RESULTS OF A SURVEY OF IGY PATROL SPECTRA AT COLLEGE, ALASKA

by

L. Herman and A. E. Belon

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Submission Date:
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Principal Investigator

C. T. Elvey
Director
FOREWORD

This report is an enlarged and revised version of an original study conducted by one of us (HERMAN, 1960*). Several additional emissions of the auroral spectrum are studied. In order to ascertain and clarify some unexpected results of the original study the spectroscopic data has been re-classified into three well defined groups which are analysed separately. Data of questionable quality are removed. It appears that this new study resolves ambiguities present in the original results and allows revised and new interpretations to be advanced.

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RESULTS OF A SURVEY OF IGY PATROL SPECTRA AT COLLEGE, ALASKA

by

L. Herman* and A. E. Belon

ABSTRACT

The behavior of prominent auroral emissions has been studied statistically using the IGY patrol spectrograms obtained at College, Alaska during the International Geophysical Year. Results are presented in the form of mean diurnal intensity variations and in the form of correlation tables. Both presentations suggest the occurrence of two types of auroras. One is relatively weak, has a broad intensity maximum around magnetic midnight, and contains the hydrogen Balmer emissions. The other gradually increases in intensity until magnetic midnight and thereafter maintains a high intensity level until dawn. Its spectrum is usually characterized by the presence of the first positive bands of $N_2^+$.

The mean diurnal intensity variation of the sodium emission suggests that the twilight enhancement of the sodium D-lines persists to much greater solar depression angles than those previously reported. Some evidence is found for a small auroral contribution to the sodium emission. This contribution is however erratic and does not correlate well with any specific auroral emission.

The $[OI] \ 6364\AA$ emission shows, as expected, a strong twilight enhancement persisting to large solar depression angles. No enhancement is observed for the $[OI] \ 5577\AA$ emission.

A weak correlation is found between the intensity of the hydrogen Balmer emissions and the occurrence of red auroras.

Appendix: It is shown that the high vibrational excitation in the $B(\sum_u^2+) \ N_2^+$ state of $N_2^+$, occasionally observed in red auroras, can be explained by a simple two-step (ionization and excitation) electron transition in $N_2$, without recourse to the more complex charge exchange process between protons and $N_2$.

INTRODUCTION

One of the purposes of the International Geophysical Year was to patrol and record auroral and airglow activity throughout the world. A complete set of instruments was installed at College, Alaska and operated continuously during the IGY. In particular, the spectrum of the aurora and airglow was recorded on a "patrol spectrograph" in the spectral region 3500A to 6800A.

Instrumentation

The IGY Patrol spectrograph (Perkin-Elmer Model 173) photographs automatically successive grating spectra having an average dispersion of 330A/mm and a resolution of 8.2A. Auroral and airglow radiations are collected by an all-sky field lens which places on the entrance slit of the spectrograph an image of the sky extending from north to south horizons along the geomagnetic meridian. Fiducial marks are shown at 45° elevations. The light is then collimated by a Petzval doublet lens of 24 inches focal length and f/8 aperture and is dispersed by a 600 lines/mm grating, blazed for first order at 5100A. The resulting spectrum is brought to a focus by a semi-solid Schmidt camera of f/0.625 aperture, and is recorded on 16 mm Eastman-Kodak 103a-F film.

Radiations measured

The patrol spectrograph was in operation every night from September 1957 to May 1958, and from November 1958 to May 1959. Spectra were usually taken continuously during twilight and night with exposure times approximately of 5 min., 15 min., and 100 min. in succession. On these spectra the photographic densities of the following lines or bands were measured:
6623.6Å (6,3) - first positive band of N₂

6562.8Å - Hα

6363.9Å - (2p⁴ 3p - 2p⁴ 1D) - of \( \frac{2}{1} [\text{OI}] \)

6300.2Å - (2p⁴ 3p - 2p⁴ 1D) - of \( \frac{2}{1} [\text{OI}] \)

5198.5Å + 5200.7 - (2p³ 4S⁰ - 2p³ 2D⁰) of \( \frac{2}{1} [\text{Ni}] \)

5890.0Å + 5895.9 - (3²S - 3²F⁰) - of NaI

5577.3Å - (2p⁴ 1D - 2p⁴ 1S) - of \( \frac{3}{2} [\text{OI}] \)

5001.1Å + 5001.5 + 5005.1 - (3p³D - 3d³F⁰) - of NII

4709.2Å (0,2) - first negative system of N⁺₂

3804.9Å (0,2) - second positive system of N₂

**Intensity estimates**

Because of the large amount of available data, considerable labor would have been required to measure the relative intensity by standard methods, even if only the main radiations were investigated. In order to reduce the labor the photographic densities of the spectrum lines were estimated visually using a calibrated neutral-density stepped filter. The width of each density strip was of the same order of magnitude as that of the spectral lines to be measured. The scale of the stepped filter is given in Table 1.

<table>
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<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
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<td>0.49</td>
<td>0.75</td>
<td>1.09</td>
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</table>

The above scale may be used to determine the true photographic characteristic curve in the red, say between 6000Å and 6500Å. For this purpose
measurements for the two oxygen red lines 6300.2A and 6363.9A were used. The ratio of their intensities was assumed to be three. The characteristic curve obtained in that way may be seen on Figure 1.

**Precision of the estimates** - As the scaling proceeded it was realized that when the photographic density of the line or band was larger than say one step above the background of the film, the precision was rather poor. Consequently, in the final analysis of the data, only density step number readings below 4.5 were considered. This lack of precision for higher densities was due to the fact that, for readings above 5, the estimates were not based on the density but on the apparent width of the broadened overexposed lines.

**DIURNAL VARIATION OF PROMINENT EMISSIONS**

The diurnal intensity variation of selected emissions at the zenith of College was calculated using the spectra obtained during the 1957, 1958 and 1959 observing periods.

Since a given emission may appear on the spectra only when the exposure time is long enough, care must be taken to use spectra obtained with about the same exposure. Consequently, the spectra were divided into two groups, one including only short exposures (10 to 20 minutes) and the other, long exposures (50 to 100 minutes).

Some auroral and airglow emissions are known to be enhanced during twilight by resonance excitation. Since most auroras are known to occur within the height range of 80-150 km, the spectra were considered to be influenced by twilight whenever the sunlight illuminated the atmosphere below 150 km during any part of the exposure.

The spectra emitted in the absence of twilight were further divided according to the absence or presence of the first positive bands of $N_2$. The former
spectra tend to be associated with quiet auroral forms, the latter with active forms.

On the basis of the above distinctions three types of diurnal curves were calculated for both short and long exposures. The first included all spectra, the second excluded the twilight influenced spectra, and the third excluded both twilight spectra and spectra showing the first positive band of N\textsubscript{2} at 6624\AA. The diurnal variations of prominent auroral emissions are shown in Figure 2. On each curve the abscissa indicates the local time and the ordinate indicates the average hourly density step reading as obtained with the stepped filter. The number above each hourly interval indicates the number of observations used to calculate the arithmetic average. When the number of observations is too small, abnormal diurnal values are obtained, which have little meaning.

**H Alpha**

Figure 2 shows the diurnal variation of H\textalpha intensity at the zenith for the long exposure spectra. No studies have been made on the twilight emission of H\textalpha. It has been shown recently, however, that narrow H\textalpha lines are emitted in high latitude regions. They are very likely due to slow ions bombarding the upper atmosphere or to fluorescence excitation by the scattered Lyman lines. In auroral regions such as Alaska, the intensity of these narrow lines is more than 100 times smaller than that of the broader hydrogen lines usually present in auroral spectra. Indeed, a comparison of curves 1 and 2 in Figure 2 shows no difference in the diurnal curves of H\textalpha intensity before and after the elimination of twilight spectra. Both curves show a definite maximum between 0100 and 0300 local time (150\degree WMT).
Curve 3 shows the diurnal variation of $H_{\alpha}$ intensity when both twilight spectra and spectra showing the first positive band of $N_2$ are eliminated. The most noticeable change is a shift of the maximum toward local midnight.

First positive system ($B^3Π - A^3Σ$) of $N_2$

The diurnal variation for the 6623.6Å (6,3) first positive band is given in Figure 2. It is very different from that shown by $H_{\alpha}$ graphs. While the $H_{\alpha}$ graph has an almost symmetrical form, the graph for 6623.6Å band is strongly asymmetric. Its intensity increases during the first part of the night and remains almost constant during the second half of the night. The remarkable feature is the fact that the average emission of the molecular bands of neutral nitrogen seems to continue during the morning twilight, and possibly during the beginning of the next day. The beginning of the plateau in the diurnal intensity variation is located at 24 hours as for $H_{\alpha}$. For the hydrogen line it lasts about 4 hours, and for the first positive about twice as long. In the evening hours the diurnal curve of $H_{\alpha}$ seems to lead that of the first positive. The maximum intensity is reached for both radiations at about the same time, and their behavior is similar for about 4 hours after midnight. The $H_{\alpha}$ emission then decreases, while that of the 6623.6Å band remains almost constant until the end of the night. Thus, at the beginning of a display both radiations seem to be related, while at the end of the night the emission of $N_2$ seems to be independent of the $H$ radiation. A similar behavior has been found by ROMICK and ELVEY (1958), MALVILLE (1959) and REES, BELON and ROMICK (1960). As for the hydrogen line, no twilight effect is known for the 6623.6 band and none is to be expected. Nevertheless, the diurnal variation for this band was also calculated with all twilight spectra eliminated. The result is shown on curve 2. The histogram is similar to that of curve 1.
Second positive system \((C^3\Pi - B^3\Pi)\) of \(N_2\)

Diurnal curves for the 3804.9A (0,2) second positive band are given in Figure 2. The results obtained are quite similar to those given for the first positive system. As expected, very little or no twilight effect is shown since curves 1 and 2 are very similar. As for the first positive system they show a plateau beginning at midnight and remain quite steady at a high level until the end of the night.

A comparison of the diurnal variation of the 3805A band before and after elimination of spectra containing the first positive bands shows a large decrease in its intensity. This decrease is however, relatively greater in the morning hours than in the evening hours, so that the 3805A diurnal curve tends to form a maximum. This observation is not compatible with a constant ratio of intensities between the first and second positive bands in all auroras, even if the fact that a certain minimum intensity is necessary to produce an image on the film is taken into account. It is also interesting to note that most of the diurnal curves of other emissions show the same effect. This fact may be interpreted as indicating that two types of auroras occur. One auroral type would contain the first positive bands which are generally attributed to electron excitation and would usually be bright. The other auroral type would be much weaker and, because of the similarity in diurnal distribution, might be associated with the hydrogen emissions indicative of proton bombardment. A similar distinction based on a detailed analysis of individual auroral spectra and photographs has been advanced by Rees, Belon and Romick (1960).
First negative system \( (B^2 \sum_u^+ - X^2 \sum_g^+) \) of \( \text{N}_2^+ \)

The diurnal variation of the 4709A (0,2) first negative band of \( \text{N}_2^+ \) is shown in Figure 2. The results obtained for this band are very similar to those given for the 3805A band of the second positive system of \( \text{N}_2 \). Curve 2, obtained after elimination of twilight spectra, is essentially the same as curve 1. This would imply that the twilight contribution is negligible compared to that of the auroral emission of this radiation. Curve 3 again shows a large decrease in the intensity of 4709 and a tendency for the curve to form a maximum.

Red Oxygen line 6363.9A - \( \text{O}_1 \)

The diurnal variation of the red oxygen line is shown in Figure 2. The high relative intensity at the beginning of the night, followed by a decrease, probably corresponds to the twilight and post twilight effects found in air-glow emission at low latitude (BARBIER 1959). The elimination of spectra exposed when the earth's shadow line is below 150 km does not appreciably change the distribution (Curve 2). Such a condition is to be expected because the 6364A emission is generally considered to originate above 150 km, and also because the post-twilight effect continues the enhancement of the red oxygen emission well below the earth's shadow line. The corresponding effect during the morning hours is masked in our data by the larger auroral contribution.

The auroral contribution to the 6364A line intensity appears on the diurnal curves in the early evening, reaches a maximum between midnight and 0300, and decreases slightly afterwards. The morning decrease is even more pronounced when the spectra containing the first positive bands of \( \text{N}_2 \) are eliminated from the data (curve 3). The same effect has already been noted and discussed for the 3805A band of \( \text{N}_2 \).
Green oxygen line 5577.3A - $^3_2 [\text{O}^+]$

Because of the great intensity of this emission in the aurora, it is usually overexposed in both short and long exposure spectra. Consequently, the diurnal curves obtained for this emission (Figure 2) have little significance. They are included only to show that there is no indication of a twilight enhancement for this emission.

Sodium D$_1$ (5895.9A) and D$_2$ (5890.0A) lines

The sodium D-lines are usually considered to be an airglow emission which exhibits a very strong twilight enhancement. Diurnal curves for the sodium lines are shown in Figure 2 for both short and long exposures. They are very different from the diurnal curves of other emissions in that they reach a minimum value during the night instead of a maximum. After elimination of twilight spectra (earth's shadow line below 150 km), the diurnal curve for short exposures becomes flat, as is found for airglow sodium at low latitudes (BERTHIER and MORIGNAT, 1955). For long exposures, however, the diurnal curve, surprisingly, still shows a minimum during the night. This is the only emission for which the diurnal curves differ significantly between short and long exposures. The reason for such a discrepancy is not entirely clear. In the long exposures the large background of underlying bands of N$_2$ and O$_2^+$ could have caused the scaler to underestimate the intensity of sodium emission. This possibility is not likely because curve 3 for long exposures only contains those spectra in which this background is absent and the minimum still appears even more markedly.

An alternate and obvious explanation might be that the evening and morning increase in curves 2 and 3 (long exposures) are real and correspond to a twilight enhancement of sodium radiation above 150 km. DUFAY and TCHENG (1946)
and BARBIER and ROACH (1950) have occasionally observed a slight enhancement of the sodium lines when only the atmosphere at great altitudes was illuminated by the sun. The presence of sodium at such great altitudes is difficult to reconcile with the recent photometric determination of the vertical distribution of sodium during twilight (RUNDLE, HUNTEN and CHAMBERLAIN 1960). However, this effect probably corresponds to a very small sodium concentration in comparison to that at the peak of the sodium layer. Indeed, the effect is apparently too weak to appear on short exposure spectra and may therefore be below the minimum sensitivity of photometric instruments.

The presence of the sodium emission in the spectrum of the aurora has not yet been proved conclusively. A study of individual spectra sometimes shows an enhancement of the sodium lines in auroral forms and sometimes does not (Figure 8). On a statistical basis, the change in shape of the sodium diurnal variation (Figure 2, curve 2 and curve 3 for long exposures) suggests that, at least in those auroral spectra which contain the first positive bands of \( N_2 \), there is a contribution due to an auroral sodium emission. It is probable that the remaining auroral spectra also contribute to the sodium emission, so that if all auroral spectra were eliminated the resulting airglow sodium variation would be symmetrical about midnight. This step, however, was not taken because the removal of all auroral spectra would have left too little data on which to base statistics.

SPECTRAL INTENSITY DISTRIBUTION

The analysis of the spectroscopic data in terms of mean diurnal variation is not very suitable for an intensity correlation study of different emissions because the averaging of values used in histograms smoothes out the rapid intensity changes. A direct comparison of two emissions measured on the same
spectrum seems to be a better investigation procedure. The spectra and the emissions used in this study are the same as those used in the calculation of the diurnal variations described in curves 2 of Figure 2 (except for the 5577 A and 6364 A lines). These data contain only the long exposure spectra emitted in the zenith of College in the absence of twilight (earth's shadow line above 150 km). Short exposure (10-20 minutes) spectra give essentially the same results as long exposure (50-100 minutes) spectra except for the much greater occurrence of zero intensities. Only long exposure spectra are included in Table 2. The results are presented in the form of tables of frequency of occurrence. In each table two emissions are compared. The intensity* of one emission is given on one coordinate and the intensity of the other on the second coordinate. In the space representing simultaneous intensities of the two emissions the number of occurrences is indicated. Correlation trends are shown by dashing the spaces with the maximum number of occurrences first in the horizontal ordinates (circles) and then in the vertical ordinates (squares). This double maximum trend minimizes the influence of zero intensities when one emission is much weaker than the other.

An interesting part of this study concerns the relative importance of Hα and the first positive bands of nitrogen. For these two emissions it can be seen in Table 2 that the largest numbers are located in the first line and the first column. This would correspond to an alternate appearance of the two radiations, as it has often been suggested (MEINEL, 1952). A second much less important trend which implies a simultaneous increase of both emissions seems to exist. These trends are consistent with the corresponding diurnal curves.

*The term "intensity" is here used in a broad sense. The "intensities" indicated in the ordinates of the tables are actually the density step numbers as defined in the introduction.
Table 2.

Spectral intensity distribution of 974 zenith auroras recorded during the IGY. For each emission the relative intensity is given in the ordinate on a scale of 0 to 9. In the space corresponding to simultaneous intensities of two emissions the number of occurrences is entered.
Table 2.

Spectral intensity distribution of 974 zenith auroras recorded during the IGY, (continued). Correlation trends are shown by indicating the spaces with the maximum number of occurrences with squares vertically, circles horizontally and dashes for secondary maxima.

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Spectral intensity distribution of 974 zenith auroras recorded during the IGY, (continued). Correlation trends are shown by indicating the spaces with the maximum number of occurrences with squares vertically, circles horizontally and dashes for secondary maxima.
of Hα and the 6624A band (Figure 2) where it was seen that during the evening hours both radiations increase while in the morning the hydrogen emission diminishes in intensity and the first positive bands of nitrogen continue to increase.

Table 2 also shows that the other auroral emissions can be present either without Hα or without the first positive bands of nitrogen. However, when either of these two emissions increases in intensity the other auroral emissions also increase. In general, the correlation trends are more systematic with the first positive bands than with Hα. This condition may be caused by the greater occurrence of high intensities in auroras which contain the first positive bands of N2.

In Table 2, a comparison of the ratio of intensities of 5577A and 6364A with the intensity of Hα suggests a possible enhancement of the 6364A emission when Hα is present. The 6364A oxygen emission shows a sharp discontinuity at I(6364) = 4 in its correlation trends with other emissions. This discontinuity, if real, could be interpreted as an altitude effect.

As expected, the oxygen 5577A emission shows a good correlation with all auroral emissions. Excellent correlation of the 3805A, 4709A, and 6624A emissions is seen in Table 2.

The sodium D-lines correlate only weakly with other emissions. Table 2 shows a tendency for large D-lines intensities to occur for higher intensities of Hα; 6624A, 5577A, and 4709A.
CLASSIFICATION OF AURORAL SPECTRA

The variation of relative intensities of different lines is evidently related to the conditions of excitation of atmospheric constituents. If we assume that the composition of the atmosphere is constant, the factors which may change are the altitude and the nature of incoming or exciting particles. Consequently, one would expect to find considerable differences from one auroral spectrum to another. Actually, most of the auroral spectra photographed, so far, exhibit a rather constant composition. Only on rare occasions, as in high altitude type A auroras, are drastic changes recorded in the spectrum. This situation is very likely due to the fact that the excitation is far from being in a steady condition. Primary auroral beams last for only a fraction of a second to a minute. But, most auroral spectra have been obtained so far with exposure times from 10 to 100 minutes. In these conditions most of the rapid spectral changes are smoothed out during the exposure. Moreover, altitude effects are often difficult to detect owing to overlapping of different auroral forms.

In spite of these difficulties, it is possible to find among the large number of spectra recorded with the patrol spectrograph a small number showing characteristic features, if not typical samples. A few of those are shown in the following figures. We will give a brief description and a tentative designation of the selected spectra. The latter is based on a particular characteristic feature. The other features are often common to many other types. Again, owing to long exposure times and to overlapping of different forms, we cannot expect to find more drastic differences from one type to another.
Type B (low altitude)

An example is shown in Figure 3. It exhibits very strong first positive bands, $B \quad \sum \quad A \quad \sum \quad \frac{3}{2}$, of neutral molecular nitrogen. The relative intensity of this system is very likely still much stronger in the infrared. In the violet the second positive system of $N_2$ is also strong; the other features in this region are normal. The hydrogen lines $H_\alpha$ and $H_\beta$ are absent or very weak. This condition is certainly of fundamental importance for the understanding of the processes of excitation. The absence of the atomic hydrogen lines suggests that the emission is mainly caused by low-energy electron excitation in the region of the atmosphere where the relative concentration of neutral molecular nitrogen is high.

Another indication of the low altitude of emission is the presence of strong bands belonging to the first negative system, $4 \quad \sum \quad - \quad \frac{3}{2}$ of $O_2^+$. In Figure 3 the bands 6026.4Å (0,0) and 5597.5Å (2,1) are easily seen.

The mercury lines indicate a partially cloudy sky.

Type AB

This spectrum is shown in Figure 4. It exhibits weak $N_2$ bands but strong atomic features. Compared with Figure 3, $H$ alpha is very strong, and so are the permitted NII lines, 5001-5005Å (3p $^3D$ - 3d $^3P^0$) and 5676 - 5680Å (3s $^3P^0$ - 3p $^3D$). The forbidden NII lines are weak but present. The red forbidden oxygen lines 6300-6364Å are stronger than the green 5577Å line. The negative bands of the $N_2^+$ molecule exhibit a high vibrational temperature, much higher than that in Figure 3. This spectrum corresponds to atmospheric densities definitely lower than in Figure 3.
Type A

The high altitude features are still more pronounced here. They appear in two ways: 1) all forbidden transitions are enhanced as compared to the permitted ones, 2) the \( \text{N}_2^+ \) emission increases in comparison with that of \( \text{N}_2 \). This condition is seen in Figure 5. The red oxygen lines are much stronger than the green line. A similar phenomenon is seen for the forbidden \( \text{NII} \) lines. Compared to the permitted 5001-5005\( \text{A} \) \( \text{NII} \) line, the forbidden 6583.6 \( (2p^2 \, 3p - 2p^2 \, 1D) \, \frac{2}{1} \, [\text{NII}] \) line is considerably more intense in Figure 5 than in Figure 4. Moreover, as for the oxygen forbidden lines, the red \( \frac{2}{1} \, [\text{NII}] \) nebular line 6583.6\( \text{A} \) is enhanced as compared to the auroral 5754.8\( \text{A} \) \( (2p^2 \, 1D - 2p^2 \, 1S) \) green line. It is interesting to note that the 5001-5005 \( \text{NII} \) line seems to be spread over the whole sky, while the 6583.6\( \text{A} \) forbidden \( \text{NII} \) line is located near the zenith and spread only over a small portion of the sky. This occurrence could be due to an overlapping effect of different auroral types or forms.

High latitude airglow

In our patrol spectrograms the OH airglow emission does not usually appear, because of the relatively short exposure times used. When much longer exposure times are used, the red and infrared OH emission is well recorded. Moreover, in absence of strong displays, narrow hydrogen lines are also photographed. The origin of the lines is not yet entirely clear. They may be due to slow positive ions stopped at high altitude or to resonance excitation by Lyman radiation scattered at high altitude by the terrestrial atmosphere. Figure 6 shows an example of such a spectrum.
Abnormal spectra

Outside the usual spectral types described above, unusual features are found in a few cases. Only two will be mentioned, one concerning the width of the Hα line, and the other involving the intensity of the sodium D-lines.

Fast protons spectra - Our survey of the patrol spectrograms reveals the existence of numerous spectra with hydrogen lines not much broader than the 8Å instrumental width. The contour of the line was not measured quantitatively. The microdensitometer tracings show, however, that the emission lines have an intensity peak sharp enough to make the line appear narrow when the exposure time is short. An example of this condition may be seen in Figure 4. In contradistinction with these sharp contours, on a few occasions, very broad Hα lines are found in Figure 7. Unfortunately, the Hβ line is too weak for comparison. The contour of this H line is rather unusual. If it is attributed to a Doppler effect it indicates a relatively flat velocity distribution of incoming protons with maximum detectable speeds in excess of 3000 km/sec. An alternative interpretation may be sought. In this spectral region the first positive system may interfere. If it did, the vibrational distribution of this system should be such that the (7,4) band would be strongly enhanced and would increase the intensity of the violet wing of the hydrogen line. A second alternative would be the interference of the twilight in this spectral region. Indeed, between H alpha and the red 6364Å oxygen line, the twilight spectrum shows a broad continuous emission band overlapping the violet wing of the auroral hydrogen line.

Sodium emission - As far as is known it is not yet certain whether or not the sodium lines are actually emitted in auroral displays. Inspection of the
data show that, as a general rule, the sodium lines are usually emitted over the whole meridian when present. However, considerable changes appear in the relative intensity of the sodium lines from one auroral spectrum to another. Such changes are shown in Figure 8. Spectrum (a) shows a usual type of aurora with $H_\alpha$ and positive bands. The sodium lines are rather strong and show the same intensity distribution along the meridian as the auroral emissions. Spectrum (b) is of type B and stronger than (a). The sodium lines however, are much weaker.
Since the discovery by Meinel of fast hydrogen atoms in the spectrum of the polar aurora, theoretical and experimental investigations have been initiated on excitation and ionization of atoms by impact with positive ions. A better understanding has been obtained concerning processes of electron capture and ionization between atoms. The mechanism of excitation of molecules seems however to be much more complicated. In a given molecule one may have electronic excitation, excitation of vibration or dissociation. The cross section curves for molecules have often different forms from that of atoms (GHOSH and SHERIDAN, 1957; STEDEFORD and HASTED, 1955). Excitation of molecular vibration has been investigated by FAN (1956) and BRANSCOMB, SHALEK and DONNER (1954). The main characteristic of the emission spectrum excited by ion impact is the high apparent vibrational temperature of the first negative system of molecular nitrogen. A tentative interpretation has been given by Fan. Using the principle of conservation of momentum and energy during the collision he calculated the amount of energy transferred to the target molecule by the incident ion. In this estimate no account is taken of the relative probability of excitation by charge exchange and by collision.

For low energy protons (1 to 5 kev) CARLETON (1957) found about the same vibrational distribution as when excited by electron impact, as is expected for charge exchange at low energies. On the other hand former studies by WIEN (1914) and by Ghosh seem to indicate that very little mechanical energy is transferred to the target molecule by the incident ion. At any rate the
process proposed by Fan although it may explain the possibility of transfer of mechanical energy, does not allow any quantitative estimate of the amount of vibrational energy gained on the different vibrational levels of the initial molecular state of the transition.

A still more confusing situation exists concerning the rotational temperature. Vegard found that the rotational temperature is higher than the gas temperature by about 85°K when nitrogen is excited by canal rays, while ROESLER, FAN and CHAMBERLAIN (1958) and CARLETON (1957) found agreement between the rotational and the gas temperatures for energies between 3 and 30 kev. BRANSCOMB, SHALEK and BONNER (1954) found a much higher temperature (700°K-1000°K) for protons of 100 kev.

In the spectrum of the aurora VALLANCE-JONES and HARRISON (1955) found low rotational temperatures (250°K to 400°K) for the 3914.4 (0,0) negative band of N₂⁺, while for the great Feb. 10, 1958 aurora, CLARK and BELON (1959) found a rotational temperature of 2500°K.

Use of Franck-Condon principle

As is well known the motion of a molecular bound electron from one orbit to another is very rapid as compared to that of the heavy nuclei. The change of position of the latter during the time of an electron transition is usually neglected in the calculation of the overlap integral. The overlap function is then estimated for a given internuclear distance \( r \), by supposing the nuclei at rest. This is known as the Franck-Condon principle. It is currently used in calculations of spontaneous molecular transition probabilities, but has also been applied to excitation of molecules by electron impact, (see for example, CRAGGS and MASSEY, 1959).
For a given electronic transition the square of the overlap integral is then

\[ \left| \int \psi(v' | R) \cdot \psi(v' | R) \cdot R^2 \, dR \right|^2 = P (v' | v'') \]

The important result is that the relative probability of excitation of a molecule by a collision with an electron is approximately independent of its energy. Similar considerations are used for collisions between ions and atoms or molecules in the near-adiabatic region for low relative velocities. For the charge exchange process the reaction would concern essentially the electron transition, the kinetic energy of relative motion of the nuclei being treated as a perturbation, (see for example, MASSEY and BURHOP 1952). In the high energy range of the ions, experiment and theory indicate also a very similar behavior for electron and ion excitation (FAN, 1956). This seems to be the case for the first negative system of ionized molecular nitrogen. The population of the initial vibrational levels of the excited ion is the same when the nitrogen is excited by 120 kev electrons or 205 kev protons.

It is only in the intermediate energy range of heavy ions where the molecular population exhibits different population distribution than for electrons. But it is not at all certain that a special mechanism should be used for this case. It might well be that a simple two step electron transition competing with the direct excitation process could explain the difference in the vibrational population of the excited \( \text{N}_2^+ \) ion. We made an attempt to calculate the relative population and the intensities of the 4709.2 (0,2); 4651.8 (1,3); and 4599.7 (2,4) bands of the \( \text{B}_u^2 \Sigma^+ - \text{X}_g^2 \Sigma^+ \) system of \( \text{N}_2^+ \) for the direct process (BATES 1949).
(1) \[ N_2(X \sum^1) + H^+ \rightarrow N_2^+ (B \sum^2, v') + H \]

or the indirect two steps process

2) \[ N_2(X \sum^1) + H^+ \rightarrow N_2^+ (X \sum^2, v'') + H^* \]

\[ H^* + N_2^+ (X \sum^2, v'') \rightarrow N_2^+ (B \sum^2, v') + H \]

They are followed by the emission of the first negative bands,

3) \[ N_2^+ (B \sum^2, v') \rightarrow N_2^+ (X \sum^2, v'') + h\nu \]

The detailed balance condition gives for the population \( N(v') \) of the \( v' \) level:

assuming process 1) and a low gas temperature,

\[ N(v') = b N(v=0) P(v=0,v') \sum_{v''} P(v',v'') \sqrt{3} (v',v'') \]

\[ = I(v',v'')/c \sqrt{4 (v',v'') P(v',v'')} \].

For process 1) and a high gas temperature, one has,

\[ N(v') = b \sum_v N(v) P(v,v') \sum_{v''} P(v',v'') \sqrt{3} (v',v'') \]

\[ = I(v',v'')/c \sqrt{4 (v',v'') P(v',v'')} \].

Actually the sum \( \sum_{v''} P(v',v'') \sqrt{3} (v',v'') \) is almost constant and

\[ I(v',v'') = a \sqrt{4 (v',v'') P(0,v') P(v',v'')} \].

\( a, b, c \) are constants, \( v, v', v'' \), vibrational quantum numbers respectively for the molecules \( N_2(X \sum^1) \), \( N_2^+ (X \sum^2) \) and \( N_2^+ (B \sum^2) \) and \( I(v',v'') \) the intensity of the band \( v' \rightarrow v'' \).
For the two step process, we have similarly for low gas temperature

\[
I(v',v'') = a \frac{P(v',v'')}{\sum_{v''} P(v'',v')} \sum_{v''} P(v=0,v'') P(v'',v')
\]

and for high gas temperatures,

\[
I(v',v'') = a \frac{P(v',v'')}{\sum_{v''} N(v) P(v,v') P(v',v'')}
\]

The relative transition probabilities \(P(v',v'')\) for the first negative system of \(N_2^+\) have been calculated by Nicholls, Pillow and Bates. The overlap integrals \(P(v,v'')\) for the \(N_2(X^1)\) and \(N_2^+(X^2)\) can be rapidly estimated using numerical tables given by BATES (1952). However this can be done only for the first integrals for which \(v'+v''\) is smaller than 4. We are calculating the other overlap integrals we need. In this report we used only the data given in Bates' tables. The preliminary results we obtained are summarized in the following table.

**TABLE 3**

Calculated and observed intensities of the first negative system

\[
\text{B} \sum^2 - \text{X} \sum^2 \text{of } N_2^+ \\
\]

<table>
<thead>
<tr>
<th>Process</th>
<th>(T = 0) °K</th>
<th>(T = 2000) °K</th>
<th>(T = 3000) °K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated by the one step process</td>
<td>1.0</td>
<td>0.25</td>
<td>0.03</td>
</tr>
<tr>
<td>Electrons (120 kev) (FAN 1956)</td>
<td>1.0</td>
<td>0.33</td>
<td>0.08</td>
</tr>
<tr>
<td>Protons (205 kev) (FAN 1956)</td>
<td>1.0</td>
<td>0.33</td>
<td>0.10</td>
</tr>
<tr>
<td>Calculated intensities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for the two step excitation process</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T = 0) °K</td>
<td>1.0</td>
<td>0.90</td>
<td>0.34</td>
</tr>
<tr>
<td>(T = 2000) °K</td>
<td>1.0</td>
<td>1.0</td>
<td>0.50</td>
</tr>
<tr>
<td>(T = 3000) °K</td>
<td>1.0</td>
<td>1.06</td>
<td>0.64</td>
</tr>
<tr>
<td>He(^+) ions (150 kev) (FAN 1956)</td>
<td>1.0</td>
<td>1.0</td>
<td>0.50</td>
</tr>
<tr>
<td>Protons (20 kev) (FAN 1956)</td>
<td>1.0</td>
<td>0.62</td>
<td>0.34</td>
</tr>
<tr>
<td>Aurora Feb. 10 1958 (CLARK and BELON 1959) integrated intensities</td>
<td>1.0</td>
<td>1.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>
As expected the two step excitation increases considerably the population of the levels \( v > 0 \) of \( \text{N}_2^+(B^2 \Sigma) \). The increase of the gas temperature from 0 °K to 3000 °K has little effect on the population of the level \( v' = 1 \). The level \( v' = 2 \) seems to be much more sensitive to the temperature. The one step excitation would agree with the electron excitation for higher temperatures.

A quite satisfactory agreement exists between the intensities obtained by a two-step excitation at 3000 °K and \( \text{He}^+ \) (150 keV) ion excitation. The spectrum obtained with protons at 20 keV would correspond to partial contribution of the two processes.

It is interesting to note that the Feb. 10, 1958 aurora has a very high population of the levels \( v > 0 \) which cannot be explained by the two-step process, and is very likely not due to collisional excitation.
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Figure 1—Characteristic curve of the film (103aF) in the red spectral region.
Figure 2. Mean diurnal intensity variation of prominent auroral and airglow emissions
1) All data
2) Twilight spectra excluded
3) Twilight spectra and spectra showing the first positive bands of N$_2$ excluded

The ordinate $I$ (relative) is the average density step number as defined in the introduction. Therefore it is a non-linear intensity scale. The numbers above each curve represent the number of observations used to calculate the average.
Figure 3. Type B Auroral Spectrum. The main features of this spectrum are: 1) strong positive bands of $N_2$ and strong first negative bands of $O_2$; 2) very weak hydrogen Balmer lines.

<table>
<thead>
<tr>
<th>$N_2$ 2nd pos.</th>
<th>$N_2$ Negative</th>
<th>$H_2$</th>
<th>$N_{II}$</th>
<th>$Ni$</th>
<th>$O_{II}$</th>
<th>$N_{II}$</th>
<th>Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>3805</td>
<td>3849</td>
<td>4709</td>
<td>5003</td>
<td>5577</td>
<td>5678</td>
<td>5892</td>
<td>6363</td>
</tr>
</tbody>
</table>

Figure 4. Type AB auroral spectrum. The positive bands are much weaker than in Figure 3 (type B). The hydrogen lines and oxygen 6300-6364A lines are very strong. The permitted $N_{II}$ lines are strong but the forbidden $N_{II}$ lines are very weak. The bands of $N_2$ show a considerable development of the vibrational structure. The mean altitude of this emission is definitely higher than in Figure 3 (type B) but lower than in Figure 5 (type A).
Figure 5. Type A auroral spectrum. The emissions of the red "nebular" lines of oxygen (6300Å) and nitrogen (6584Å) are much stronger than the corresponding green "auroral" lines (5577Å and 5755Å). All forbidden lines are stronger than the permitted ones. The bands of ionized molecular nitrogen are relatively more intense than in Figure 3 and 4 and show a very large development of the vibrational structure.
Figure 6. High Latitude Airglow Spectrum. It has been obtained on weak glows by G. Weill at Terre Adelie, Antarctica with a grating spectrograph having a dispersion of 40Å per millimeter. It shows strong OH vibration - rotation bands and a narrow H_α line.

Figure 7. Spectrum Showing an Unusually Broadened H Line. Scattered sunlight and the 6544Å (7,4) first positive band of N_2 may contribute to the apparent broadening of H_α.
Figure 8. Sodium Emission in the Aurora. Spectrum (a) shows strong sodium D-lines in an aurora of moderate intensity. Spectrum (b) shows very weak sodium D-lines although the other auroral features are much more intense than in spectrum (a).