Intensity reported here.
c: Intensities from spectra No. 6 of Clark & Belon (1959). Averaged over the whole sky and normalized giving I(4591/97) = 120.
d: The difference between the theoretical intensity and the intensities of Clark & Belon (Column Nos. 4 and 5).

Table II, column 5 shows the Clark & Belon (1959) abnormal band intensities obtained by Clark & Belon (1959) normalized such that the (2,4) band is equal to the OII-4591/97 emission listed in column 2. The theoretical expected intensity of the N_2^+-bands within this sequence is readily obtained from the $q_{v'0}$ values of Nicholls (1961) and the $A_{v'v''}$ values of Broadfoot (1967) and is listed in Table II, column 4 and scaled such that the intensity of the $1N(0,2)$-band is equal to the one from the anomalous spectrum. Looking at the difference between the two latter columns, we obtain two emissions whose intensities are the same as those of Dufay's (1966) for the lines at 4591/97 and 4650 Å. From this we conclude that Clarke & Belon's (1959) band intensities are contaminated by OII lines, and also that the N_2^+ ($\Delta v = 2$)-sequence is not very suitable for band intensity measurements.

CONCLUSION

The result obtained here failed to show any vibrational enhancement of the N_2^+ first negative bands emitted from proton aurora, as compared to ordinary electron aurora. This is in agreement with laboratory measurements.

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