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TYPE-B RED AURORA; THE O_2^+ FIRST NEGATIVE SYSTEM AND THE N_2 FIRST POSITIVE SYSTEM*

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Abstract—The O_2^+ first negative (1N) and N_2 first positive (1PG) systems have been observed in type-B red aurora with a scanning spectrometer. The O_2^+ system is enhanced by a factor between 2 and 3 relative to the N_2 1PG. The change in relative intensity of the two systems is comparable to the change in relative abundance of O_2 and N_2 from normal to type-B red auroral heights. The N_2 1PG displays a gradual change in relative vibrational populations, as a function of auroral height. No evidence was found of an enhancement of this system in type-B aurora, contrary to previous published observations. The estimated total system intensities in IBC III type-B red aurora, determined from intensities relative to the N_2^+ Meinel system (I[M] = 2000 kR), are: I[O_2^+ 1N] = 100 kR, I[N_2 1PG] = 2400 kR.

1. INTRODUCTION

The term, type-B red aurora, is applied to forms having red or occasionally, purple lower borders. The lower edge of this type of aurora has been reported to occur generally at an altitude between 60 km and 85 km, much lower than the average normal auroral height. The displays are always bright, IBC III or greater, active and usually of short duration. The maximum frequency of occurence appears to be associated with the minimum in solar activity (Vegard, 1938).

The red lower border had been attributed by earlier observers to an enhancement of the N_2 1PG (first positive system). Vegard noted this as early as 1917, and later presented spectrogram measurements indicating an enhancement by a factor of about 1·5 over the oxygen green line and the N_2^+ 1N (first negative system) (Vegard and Tönsberg, 1937; Vegard, 1940). Later observers have supported the Vegard results. Malville (1959) claims to have observed an enhancement relative to the N_2 2PG (second positive system), although no quantitive measurements were given. Herman (1960) indicated a minimum enhancement over the second positive system by a factor of 3·7. The most recent observations (Evans and Vallance Jones, 1965) indicated an average enhancement by a factor of 1·4 over N_2^+ 1N. An additional feature characterizing type-B red aurora, the enhancement of the O_2^+ 1N (first negative system) relative to both the N_2^+ 1N and N_2 1PG, was first noted by Dahlstrom and Hunten (1951). Hunten (1955) confirmed the observations with better spectra. However, Evans and Vallance Jones (1965) in their recent observations reported that the enhancement of the O_2^+ 1N bands were less than 50 per cent and suggested that the phenomenon was not a regular feature in type-B aurora.

Recent observations (Shemansky, 1966) of the auroral spectrum in the 6000–7000 Å region have been obtained at Saskatoon using a rapid scanning spectrometer connected to a digital memory system. Analysis of these spectra as well as some earlier spectra obtained

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by Hunten, indicated that: (1) The enhancement of the O_2^+ 1N relative to the N_2 1PG and N_2^+ 1N is a regular characteristic of type-B red aurora. (2) There is no evidence indicating an enhancement of the N_2 1PG, contrary to the previous observations.

The experimental details resulting in the above two points, and a discussion of the disagreement with the earlier observations will be given below.

2. EXPERIMENTAL

2. 1 *Apparatus*

The recent observations discussed in this paper were obtained using a rapid-scanning photoelectric spectrometer in conjunction with a delay-line digital memory unit. The system, with the exception of minor modifications, was the same as that described by Broadfoot and Hunten (1964).

The spectrometer employed a 4 in. × 4 in., 600 lines/mm grating, in the first order. The field of the instrument was about 1° square.

The spectrum was scanned every 10 sec. Successive scans were summed and stored in the memory unit in order to obtain a satisfactory signal to noise ratio. The detector was a cooled EMI 9558B photomultiplier, operated at 1300 V in the pulse counting mode.

All of the auroral spectra were placed on an absolute differential brightness scale with the use of a tungsten continuum source, which in turn had been calibrated by comparison with a black body source of known temperature.

2. 2 *Observational and reduction procedures*

Most of the observed spectra were obtained with a scan 1200 Å long, roughly between 5800 and 7000 Å. This region is dominated by bands of the $\Delta v = 4$, 3 and 2 sequences of the N_2 1PG and N_2^+ M (Meinel system). Bands of the $\Delta v = 0$, -1 and -2 sequences of the O_2^+ 1N also occur in this wavelength interval. The spectral slit width for all of the observed spectra was 15 Å.

The observations were conducted in a manner calculated to minimize the mixture of auroral heights contributing to a given accumulated spectrum. Thus an attempt was made, for the most part, to observe single auroral forms at a constant zenith angle. Confining the observations in this way has the additional advantage of simplifying the corrections for atmospheric extinction. This is a difficult rule to follow in the case of rapidly moving forms, which are typical of type-B red aurora. However the type-B red spectra reported here were obtained at or near the zenith, and consequently represent a wide range of auroral heights. But the spectra in cases such as this are dominated by radiation from the very bright lower border, as is evidenced by low rotational temperatures and very weak [OI] $\lambda\lambda$6300–64 lines. In cases of weak, rapidly fluctuating aurora no attempt was made to follow the moving forms. The integration time of a given spectrum was kept to a minimum; generally less than 20 min. Spectra with very similar characteristics were summed later in a computer to improve the signal to noise ratio.

In addition to the calibration of the spectra with a standard source, unaided eye estimates of the auroral brightness were made during the observations. The eye estimates of the international brightness coefficient were generally low by about an order of magnitude in comparison to the brightness indicated by the standard source calibration. This appears to be a general tendency of visual observers, at least at Saskatoon. The subject of eye estimates has been introduced because it has acquired relevance to the estimate of relative band system intensities, as a result of a recent publication by Benesch *et al.* (1967).*

The spectra reported in this paper were reduced with the use of synthetic comparison spectra of bands of the N_2 1PG, N_2^+ M and O_2^+ 1N. The comparison was made with the use of overlays of synthetic spectra plotted on the same wavelength scale as the observed spectra. The overlap of adjacent features was not severe in most cases and presented little difficulty in the relative intensity estimates. The blends that did give some difficulty were: (1) The blend of the (3, 0) N_2^+ M with the (3, 0) N_2 1PG band, (2) the blend of the (9, 6) and (10, 7) N_2 1PG bands with the [OI] $\lambda\lambda$6300–64 nebular lines and the $\Delta v = -1$ sequence of the O_2^+ 1N, (3) the blend of the $\Delta v = 4$ sequence of the N_2 1PG with the $\Delta v = 0$ sequence of the O_2^+ 1N.

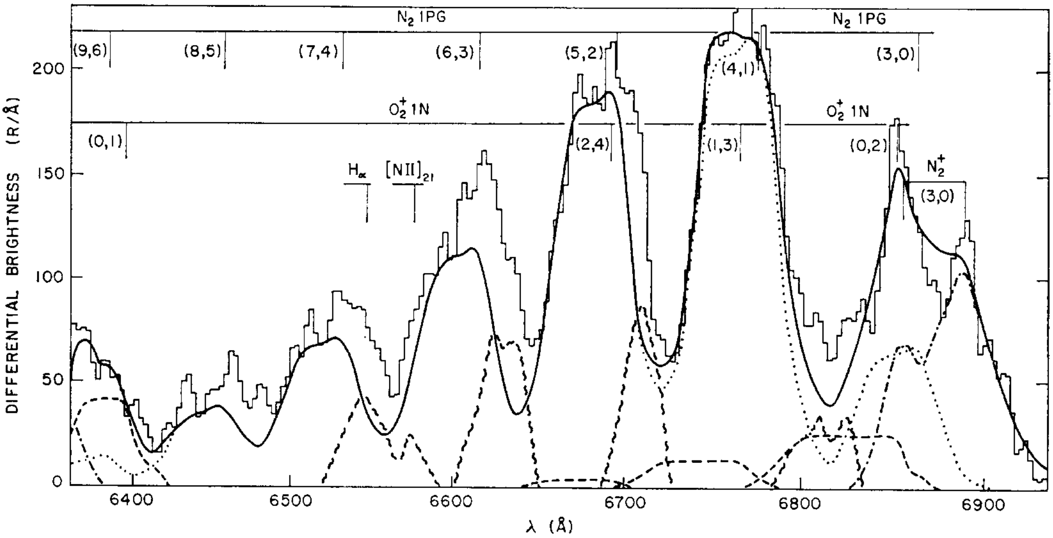

FIG. 1. TYPE-B RED AURORA, SPECTRUM NO. 1766.
Total synthetic spectrum———N_2 1PG · · · (250°K), N_2^+ Meinel—·—·—, O_2^+ 1N – – –, Difference Spectrum∼∼∼. $\Delta\lambda = 15$ Å.

Blend (1) is not as difficult to analyze as the profile might suggest; the Q_{11} head of the N_2^+ M band at λ6890 lies almost clear of the long wavelength edge of the N_2 band (see Fig. 1). Thus the intensity of the N_2^+ band could be determined immediately, without iteration. The intensity of the synthetic N_2 band would then be adjusted to fit the composite profile of the two bands to the experimental spectrum. Blend (2) was generally much more difficult to analyze, due mostly to the usually bright [OI] nebular lines. It was not possible to separate the components of this blend in the weaker high level aurora. Figure 2 shows a

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* Benesch *et al.* quantitatively re-analyse earlier published observations, for which eye estimates of the international brightness coefficient were given in many cases, due to the lack of a measured intensity of either the OI λ5577 line or N_2^+ λ3914 band. One of the conclusions of the re-analysis was that the N_2 2PG did not change in intensity from an IBC III to an IBC IV aurora, and that the N_2 1PG increased by only a factor of 2 under the same conditions. This implies that the two N_2 positive systems undergo a drastic decrease of an order of magnitude in intensity relative to the N_2^+ 1N, in the transition from an IBC III to an IBC IV aurora. This erroneous conclusion stems directly from the tendency of observers to underestimate the intensity of the aurora. There is no suggestion of a phenomenon of this magnitude in the literature, on which the analysis is based.

type-B auroral spectrum in which the (9, 6) N_2 and (0, 1) O_2^+ bands were separated from the weak λ6364 line. The brightness of the (0, 1) O_2^+ band was determined from the measured brightness of the (0, 0) band (λ6000) of the same system. The O_2^+ 1N in this spectrum is enhanced by a factor of 2 relative to the N_2 1PG compared to the ratio in normal aurorae in the 130 km region. In the case of blend (3) the $\Delta v = 4$ sequence of the N_2 1PG was separated from the other emissions in the 5800–6200 Å region by determining their intensities from bands of the $\Delta v = 3$ sequence originating from the same upper vibrational levels. It is worth noting at this point that the broad feature at about 6125 Å cannot be accounted for by the combination of N_2 1PG bands and the N_2^+ M (4, 0) band as has been previously suggested in the literature. The Meinel band intensity, as calculated from the measured intensities of the (4, 1) and (3, 0) bands, would have to be multiplied by a factor between 2 and 4 to account for the feature. Although the transition probabilities of the N_2^+ M bands are not as well established as those of the N_2 1PG, it seems rather unlikely that they could be in error by a factor this large. The feature appears with variable relative intensity in all of the observed spectra.

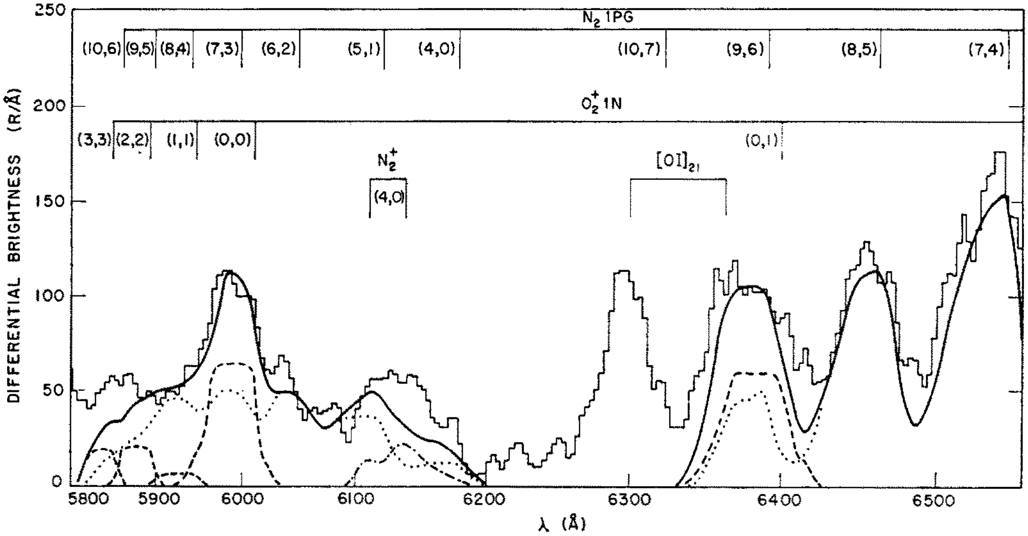

FIG. 2. TYPE-B RED AURORA, SPECTRUM NO. 1760.
Total synthetic spectrum———, N_2 1PG · · ·, N_2^+ Meinel—·—·—, O_2^+ 1N – – –, $(OI)_{21}$ λ6364 –· ·–· ·–, N_2 1PG synthetic spectra, $T = 250°K$, $\Delta\lambda = 15$ Å.

Synthetic spectra of the N_2 1PG were produced with the aid of an LGP -30 computer. These bands are rather complex due to the fact that the transition involves intermediate coupling between Hund's case a and case b. There are 27 branches, of comparable intensity. The energy equations for the upper state for the intermediate coupling case are given by Budó (1935, 1936). The equations for the lower state are given by Schlapp (1937). Molecular constants used in the calculation are given in Table 1. The relative populations of the rotational levels of the $B^3\Pi_g$ state were assumed to be determined entirely by electron excitation of ground state molecules. In other words, it was assumed that collisional redistribution could not take place before emission, and that the effect of cascade from higher states was negligible. The former assumption would appear to be valid for normal

TABLE 1. MOLECULAR CONSTANTS FOR N_2 SYNTHETIC SPECTRA

State	T_e	ω_e	$\omega_e x_e$	$\omega_e y_e$	$\omega_e z_e$	B_e	α_e	γ_e	r_e(Å)	D_e	B_e
$B^3\Pi_g$	59,621·51 a	1733·92 a	14·399	−4·01–3	5·13–4	1·63748 b, c	1·794–2	−7·38–5	1·2125	5·80–6 a	3·7–8
$A^3\Sigma_u^+$	50,205·96 a	1460·60	13·851	6·25–3	1·72–3	1·4545 b, d	1·798–2	−8·44–5	1·2865	5·77–6 a	4·1–8

(a) Recalculation based on Dieke and Heath (1959) data.
(b) From Dieke and Heath (1959).
(c) $y_v = 25{\cdot}68 + (0{\cdot}253)v + 2{\cdot}81(10^{-3})v^2$.
(d) $\lambda_v = -1{\cdot}335 + 7\,.\,(10^{-3})v,\ \gamma = -0{\cdot}003$.

auroral heights; it is possible there would be some redistribution at heights below 80 km, due to the rather long lifetime of the $B^3\Pi_g$ state (Jeunehomme, 1966a). The latter assumption should be valid for all of the bands examined here. The major contributor to the population of the $B^3\Pi_g$ state by cascade, the N_2 2PG, appears to be only 10 per cent or less of the intensity of the N_2 1PG. This amount of cascade would measureably affect only the $v = 0$ level of the $B^3\Pi_g$ state (Shemansky, 1966). The complexity of these bands has, up to this point, precluded the measurement of rotational temperatures in auroral spectra. It is virtually impossible to make rotational temperature measurements of the bands in auroral spectra without synthetic comparison spectra. Even relatively small spectral slit widths of the order of 1 Å, the branch structure and the rotational structure of most of the bands remain unresolved. Figure 3 shows a comparison of synthetic spectra with an observed spectrum. The temperature estimates were made by a combination of the band shape, and the depth of the troughs between the blended bands. The measured temperatures ranged from about 250°K to 700°K, with error estimates varying between ±100 and ±200°K.

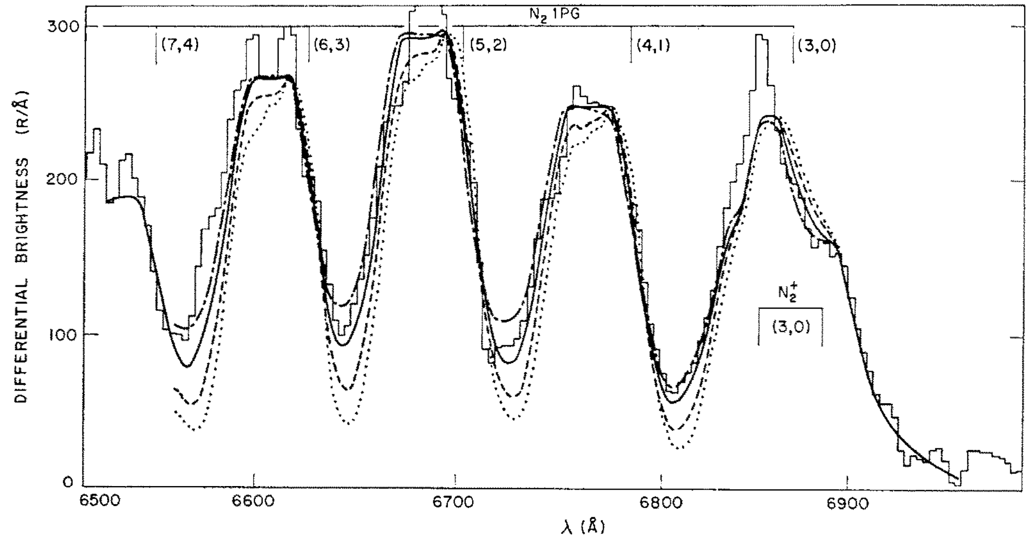

FIG. 3. COMPARISON OF SPECTRUM NO. 1771 WITH SYNTHETIC SPECTRA.
$T = 250°$K · · ·, $T = 350°$K - - -, $T = 500°$K ———, $T = 700°$K —·—·—. $\Delta\lambda = 15$ Å.

Bands of the N_2^+ M system are far simpler to reconstruct, although the coupling is also intermediate between Hund's case a and case b. The energy equations of the upper state rotational levels have been calculated by Hill and Van Vleck (1932), for the intermediate coupling case. Formulae for the line strength factors are given by Earls (1935). There appears to have been some question as to whether the upper state is a normal or inverted doublet. It is shown in the Appendix that the state is very likely inverted. The molecular constants used in the computations are given in Table 2. No attempt was made to determine the rotational temperature of the auroral Meinel band. The band shape at the resolution applied here changes rather slowly with temperature (see Mathews and Wallace, 1961).

Synthetic comparison spectra for the O_2^+ 1N bands were obtained from Nicolet and Dogniaux (1950). The spectra were produced for 200°K; no attempt was made to determine rotational temperatures in the auroral spectra.

TABLE 2. MOLECULAR CONSTANTS FOR N_2^+ SYNTHETIC SPECTRA

State	T_e	ω_e	$\omega_e x_e$	$\omega_e y_e$	B_e	α_e	D_v
$A^2\Pi_u$	9168·4 a	1902·84 a	14·91		1·742 b, c	1·85–2	4·0–6
$X^2\Sigma_g$	0	2207·19 d	16·136	−4·0–2	1·932 d	2·0–2	2·9–6

(a) From Douglas (1953).
(b) Recalculation based on Douglas (1953) data.
(c) $A_s = -74·60$, from Mathews and Wallace (1961).
(d) From Herzberg (1950).

3. RESULTS

About 60 auroral spectra were obtained in the peroids 20–27 September 1963, 3–4 and 29–30 March 1964. Two spectra in the $\lambda\lambda$5800–7000 region and two in the $\lambda\lambda$6400–7600 region, representing a total of about 25 scans were obtained on type-B red aurora. The notable characteristics of the observed spectra are: (a) The (0, 0) O_2^+ 1N band is enhanced relative to the N_2 1PG by a factor between 2 and 2·5, compared to normal aurora. (b) The average relative intensity of the N_2^+ M as represented by the ratio I[M(3, 0)]/I[1PG(4, 1)] is slightly higher than the average for normal aurora. That is, there appears to be no enhancement of the first positive system relative to the Meinel system. (c) There is a lower vibrational development for levels beyond $v' = 4$ in the N_2 1PG, relative to the vibrational development in normal aurora. Under the same conditions the $v' = 3$ population decreases relative to that of the $v' = 4$ level. (d) The [OI] lines at 6300 Å and 6364 Å are very weak and probably would not have been measurable, but for the fact that the memory system had been accumulating a spectrum of higher, weaker aurora for several minutes in each case before the onset of the type-B display. Each of these points will be discussed in turn.

3. 1 *Enhancement of the* O_2^+ 1N

Quantitive measurements of this system in type-B red aurora are very scarce. The only observations comparable to the spectra reported here appear to be those of Hunten (1955), obtained in 1952. These spectra covered a broad spectral region, about 4500–7000 Å, and were obtained with the same spectrometer used here, but without the memory system However, Hunten did not make quantitative measurements of the O_2^+ bands, and therefore the original spectra were reanalyzed by one of us (D. E. S.) using the same method described above. Table 3 shows the average enhancement of the O_2^+ (0, 0) band relative to the N_2 1PG (7, 3) band for a sequence of eight spectra obtained 31 March, 1952. The auroral display was type-B, with an estimated IBC of IV. The third spectrum in the sequence is shown in the Hunten (1955) paper. An increase by a factor of 3·6 in the ratio I[O_2^+(0, 0)]/I[1PG(7, 3)] was estimated for this particular spectrum. The table also shows the measured enhancement factor for the intensity of the O_2^+ bands at ~5270 Å over the N_2^+ 1N (1, 4) band at 5149 Å (I[O_2^+ (2, 0) + O_2^+ (3, 1)]/I[1N(1, 4)]). The average enhancement in the latter case is slightly higher. This could easily be due to error in the estimation of the normal ratio I[O_2^+ (2, 0) + O_2^+ (3, 1)]/I[1N(1, 4)] (the average of four weak spectra obtained March 6, 1952), or to the variation in auroral intensity during the scan. The greater range of values in the measured ratio I[O_2^+ (0, 0)]/I[1PG(7, 3)] may be due to a combination of auroral intensity variation during the scan (I[1PG(7, 3)] is determined from I[1PG(7, 4)]) and the

TABLE 3. MEASURED ENHANCEMENT OF THE O_2^+ 1N (0, 0) BAND IN TYPE-B AURORA, FROM SPECTRA OBTAINED BY HUNTEN IN 1952 AND BY SHEMANSKY IN 1963

Ratio	Normal ratio	Enhancement factor		Number of displays	Observer
		Average	Range of values		
$\frac{I[O_2^+(0, 0)]}{I[1PG(7, 3)]}$		2·6	1·2 → 3·6	1	Hunten
	0·7	2·2	2·0 → 2·5*	2	Shemansky
$\frac{I[O_2^+(2, 0) + (3, 1)]}{I[N_2^+ 1N(1, 4)]}$		2·9	2·2 → 3·4	1	Hunten
$\frac{I[M(3, 0)]}{I[1PG(4, 1)]}$		1·2	0·76 → 1·6	1	Hunten
	0·50	1·1	0·92 → 1·4*	4	Shemansky

* These values are already averages of several 10 sec scans obtained on single displays.

differences in excitation functions; the O_2^+ and N_2^+ 1N have similar electron excitation functions, which differ considerably in shape from that of the N_2 1PG. The normal ratio I[O_2^+ (0, 0)]/I[1PG(7, 3)] $\approx$ 0·7 was determined by averaging a number of the weak auroral spectra mentioned above. Thus both the Hunten observations in 1952 and the present observations indicate an enhancement of the O_2^+ (0, 0) band relative to the N_2 1PG by a factor between 2 and 3 in type-B red aurora. In addition, the Hunten spectra indicate a similar enhancement of the O_2^+ (2, 0) and (3, 1) bands over the N_2^+ 1N (1, 4) band.

The only other quantitive measurements in the literature are those of Evans and Vallance Jones (1965), who reported a maximum increase in the ratio I[O_2^+ 1N (0, 0)]/I[1PG] of 1·5, in the transition from normal to type-B aurora. However the measurements were made using filter photometers having characteristics which resulted in uncertainty in the interpretation of the data. It will be pointed out later that the maximum enhancement factor (1·5) must actually be interpreted as a minimum value.

The intensity of the O_2^+ 1N (0, 0) band was related to the international brightness coefficient by comparison with the intensity of the N_2^+ M (3, 0) band. IBC I is defined here as I[M(3, 0)] = 0·31 kR, I[M] = 20 kR.* The intensity of the O_2^+ 1N (0, 0) band in an IBC III type-B red aurora would then be 13 kR. The intensity of the band system can be determined from the (0, 0) band provided one has knowledge of, or assumes, an excitation mechanism. Table 4 gives the theoretical relative population rates of the $b^4\Sigma_g^-$ state for simultaneous ionization–excitation by electron impact. These values were determined from the Franck–Condon factors for the transition [$b^4\Sigma_g^- - X^3\Sigma_g^-$ ($v = 0$)], calculated by Wacks and Krauss (1961). Table 5 gives the absolute transition probabilities and estimated

TABLE 4. PREDICTED RELATIVE POPULATION RATES ($g_{v'}$) FOR THE $O_2^+ - O_2$, [$b^4\Sigma_g^- - X^3\Sigma_g^-(v = 0)$] EXCITATION TRANSITION (FROM THE FRANCK–CONDON FACTORS CALCULATED BY WACKS AND KRAUSS (1961)

v'	0	1	2	3	4	5	$\Sigma_{g_{v'}}$
$g_{v'}$	100	83	40	15	5	1·6	245

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* A high degree of accuracy is not claimed for this definition, since the comparison with the N_2^+ 1N (0, 0) band intensity was indirect (Shemansky, 1966). The figure given differs by about 20 per cent with the estimate given by Chamberlain (1961).

TABLE 5. O_2^+ FIRST NEGATIVE SYSTEM ($b^4\Sigma_g^- - a^4\Pi_u$). TRANSITION PROBABILITIES*. PREDICTED AURORAL INTENSITIES†

v' \ v''	0	1	2	3	4	5	6	7	8	9	10	Σ
0	5999·9 2·710 2·71 + 5 13	6389·0 2·477 2·82 + 5 13	6822·3 1·427 1·81 + 5 8·7	7307·6 6·620 − 1 9·17 + 4 4·4	7854·4 2·706 − 1 4·05 + 4 1·9	8474·6 1·018 − 1 1·65 + 4 0·79	9183·6 3·610 − 2 6·0 + 3 0·29	10001·2 1·225 − 2 2·2 + 3 0·10	10953·7 4·014 − 4 8·0 + 2	12076·4 1·275 − 3 3·0 + 2	13417·9 3·939 − 4	7·702 8·929 + 5
1	5608·7 5·299 4·35 + 5 17	5947·2 2·225 − 1 2·16 + 4 0·86	6320·9 3·783 − 1 4·21 + 4 1·7	6735·3 9·049 − 1 1·12 + 5 4·5	7197·2 8·004 − 1 1·09 + 5 4·3	7714·5 4·924 − 1 7·25 + 4 2·9	8297·7 2·496 − 1 3·84 + 4 1·5	8959·5 1·121 − 1 1·88 + 4 0·75	9716·4 4·628 − 2 8·2 + 3 0·33	10589·6 1·798 − 2 3·4 + 3 0·13	11607·2 6·654 − 3 1·3 + 3	8·530 8·623 + 5
2	5274·8 3·608 2·21 + 5 4·2	5573·2 2·293 1·84 + 5 3·5	5900·1 1·456 1·40 + 5 2·7	6259·6 4·573 − 2 5·0 + 3 0·1	6656·6 2·055 − 1 2·51 + 4 0·48	7096·7 5·000 − 1 6·69 + 4 1·3	7587·3 4·917 − 1 6·95 + 4 1·3	8136·9 3·387 − 1 5·24 + 4 1·0	8756·3 1·917 − 1 3·16 + 4 0·61	9459·3 9·558 − 2 1·66 + 4 0·32	10263·0 4·363 − 2 8·0 + 3 0·15	9·270 8·260 + 5
3	4987·0 1·006 3·53 + 4 0·25	5252·9 5·226 3·13 + 5 2·3	5542·3 3·649 − 1 2·86 + 4 0·21	5858·3 1·560 1·46 + 5 1·05	6204·6 4·960 − 1 5·35 + 4 0·39	6585·3 5·026 − 4 — —	7005·6 1·680 − 1 2·20 + 4 0·16	7471·6 3·325 − 1 4·71 + 4 0·34	7990·7 3·266 − 1 4·97 + 4 0·36	8572·0 2·354 − 1 3·83 + 4 0·28	9226·8 1·416 − 1 2·46 + 4 0·18	9·857 7·581 + 5
4	4736·6 9·817 − 2 — —	4975·8 2·474 8·45 + 4 0·20	5234·7 5·099 2·97 + 5 0·71	5515·8 1·213 − 2 9·0 + 2 —	5821·7 9·774 − 1 8·98 + 4 0·22	6155·6 8·152 − 1 8·65 + 4 0·21	6521·3 1·418 − 1 1·66 + 4 0·04	6923·3 1·084 − 2 1·4 + 3 —	7366·7 1·501 − 1 2·09 + 4 0·05	7858·0 2·402 − 1 3·61 + 4 0·09	8404·8 2·278 − 1 3·66 + 4 0·09	10·247 6·703 + 5

v' \ v''
Band Origin $\nu^3 q_{v'v''}$ $A_{v'v''}$ (sec^{-1}) Intensity kR (IBC III Type-B Red).

* Franck–Condon Factors from Nicholls (1965), Re curve from Jeunehomme (1966c).

† I[O_2^+] = 100 kR IBC III type-B red aurora, 0·42 kR IBC I normal aurora.

intensities of the bands of the O_2^+ 1N for an IBC III type-B red aurora. The total intensity of the system using the above model is estimated to be I[O_2^+ 1N] = 100 kR. In an IBC I normal aurora, I[O_2^+ 1N] = 0·4 kR. The transition probabilities for the $(b^4\Sigma_g^- - a^4\Pi_u)$ transition were determined, taking into account the variation in electronic transition moment, using the Franck–Condon factors calculated by Nicholls (1965). The variation in electronic transition moment was determined from the lifetime measurements of the $b^4\Sigma_g^-$ state vibrational levels made by Jeunehomme (1966b).* The literature contains no previous measurements of relative band intensities in the aurora, and no measured values of relative upper state vibrational populations are available. However, rough measurements of the ratio I[O_2^+ 1N (0, 0)]/I[O_2^+ 1N (2, 0) + O_2^+ 1N (3·1)] have been made on seven spectra obtained by Hunten on 3, March 1952. The measured ratios varied from 1·1 to1·9 and gave an average value of 1·5, corrected for transmission through a normal atmosphere. This compares fairly well with the predicted ratio, 2·0.

The explanation of the observed enhancement presents no real difficulty; no excitation mechanism other than simultaneous ionization–excitation need be considered. The increased relative intensity can be explained largely by the increase in O_2 abundance relative to N_2 in the lower auroral levels. An additional small increase may take place as a result of moderate changes in the electron energy distribution at lower altitudes.

3. 2 *Relative intensity of the* N_2^+ M *and* N_2 IPG

The ratio I[M(3, 0)]/I[1PG(4, 1)] has been measured as a function of auroral height and type, using the spectra reported here. The relative intensity of the two band systems as determined by this ratio can vary by as much as a factor of 5. However, the variability is a function of auroral height as determined by rotational temperatures and average relative intensities if the [OI] λλ6300–64 lines. The low level bright aurorae display a considerably smaller variation than weak, high level aurorae. There is a gradual increase in the average relative intensity of the Meinel system with decreasing auroral height. Some measured values are given below in Table 6. Vegard and Tönsberg (1937) report similar results in comparing gray surfaces and spots with ordinary arcs and draperies. Thus Vegard and Tönsberg claimed to observe an enhancement of the N_2 1PG in both high level and low level aurorae, as compared to ordinary arcs and draperies. Omholt (1957) obtained a variation with height in good agreement with the above recent measurements, by comparing the total intensities of the (2, 0) and (4, 2) bands of the N_2 1PG, with the intensities of the (2, 0) and (3, 1) bands of the N_2^+ M. However, the Omholt spectra did not include type-B red aurorae.

TABLE 6. RELATIVE INTENSITY OF THE N_2^+M AND N_2 1PG

I[M(3, 0)]/I 1PG(4, 1)	Remarks	Observer
0·38	Weak, high aurora average of 1600 scans	Shemansky
0·58	Type-B red	Shemansky
0·51	Overall average	Shemansky
0·6	Type-B red	Hunten

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* The value of $\alpha(= -2{\cdot}7)$, in the equation $R_{v'v''} = [1 - \alpha(r_{v'v''} - r_{0,0})]$, given by Jeunehomme (1966b) as the best-fit value, was incorrect due to computational error (Jeunehomme 1966c). The new value is $\alpha = -2{\cdot}1$.

Thus, the behavior of the two systems as a function of height relative to one another appears to be well established at least down to type-B auroral heights. According to the measurements on the spectra reported here and the Hunten spectra, the trend established at the greater heights continues smoothly on into the type-B auroral levels. Therefore there can be no enhancement of the N_2 1PG in these spectra if one assumes that the N_2^+ M is well correlated with the N_2^+ 1N. There is no reason to believe this is not the case. The arguments indicating simultaneous ionization–excitation of the N_2^+ 1N by electrons (Bates, 1949) are just as applicable to the Meinel system. The excitation functions for the two systems are very similar in shape (e.g. see Fan, 1956), and one could expect negligible change in relative intensity due to changes in the energy distribution of the exciting electrons. Observations of the auroral N_2^+ M to date, although not extensive, are compatible with the assumed excitation mechanism (Shemansky, 1966).

3. 3 *Vibrational development in the* N_2 1PG

The relative populations of the vibrational levels of the $B^3\Pi_g$ state vary gradually as a function of auroral height. The measures of relative auroral height in this case were the rotational temperature of the first positive bands, and the average relative intensity of the [OI] $\lambda\lambda$6300–64 lines. Table 7 shows a comparison of the relative populations in type-B aurora with those of the high level weak aurorae (cf. Figs. 1 and 3). The relative populations obtained from the Hunten spectra are an average from the sequence of type-B red spectra mentioned earlier. The comparison with the average from the spectra reported here is rather good. But neither set of values is in good agreement with the theoretical populations calculated on the basis of electron impact excitation of $X^1\Sigma_g^+$ molecules. However, the average relative populations from weak high level aurorae display a greater vibrational development in the levels beyond $v' = 3$, and are in much better agreement with the theoretical values (with the exception of the $v' = 3$ level).

TABLE 7. RELATIVE POPULATIONS ($N_{v'}$) AND POPULATION RATES ($g_{v'}$) FOR THE $N_2B^3\Pi_g$ STATE

v'	0	1	2	3	4	5	6	7	8	9	10	Source
$N_{v'}$				131	100	47	26	12	8			Hunten: Type-B red
$N_{v'}$				122	100	52	28	14	9			Shemansky: Type-B red
$N_{v'}$				176	100	61	37	21	12			Shemansky: Weak, high level
$N_{v'}$	65	117	143	132	100	67	40	20	12	6	3	Theory, 5% cascade from $C^3\Pi_u$
$g_{v'}$	53	102	130	125	100	70	43	25	15	8	4	Theory, 5% cascade from $C^3\Pi_u$

The first possibility that comes to mind as an explanation to the observed variation in N_2 is a variation in cascade from the $C^3\Pi_u$ state. However this would appear to be an unlikely possibility. The observed variation would require a very large variation in the relative intensities of the N_2 first and second positive systems (e.g. see Broadfoot and Hunten, 1964). Both systems appear to be excited mostly by electron impact with $X^1\Sigma_g^+$ molecules, and have very similar excitation functions separated by about 2 eV (Stewart, 1955; Stewart and Gabathuler, 1958). One would expect very little change in relative intensity as a function of changes in the auroral electron energy distribution.* In addition, a variation in cascade from the $C^3\Pi_u$ state could not explain the observed relative population variation in the $B^3\Pi_g$, $v = 3$ level. This behavior of the first positive system will be discussed in more detail in a later publication.

Theoretical and measured populations of the $B^3\Pi_g$ state are compared in Table 7. The theoretical relative population rates (g_v) given in the Table were determined from the Franck–Condon factors for the $[B^3\Pi_g - X^1\Sigma_g{}^+(v = 0)]$ transition. The Franck–Condon factors applied here are very similar to the values given by Benesch *et al.* (1966a). The moderate differences between the g_v values and the theoretical N_v values are due to a variation in lifetime in the vibrational levels of the $B^3\Pi_g$ state (Jeunehomme, 1966a). A contribution of 5 per cent from the $C^3\Pi_u$ state to the total population rate of the $B^3\Pi_g$ state was assumed in the determination of the theoretical population rates. A contribution as high as 20 per cent would not measurably affect the relative populations of the levels beyond $v' = 3$.

The theoretical relative populations have been applied here to determine the total system intensity in IBC I aurora. The transition probabilities and predicted intensities of the bands are given in Table 8. The transition probabilities were calculated using the Franck–Condon factors computed by Benesch *et al.* (1966b), and the '$R_e(r)$' curve given by Jeunehomme (1966a). The absolute values are from the Jeunehomme (1966a) measurements. The transition probabilities appear to be rather well established; the '$R_e(r)$' curve determined by Jeunehomme is quite similar to an earlier curve established by Turner and Nicholls (1954). The relative transition probabilities of some of the bands are quite different from those given by Turner and Nicholls, due to differences in the Franck–Condon factors. The more recent Franck–Condon factors (Benesch *et al.*, 1966b) differ from the older values mostly as a result of an improved value for the equilibrium internuclear distance for the $A^3\Sigma_u{}^+$ state. The predicted intensities for an IBC I aurora were determined using the $N_2{}^+$M as a reference; I[M(3, 0)] = 0·31kR, I[M] = 20kR for an IBC I aurora.

4. DISCUSSION AND CONCLUSIONS

The enhancement of the $O_2{}^+$ 1N is a characteristic feature of type-B red aurora, according to the observations of Dahlstrom and Hunten (1951), Hunten (1955), and the measurements presented here. The measured enhancement is generally between a factor of 2 and 3 relative to the N_2 1PG. The Hunten spectra indicate a similar enhancement over the $N_2{}^+$ 1N. This disagrees with the results of a large number of photometer measurements by Evans and Vallance Jones (1965), which indicated a maximum enhancement of 1·5 relative to the N_2 1PG. However, Evans and Vallance Jones considered the contribution to their 1PG photometer channel of the (0, 1) $O_2{}^+$ band at 6400 Å to be negligible, whereas it may have been sufficiently large to mask the $O_2{}^+$ enhancement reported here, with the

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* The argument for this is based on the assumption that there is not a significant amount of fine structure in the electron energy distribution in the relevant energy region. It is argued that this is a safe assumption, on the basis of auroral observations of the relative intensity variations of the N_2 2PG and $N_2{}^+$ 1N, in comparison with the relative intensity variations of the N_2 1PG and $N_2{}^+$ M systems; both pairs of systems seldom vary by more than a factor of two in relative intensity (Hunten, 1955; Omholt, 1961; Shemansky, 1966). Due to the significant differences in the excitation functions of the $N_2{}^+$ systems in comparison with the N_2 positive systems, only moderate changes in the electron energy distribution would be required to reproduce the auroral observations (Shemansky, 1966). If one observes only a factor of 2 variation in the intensities of the N_2 positive systems relative to the $N_2{}^+$ systems, there should be a much attenuated variation in the relative intensities of the N_2 systems.

TABLE 8. N_2 FIRST POSITIVE SYSTEM TRANSITION PROBABILITIES AND PREDICTED INTENSITIES* IN IBC I AURORA

v' \ v''	0	1	2	3	4	5	6	7	8	9	10	$\sum_{v''} A_{v'v''}$
0	10,508·3 6·62 + 4 0·98	12,373 4·12 + 4 0·61	14,977 1·36 + 4 0·20	18,874 3·19 + 3 0·05	25,328 5·4 + 2 0·01	38,080						1·25 + 5
1	8912·4 8·48 + 4 2·26	10,217·5 5·1 + 2 0·01	11,925 2·12 + 4 0·56	14,269 1·80 + 4 0·48	17,687 7·21 + 3 0·19	23,060 1·91 + 3 0·05	32,920					1·34 + 5
2	7753·7 3·96 + 4 1·29	8723·0 5·98 + 4 1·95	9939·9 1·25 + 4 0·41	11,516 3·12 + 3 0·10	13,635 1·25 + 4 0·41	16,643 9·25 + 3 0·30	21,210 3·64 + 3 0·12	28,990				1·40 + 5
3	6875·2 9·26 + 3 0·28	7626·8 6·82 + 4 2·05	8542·5 2·13 + 4 0·64	9680·4 2·88 + 4 0·87	11,137·9 7·7 + 2 0·02	13,061 4·70 + 3 0·14	15,717 7·93 + 3 0·24	19,619 4·85 + 3 0·15	25,906			1·46 + 5
4	6186·7 1·39 + 3 0·03	6788·6 2·68 + 4 0·61	7504·7 7·46 + 4 1·70	8370·1 1·69 + 3 0·04	9436·4 2·98 + 4 0·68	10,781·4 8·29 + 3 0·19	12,529 2·7 + 2 0·01	14,890 4·56 + 3 0·10	18,252 4·90 + 3 0·11	23,414		1·52 + 5
5		6127·3 5·82 + 3 0·09	6704·8 4·73 + 4 0·72	7387·2 6·15 + 4 0·94	8205·5 2·44 + 3 0·04	9203·9 1·94 + 4 0·30	10,448·2 1·60 + 4 0·24	12,040 1·14 + 3 0·02	14,147 1·31 + 3 0·02	17,063 3·61 + 3 0·06	21,357	1·59 + 5
6		5592·5 9·8 + 2 0·01	6069·7 1·45 + 4 0·13	6623·6 6·61 + 4 0·60	7274·0 4·02 + 4 0·37	8047·9 1·38 + 4 0·13	8983·4 7·41 + 3 0·07	10,133·3 1·85 + 4 0·17	11,588·5 5·58 + 3 0·05	13,474	16,018 1·79 + 3 0·02	1·69 + 5
7			5553·4 2·92 + 3 0·01	6013·5 2·78 + 4 0·13	6544·9 7·76 + 4 0·35	7164·8 1·92 + 4 0·09	7896·9 2·54 + 4 0·12	8773·7 6·5 + 2	9841·8 1·51 + 4 0·07	11,169·7 1·02 + 4 0·05	12,863 1·20 + 3 0·01	1·80 + 5
8				5515·3 7·18 + 3 0·02	5959·0 4·52 + 4 0·12	6468·6 8·07 + 4 0·22	7059·5 5·24 + 3 0·01	7752·0 3·13 + 4 0·09	8574·2 1·07 + 3	9564·9 8·63 + 3 0·02	10,779·9 1·25 + 4 0·03	1·92 + 5
9					5478·2 1·48 + 4 0·02	5906·0 6·67 + 4 0·09	6394·7 7·68 + 4 0·10	6957·8 4·0 + 1	7612·9 2·97 + 4 0·04	8383·9 6·69 + 3 0·01	9303·0 2·71 + 3	1·97 + 5
10						5442·2 2·68 + 4 0·02	5854·4 8·92 + 4 0·06	6322·8 6·50 + 4 0·04	6859·3 2·80 + 3	7479·0 2·25 + 4 0·02	8201·9 1·38 + 4 0·01	2·20 + 5

	v''
v_e	λ(Å)P_{11} Head $A_{v'v''}$ (sec^{-1}) Intensity (kR) IBC I Aurora

* 5% cascade from $C^3\Pi_u$ assumed.
I[1PG] = 24 kR, IBC I aurora.

result that the 1·5 enhancement factor must be considered a minimum, rather than a maximum value. The observations are therefore not necessarily in conflict. The O_2^+ 1N enhancement of the order given above seems well established. This behavior of the O_2^+ 1N may be easily explained because the change in relative abundance of O_2 and N_2, from high to low auroral heights, is of the same magnitude as the enhancement; no variation or change in the excitation mechanism would be required to explain the phenomenon. Rough measurements of the relative intensities of the (0, 0) and [(2, 0) + (3, 1)] bands are in fair agreement with the value predicted by the assumed simultaneous ionization-excitation by electrons. The estimated total O_2^+ 1N intensity in 1BC III type-B red aurora is about 100 kR. This is about a factor of 10 greater than the very rough estimate made by Chamberlain (1961).

The type-B auroral spectra reported in this paper, and those obtained by Hunten (1955) indicate no enhancement of the N_2 1PG relative to the N_2^+ M. According to the argument given earlier, the N_2 1PG should also display little change relative to the N_2^+ 1N, on the average. This is in disagreement with the earlier observations, with the probable exception of the observations of Evans and Vallance Jones (1965). The Evans photometer measurements indicated an average enhancement of N_2 1PG by a factor of 1·4, over the N_2^+ 1N. However, this enhancement factor, which is already low in comparison to earlier published results, must be considered a maximum value, for the same reason cited in the paragraph above. The amount by which the factor (1·4) should be reduced is uncertain, due mostly to the fact that the instrumental function of the Evans N_2 1PG photometer was not a measured quantity. The reasons for the disagreement with the spectrographic measurements of Vegard and Tönsberg (1937), Vegard (1940), Malville (1959) and Herman (1960), are not entirely clear. The explanation may arise in the type of observation common to this group of observers. The measurements were made low on the horizon with long-slit spectrographs, resulting in brightness profiles of the spectral features, as a function of zenith angle. The estimation of relative intensities of long and short wavelength features depends rather critically on an accurate determination of the zenith angle in order to take into account the differential extinction in the lower atmosphere. In addition, the brightness distribution of the short wavelength features may be distorted to some degree by scattered light from the very bright lower border of the aurora, giving the impression of an enhancement of the long wavelength features in the lower border. The spectra presented by Herman (1960) are illustrative of the difficulties involved in making the measurements. The author presents two spectra obtained from the same photographic film exposed in a patrol spectrograph. One spectrum corresponds to an elevation angle of 20°N the other, 20°S. The analysis by Herman indicated a change in relative intensity of the two N_2 positive systems by a factor of 3·7, based on the assumption that extinction would be the same in both spectra. However, a re-examination of the spectra indicates a change in intensity of the N_2^+ 1N (0, 2) λ4709 band relative to the N_2 1PG of only ~25 per cent. But the relative intensities of the λ4278 (0, 1) and λ4709 (0, 2)N_2^+ 1N bands change by a factor of about 2, strongly suggesting a difference in extinction or scattering for the two spectra. The change measured by Herman in the relative intensity of the N_2 2PG (1, 4) band, at a shorter wavelength (3998 Å), could therefore easily have been due to differences in extinction and scattering.

The results and conclusions presented here cannot be considered without question. Further measurements of the O_2^+ 1N would be desirable. Measurements of relative population rates in normal and low level aurorae would be particularly useful in determining the excitation mechanism. Additional observations of the N_2 1PG would also be desirable in view of the fact that, up to this point, the enhancement of the system has been widely accepted as characteristic of type-B aurorae.

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APPENDIX

THE N_2^+M COUPLING CONSTANT

Meinel (1951), who made the original analysis of the system, applied a negative coupling constant on the basis that the transition was isoelectronic with the corresponding transition in CN. Douglas (1953), who made an analysis of the system at higher resolution, chose the positive root without giving an explanation. There are three ways of determining whether the $^2\Pi$ state is normal or inverted:

(1) The Λ-type splitting of the $^2\Pi_{3/2}$ sub-state is smaller than that of the $^2\Pi_{1/2}$ sub-state (see Herzberg, 1950).

(2) Missing lines in the neighborhood of the zero gap are different for the two subbands.

(3) The intensity distribution of the lines of a given band are different for normal and inverted sub-states.

The available measurements are not accurate enough to make a determination by the first method. Douglas (1953) indicates the presence of $Q_2(1)$ lines in two of the bands that were analyzed. $Q_2(1)$ lines would not be present if the $^2\Pi$ state were normal. It therefore seems fairly certain that the upper state is inverted. However, comparison of experimental and synthetic spectra at relatively high resolution should be made as a confirmation.