Auroral Spectroscopy and Its Application to the Characterization of Primary Particle Fluxes

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The main features of the ultraviolet, visible and infrared spectra of aurora are described. Excitation processes by auroral primary particles are summarized. A simple approach is followed to provide an understanding of the main factors influencing the dependence of the relative intensity of features of the auroral spectrum on incident particle energy and atmospheric parameters. The status of the use of various optical measurements to infer average particle energies and total energy fluxes is reviewed including comments on precautions to be observed and limitations to be considered in the application and interpretation of optical measurements.

1. Introduction

Over the past few decades, knowledge of the spectrum of the aurora has been very much improved and extended to the extreme ultraviolet at short wavelengths and to the middle infrared at long wavelengths. Theoretical understanding of the processes involved in the excitation and emission of features of the spectrum, has also been vastly improved so that the intensities of many, if not most, emissions can be predicted in the most common case of excitation by fluxes of primary electrons. Because the relative intensities of some lines and bands of the spectrum are sensitive to the energy of the incoming electrons, it is becoming possible to infer the average energy of the incident fluxes from observations of two or more spectral features. Provided that certain precautions are observed, optical techniques can provide a reliable and convenient method for monitoring the characteristics of incident particle fluxes. The earlier theoretical work of Rees and Luckey (1974) who calculated ratios of \( I(6300) \), \( I(5577) \) and \( I(N_2^+) \) has been widely used in inferring particle energies. Recent refinements and extensions of this work will be discussed.

This paper is not intended to be a full historical review of the subject nor to cover all the possible spectral ratios which have been suggested or used to estimate particle energies. The references should provide starting points for more detailed material. Likewise the sections on the auroral spectrum and its excitation mechanisms constitute no more than a brief introduction.

2. Spectrum of Aurora

The optical spectrum of aurora has been explored for many years. The region from 3150 Å to 9000 Å which is easily accessible from the ground with photographic spectrographs and photomultiplier spectrometers, has been extensively studied. Sum-
maries of earlier progress may be found in the books by Chamberlain (1961) and Vallance Jones (1974). At shorter wavelengths rocket and satellite instruments have provided detailed information down to 400 Å in the extreme ultraviolet while Fourier spectroscopy has provided the means to map the spectrum in detail to at least 16000 Å. Further into the infrared, the spectrum has been explored at lower resolution with rocket-borne photometers and interferometers. A detailed set of spectra, from the extreme ultraviolet to the near infrared, has been assembled by Vallance Jones (1990). Many key spectra are to be found in the book by Rees (1989).

In this review, we reproduce only a few examples of spectra which are relevant to the discussion to follow. In Fig. 1 is presented a typical lower-resolution spectrum of the visible region of the spectrum. This shows the best known and mostly easily studied emission features including the 5577 Å (“green”) and 6300–64 Å (“red”) atomic oxygen lines, the N₂ First Negative Bands (1N) at 3914 Å, 4278 Å and 4709 Å, the N₂ First Positive (1P) bands in the 6500 Å to 7000 Å region. This spectrum also shows the Hα and Hβ lines at 6563 Å and 4861 Å respectively. These lines are prominent in aurora excited by primary fluxes consisting partly or wholly of protons but are weak or absent in bright aurora which is normally excited primarily by electrons.

Figure 2 shows the near ultraviolet spectrum, as obtained with a digital photomultiplier spectrometer. This shows the N₂ Second Positive (2P) bands, the N₂ Vegard-Kaplan (VK) bands as well further strong N₂ 1N bands. Features which will be discussed later, include the strong 0,0 2P band at 3371 Å and the strong 1,10 VK band at 3425 Å. The prominent forbidden atomic nitrogen line at 3466 Å is also of interest.

In Fig. 3 is reproduced a rare photographic spectrum of the near infrared spectrum of a great high-altitude red aurora. In this spectrum, the allowed strong lines of neutral atomic oxygen are particularly prominent at 8446 Å and 7774 Å as well as the forbidden

\[ \text{Fig. 1. Microphotometer tracing of low-resolution auroral spectrum from Saskatoon, November 15/16, 1960 obtained at 20° in north 02:05-02:35 MST.} \]
The most important lines and band systems of the auroral spectrum are summarized in Tables 1, 2 and 3 in which the wavelength of atomic lines or the spectral region of molecular band systems are indicated, together with the emitting excited species and the approximate intensity for IBC 3 aurora. For completeness, these include important multiplet of $O^+$ at 7320–29 Å.
Table 1. Forbidden atomic lines in the auroral spectrum.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Emitter</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>5577 Å</td>
<td>OI (1S)</td>
<td>100 kR</td>
</tr>
<tr>
<td>6300-64 Å</td>
<td>OI (1D)</td>
<td>Variable</td>
</tr>
<tr>
<td>5200 Å</td>
<td>NI (1D)</td>
<td>Variable</td>
</tr>
<tr>
<td>3466 Å</td>
<td>NI (1P)</td>
<td>Variable</td>
</tr>
<tr>
<td>10400 Å</td>
<td>NI (1P)</td>
<td>Variable</td>
</tr>
<tr>
<td>7320 Å</td>
<td>OII (1P)</td>
<td>Variable</td>
</tr>
</tbody>
</table>

Table 2. Allowed atomic lines in the auroral spectrum.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Emitter</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1304 Å</td>
<td>OI (1S)</td>
<td>160 kR</td>
</tr>
<tr>
<td>1356 Å</td>
<td>OI (1S)</td>
<td>16 kR</td>
</tr>
<tr>
<td>989 Å</td>
<td>OI (1D)</td>
<td>10 kR</td>
</tr>
<tr>
<td>834 Å</td>
<td>OII (1P)</td>
<td>6 kR</td>
</tr>
<tr>
<td>7774 Å</td>
<td>OI (1P)</td>
<td>10 kR</td>
</tr>
<tr>
<td>8446 Å</td>
<td>OI (1P)</td>
<td>12 kR</td>
</tr>
<tr>
<td>1200 Å</td>
<td>NI (1P)</td>
<td>32 kR</td>
</tr>
<tr>
<td>5001 Å</td>
<td>NII (1F)</td>
<td>600 kR</td>
</tr>
<tr>
<td>6563 Å</td>
<td>HI Balmer-alpha</td>
<td>0-1000 R</td>
</tr>
<tr>
<td>4861 Å</td>
<td>HI Balmer-beta</td>
<td>0-300 R</td>
</tr>
<tr>
<td>1216 Å</td>
<td>HI Lyman-alpha</td>
<td>0-10 kR</td>
</tr>
</tbody>
</table>

Table 3. Molecular bands in the auroral spectrum.

<table>
<thead>
<tr>
<th>Common name</th>
<th>Region</th>
<th>Emitter</th>
<th>Intensity kR</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2; 1st Neg.</td>
<td>Blue-near UV</td>
<td>N2(B)</td>
<td>150</td>
</tr>
<tr>
<td>N2; Meinel</td>
<td>Red-near IR</td>
<td>N2(A)</td>
<td>600</td>
</tr>
<tr>
<td>N2 2nd Pos.</td>
<td>Blue-near UV</td>
<td>N2(C)</td>
<td>110</td>
</tr>
<tr>
<td>N2 1st Pos.</td>
<td>Red-near IR</td>
<td>N2(B)</td>
<td>900</td>
</tr>
<tr>
<td>N2 LBH</td>
<td>Far UV</td>
<td>N2(a)</td>
<td>100</td>
</tr>
<tr>
<td>N2 VK</td>
<td>Near UV</td>
<td>N2(A)</td>
<td>Variable</td>
</tr>
<tr>
<td>O2; 1st Neg.</td>
<td>Green-red</td>
<td>O2(b)</td>
<td>30</td>
</tr>
<tr>
<td>O2 Atmos.</td>
<td>Near IR</td>
<td>O2(b)</td>
<td>Variable</td>
</tr>
<tr>
<td>O2 IR Atmos.</td>
<td>Near IR</td>
<td>O2(a)</td>
<td>2000</td>
</tr>
</tbody>
</table>

emissions in the extreme UV, far UV and in the IR which are not discussed in detail in this review. The features for which the intensity is indicated to be “variable”, have metastable upper states i.e. the radiative lifetime of these states is long enough for the excitation energy to be lost in collisions with other atmospheric particles rather than by emission. Transitions may be classified as being “allowed” (i.e. for which the selection
rules of electric dipole transitions are satisfied) or "forbidden" (for which these selection rules are not satisfied). Allowed transitions correspond to lifetimes of the order of $10^{-8}$ sec while for forbidden transitions the lifetime may range from milliseconds to hours. Table 4 contains a list of the lifetimes of metastable species important in aurora.

3. Excitation of the Spectrum

3.1 Excitation processes

The excitation processes for auroral emissions have been studied extensively over the past 40 years or more and in many cases are now well understood, so that variations in the spectrum and spectral ratios with the energy and nature of the exciting particles and with atmospheric composition can be predicted.

The major excitation processes are listed in the next subsections.

3.1.1. Direct electron impact

Direct electron impact processes include the reactions,

$$M + e \rightarrow M^* + e,$$
$$M + e \rightarrow M^{**} + 2e,$$
$$MN + e \rightarrow M^* + N + e,$$
$$MN + e \rightarrow M^{**} + N + 2e,$$

where M represents an atom or molecule and MN a molecule which is dissociated in the excitation process. The asterisk indicates an excited species.

3.1.2. Energy transfer from metastable excited species

A number of excited atoms or molecules have long radiative lifetimes and consequently may transfer their excitation energy to other atoms or molecules in collisions. Examples include,

$$O(1D) + O_2 \rightarrow O^*_2 + O(1P)$$
$$N_2(A) + O \rightarrow O(1S) + N_2.$$

Many other examples are known or suspected.

Table 4. Lifetimes of metastable states.

<table>
<thead>
<tr>
<th>Species</th>
<th>Emission(s)</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>O(1S)</td>
<td>5577 Å, 2972 Å</td>
<td>750 ms</td>
</tr>
<tr>
<td>O(1D)</td>
<td>6300–64 Å</td>
<td>134 s</td>
</tr>
<tr>
<td>N(1D)</td>
<td>5200 Å</td>
<td>26 h</td>
</tr>
<tr>
<td>N(1P)</td>
<td>3466 Å, 10400 Å</td>
<td>12 s</td>
</tr>
<tr>
<td>N2(A)</td>
<td>VK bands</td>
<td>2 s</td>
</tr>
<tr>
<td>N2(a)</td>
<td>LBH bands</td>
<td>140 µs</td>
</tr>
<tr>
<td>O2(a)</td>
<td>IR Atmospheric bands</td>
<td>1 hr</td>
</tr>
<tr>
<td>O2(b)</td>
<td>Atmospheric bands</td>
<td>12 s</td>
</tr>
<tr>
<td>O2(c)</td>
<td>Herzberg II</td>
<td>10 s</td>
</tr>
</tbody>
</table>
3.1.3. Ion reactions

Ions produced by electron impact may react with neutral molecules or atoms to give excited species. One important example is,

\[ \text{N}_2^+ + \text{O} \rightarrow \text{NO}^+ + \text{N}^2(\text{D}). \]

Dissociative recombination is another type of ion reaction leading to auroral emission, as in the case of

\[ \text{O}_2^+ + \text{e} \rightarrow \text{O} + \text{O}^1(\text{D}). \]

3.1.4. Excitation by energetic protons or heavier ions

Energetic protons may excite atmospheric species directly in inelastic collisions as do energetic electrons. In addition charge exchange collisions may result in the production of excited ions and energetic neutral hydrogen or heavier atoms which may themselves excite atmospheric species in further inelastic collisions. In addition, the secondary electrons produced in some of these collisions, can produce further excitation as discussed earlier in 3.1.1 and 3.3.

3.2 Energy loss processes

The main energy loss processes are radiation, giving rise to the emission, and quenching of which the energy transfer processes discussed in 3.1.2 are special cases. In other cases the excitation energy may be converted to translational energy or appear as rotational or vibrational excitation.

3.3 Excitation models

An important guide to the understanding and prediction of variations in the auroral spectrum, is provided by the theoretical calculation of the energy loss and excitation processes associated with the penetration of a flux of primary electrons or ions into the atmosphere. This theory can provide the means to predict the absolute and relative intensities of the features of the spectrum, from a knowledge of the energy distribution of the incident primary particle flux and the composition and temperature profile of the atmosphere. Reviews of earlier developments of the theory have been given by CHAMBERLAIN (1961) and VALLANCE JONES (1974). The approach in recent treatments falls into three parts. First, the steady state angular and energy flux of electrons is calculated as a function of position within the atmosphere. Secondly, the excitation rates of different excited species are calculated from this flux and a knowledge of the excitation cross sections of the target atoms or molecules of the atmosphere. Thirdly, relevant photochemical equations are solved to calculate the emission rates of processes which involve ion reactions, energy transfer and quenching.

Major improvements over the past 15 years in modelling have been described by STRICKLAND et al. (1976), STAMNES (1980, 1981) and REES and LUMMERZHEIM (1990). They have shown how the transport equations of a flux of electrons can be solved numerically with full consideration of the elastic and inelastic collisions of the electrons with atmospheric species. These methods have been applied by STRICKLAND et al. (1983, 1989), DANIELL and STRICKLAND (1986), HECHT et al. (1989), MEIER et al. (1989) and REES and LUMMERZHEIM (1989).
Progress has also been made in modelling excitation due to proton fluxes. The proton transport equations which yield ionization profiles and energy deposition relations have been solved by Jasperse and Basu (1982) and compared with observation by Basu et al. (1987). Another approach to the theory of optical excitation in proton aurora was explored by Rees (1982). The theory of the emission of the HI lines has most recently been considered by Van Zyl et al. (1984) and Van Zyl and Neumann (1988).

The full solution for proton excitation is much more difficult than the corresponding electron problem largely because excitation by both H and H\(^+\) and by secondary electrons must be considered and because not all the relevant cross sections are well known.

The even more difficult problem of excitation by O\(^+\) ions has been considered by Ishimoto et al. (1986) and that of He\(^+\) by Ishimoto and Torr (1987).

In this review, we will illustrate some general trends by means of the simpler and easily understood method used by Rees (1963). This method is based on an empirical expression for the energy loss rate for a stream of penetrating electrons as a function of mass depth in the atmosphere. The empirical expression was obtained by measurements in the laboratory of the luminosity distribution along an electron beam penetrating into gaseous nitrogen. By means of appropriate transformations from the laboratory to the atmospheric case, and taking into account the difference in composition in the two cases, it is possible to make a good estimate of the ion production rate in the atmosphere for a given primary electron stream. Ionization rate profiles, computed by this method, agree well with profiles calculated by the more exact methods mentioned above. It is then assumed that the secondary electron produced in each ionizing collision, loses its energy locally in various inelastic collisions some of which give rise to various excited atoms and molecules. To a good approximation, the excitation rate of excited species are then proportional to the relative concentration of the target species and the local ionization rate. Thus plots of ionization rate versus height and of atmospheric constituents versus height provide a means of visualizing the main factors controlling the emission profiles of many auroral features.

Because the insights provided by the approach described in the preceding paragraph are not quantitative, we have added results calculated using the Rees-type model described by Vallance Jones (1975). This takes into account properly all the factors which we discuss in the qualitative approach (although not in as rigorous a way as the more exact methods discussed above).

### 4. Variations Associated with Primary Energy Spectra

Variations in the energy spectra of incident primary electrons lead to variations in the relative intensity of features of the spectrum and consequently to the possibility of inferring the energy of the incident electrons from spectral observations. The rest of this review will be devoted to some illustrations of how such variations arise and some conclusions on the usefulness of different spectral features for this purpose as well as the sensitivity of various methods to changes in atmospheric parameters and observing conditions.

The primary effect of the variation in average primary electron energy is on the height distribution of the ion production rate in the atmosphere and the height distributions of energy deposition. For illustration we will assume that the primary electrons have a Maxwellian energy distribution of the form,
The average particle energy of such a distribution is $2E_0$. The parameter, $E_0$, is usually called the characteristic energy. Energy spectra measured in aurora often approximate to this distribution. Figure 4 shows the theoretical emission rate profile of the 4278 Å N$_2^+$ emission for three different characteristic energies spanning the range of energies usually observed. These profiles were calculated by the Rees method. Two sets of profiles are reproduced for two very different assumed conditions of the atmosphere. The atmospheric models used were the MSIS86 model for conditions of low and of high solar and geomagnetic activity. The exact parameters chosen to illustrate extremes of conditions are listed in Table 5. Some resulting atmospheric quantities are summarized in Table 6.

\[
\Phi(E) = \text{const} \cdot E \cdot \exp \left(-\frac{E}{E_0}\right).
\]

Fig. 4. Profiles for volume emission rate of 4278 Å N$_2^+$ band for Maxwellian downward isotropic primary electron fluxes with characteristic energies 0.38, 1.9 and 9.5 keV for extreme geophysical conditions as described in text.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Day No.</th>
<th>$F_{10.7}$</th>
<th>$F_{10.7}$</th>
<th>$a_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter, quiet</td>
<td>1</td>
<td>70</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td>Summer, quiet</td>
<td>180</td>
<td>70</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td>Winter, disturbed</td>
<td>1</td>
<td>200</td>
<td>200</td>
<td>160</td>
</tr>
<tr>
<td>Summer, disturbed</td>
<td>180</td>
<td>200</td>
<td>200</td>
<td>160</td>
</tr>
</tbody>
</table>
Table 6. Atmospheric constituent densities and temperatures.

<table>
<thead>
<tr>
<th>Condition</th>
<th>120 km [O]</th>
<th>120 km [N₂]</th>
<th>200 km [O]</th>
<th>200 km [N₂]</th>
<th>Tₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter, quiet</td>
<td>8.8(10)</td>
<td>3.1(11)</td>
<td>3.2(9)</td>
<td>1.24(9)</td>
<td>610 K</td>
</tr>
<tr>
<td>Summer, quiet</td>
<td>5.4(10)</td>
<td>3.2(11)</td>
<td>1.8(9)</td>
<td>2.2 (9)</td>
<td>724 K</td>
</tr>
<tr>
<td>Winter, disturbed</td>
<td>6.4(10)</td>
<td>3.3(11)</td>
<td>4.3(9)</td>
<td>6.7 (9)</td>
<td>1430 K</td>
</tr>
<tr>
<td>Summer, disturbed</td>
<td>3.5(10)</td>
<td>3.4(11)</td>
<td>1.7(9)</td>
<td>8.5 (9)</td>
<td>1733 K</td>
</tr>
</tbody>
</table>

The two sets of curves shown in Fig. 4 are for winter, quiet conditions and for summer, disturbed, that is for the most extreme conditions of Table 6. It may be seen that the absolute height distribution is very different for conditions of high exospheric temperature because of the upward expansion of the thermosphere. If the curves are plotted as a function of pressure (which is approximately proportional to the mass thickness of the atmosphere), the differences in the N₂ 4278 Å height profiles become much smaller. However, plots against pressure are less easily related to the conventional height profiles and consequently we use here an "equivalent height". This is the actual height for the winter, quiet case and for others is the height under winter quiet conditions at which the pressure is equal to the pressure in the other case. (One could transform back to the original plot against height using the pressure-height relation for the conditions in question.) The value of using pressure as a height coordinate has been pointed out by Walker (1975) and Rees et al. (1983). In Fig. 5, the curves of Fig. 4 are replotted against equivalent height and it will be seen that the corresponding profiles for the two cases almost coincide. This makes it possible to simplify the discussion of the effects of changes in atmospheric composition with height and lower boundary conditions independently of the scale change arising from differences in exospheric temperature. (The two sets of curves in Fig. 5 do not coincide exactly because pressure is not exactly proportional to the "effective thickness" of the atmosphere.)

4.1 Variations primarily due to height changes in atmospheric composition

4.1.1. Ratios of permitted OI lines to I(4278)

This concerns the ratios of features excited by direct electron impact on atomic oxygen and molecular nitrogen. The situation is illustrated in Fig. 6 where the height curve for N₂ emissions is plotted together with four curves for the [O]/[N₂] ratio. The latter are plotted on a logarithmic scale to cover the very wide change in this ratio with height. To a first approximation, the ratio of the excitation rate of an emission such as the 8446 Å OI line or the N₂ bands (which have been shown to arise primarily from electron impact on O and N₂) will be proportional to the local concentrations of these species. It is clear that the ratio of such features will be related to the weighted average of the [O]/[N₂] ratio across the excitation profile for each value of E₀. Ratios calculated by our model for the same cases are plotted in Fig. 7. In this case the intensity of the 8446 Å OI line is computed simply as if it were excited by electron impact on atomic O by secondary electrons. (The real situation may be more complicated e.g. Hecht et al. (1989), Link et al. (1988).) Two conclusions may be drawn from Figs. 6 and 7. First, the emission feature ratios are sensitive to energy changes and secondly, the effect of atmospheric composition changes are important. Thus this ratio is a useful indicator of
absolute energy only if the atmospheric composition profile is known; it should be useful for measuring changes in incident particle energy over periods where the atmospheric parameters remain constant. Conversely if the particle energy is known this ratio may provide information on atmospheric composition. This question has been discussed by HECHT et al. (1989).

4.1.2. Ratios of emissions excited directly from O$_2$ and N$_2$

Curves for this ratio are plotted on Fig. 8. The more quantitative results from the model, are plotted in Fig. 9. Here the composition ratio is plotted on a linear scale. The changes to be expected, both with energy and composition, are less marked although quite significant over the normal auroral energy range. This case would be realized in comparing the ratio of bands of the First Negative O$_2$ and N$_2$ band systems. The results of such a comparison have been reported by NICIEJEWSKI et al. (1989) and the results, summarized in Fig. 10, are in agreement with expectations. Another recent study of this ratio has been reported by HENRIKSEN et al. (1987).

4.2 Variations primarily due to quenching of metastable emitters

4.2.1. Ratio of I(6300) to I(4278)

The first example is the classical case of the ratio of the [OI] 6300 Å “red line” to one of the N$_2$ bands such as the easily measured 4278 Å N$_2$ band. The important factors controlling the situation are first, the composition ratio [O]/[N$_2$] as discussed above and
secondly, the relative probability that an excited O(1D) atom will emit radiation compared to the total rate of de-excitation by radiation and quenching. This probability may be expressed by the emission factor,

\[
\beta\{O(1D)\} = \frac{1}{1 + [k_0(N_2) \cdot [N_2] + k_0(O_2) \cdot [O_2]] \cdot \tau}
\]

where \(k_0(N_2)\) represent the rate constant for quenching of O(1D) by N\(_2\) and \(k_0(O_2)\) the corresponding quenching constant with O\(_2\). We have taken values of \(2.3 \times 10^{-11}\) and \(2.9 \times 10^{-11}\) cm\(^3\) s\(^{-1}\), respectively, for these rate constants. \(\tau\) is the radiative lifetime.

In Fig. 11 are plotted, for the different conditions, the product of the emission factor and the ratio \([O]/[N_2]\). It is immediately obvious that the composition-emission factor values vary very rapidly with height, so that their product, which to a first approximation gives the volume emission rate of 6300 Å, maximizes well above the peaks of the corresponding N\(_2\) emission profile. The model ratios, plotted in Fig. 12, provide a more quantitative measure of the variation although in this case our model may be less accurate because the local energy deposition assumption is certainly violated in the height range where much of the emission originates. The ratio, I(6300)/I(4278) is very sensitive

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**Fig. 6.** Profiles of concentration ratio \([O]/[N_2]\) versus equivalent height for the four geophysical conditions as described in the text. The production curves for 4278 Å N\(_2\) are also plotted. The total production rate of N\(_2\) is proportional to the 4278 Å volume emission rate.
to primary electron energy and there is also an important sensitivity to composition. The ratio is most useful as a measure of energy in the range of average energy below 10 keV because for higher energies the very small value of \( I(6300)/I(4278) \) is difficult to measure accurately especially when the effects of scattering are considered, as discussed below. Important progress has recently been made by HECHT et al. (1989) who have shown that one may combine measurements of \( I(6300)/I(4278) \) with high resolution measurements of the 7774 Å OI line to obtain information on the atmospheric composition and the incident electron energy.

Even without an exact knowledge of atmospheric composition profiles, this ratio has been widely used as an indicator of primary electron energy on the basis of the theoretical relations given by REES and LUCKEY (1974). Examples of such studies are those of MENDE and EATHER (1975), GUSTAFSSON et al. (1985), VALLANCE JONES et al. (1987) and ONO et al. (1987). More recent theoretical ratios calculated by the method of STRICKLAND et al. (1983) have been used in an important study by CHRISTENSEN et al. (1987). REES and ROBLE (1988) have also recalculated the \( I(6300)/I(4278) \) ratio using their more recent model. Points for these model results are also plotted on Fig. 12.

4.2.2. Ratio of \( I(VK) \) to other \( N_2 \) bands

A second important example is that of the intensity of bands of the Vegard-Kaplan system from the \( N_2(A) \) relative to those of another \( N_2 \) band such as the nearby strong Second Positive Band at 3371 Å. The emission factor for \( N_2(A) \) is given by the expression,

![Fig. 7. Ratios of \( I(8446)/I(4278) \) calculated from model for range of average primary electron energies for the four geophysical conditions described in the text.](image-url)
where $k_0(O)$ and $k_0(O_2)$ are the quenching rate constants of $N_2(A)$ by O and $O_2$ respectively. Values of $2.5 \times 10^{-11}$ and $4 \times 10^{-11} \text{ cm}^3 \cdot \text{s}^{-1}$ were used in the plots and modelling. Values of $\beta\{N_2(A)\}$ for different conditions, are plotted in Fig. 13. From the range of values of this factor, averaged over the height profiles, it is clear that the ratio of a Vegard-Kaplan band such as the 1,10 at 3425 Å to that of an $N_2$ band is highly sensitive to particle energy and somewhat less sensitive to atmospheric composition changes because both emissions are excited from $N_2$. This is borne out by the modelled ratios of the Vegard-Kaplan system intensity to I(4278) which are plotted in Fig. 14. A comparison of the value of the $I(3371)/I(3425)$ ratio has been done by comparing energies inferred from the Sonderstrom incoherent scatter radar with values of the ratio measured simultaneously in the magnetic zenith. The results are shown in Fig. 15. The measured ratios show a similar change, over the 2–20 keV energy range, as the modelled values. Further comments will be made on this results in 5.3. ISHIMOTO et al. (1988) used this ratio in a satellite study. Recent theoretical work on the behaviour of the $N_2$ 2P and VK bands has recently been done by SOLOMON (1989).

4.2.3. Ratio of I(7320) to I(4278)

A third example of a ratio which is sensitive to energy as a consequence of quenching, is that of the intensity of the 7320 Å $[OII]$ to that of an $N_2$ band (REES et al.,
Fig. 9. Similar to Fig. 7 but for the ratio I(1N 2,0 O+2)/I(1N 0,3 N+2). The ratios are plotted on a linear scale.

Fig. 10. Observed and theoretical I(1N 2,0 O)/I(1N 0,3 N) ratio as a function of mean primary energy (NIEJEWISKI et al., 1989). The mean energies were estimated from electron density profiles obtained simultaneously with the Sondrestrom incoherent scatter radar in Greenland and the modelling was done using the MSIS86 atmosphere for the night of observation, February 28, 1988. (Courtesy of Planetary Space Science.)
Fig. 11. Similar to Fig. 6 except that the abscissa quantity plotted is the product of $\beta[O^+(1D)]$ and the concentration ratio $[O]/[N_2]$. To a first approximation this quantity multiplied by the volume emission rate of 4278 Å $N_2^+$ should be proportional to the volume emission rate of I(6300).

1982). The advantage of this ratio, is that the excitation mechanism for both emissions is simple. A disadvantage is that while the [OII] emission is prominent in special cases such as the spectrum of Fig. 3, for more ordinary aurora the emission is heavily blended into the 5,3 1P $N_2$ band. Moreover variations in atmospheric composition must be considered in the interpretation. This ratio was used as an energy indicator in the work of Cogger et al. (1987).

4.2.4. Ratio of $I([NII])$ to $I(N_2)$ or $I(N_2^+)$

A fourth example is that of the [NII] lines at 3446 Å and 10400 Å. As noted in Table 4, these two lines originate from the same upper level and their intensity relative to an allowed $N_2$ or $N_2^+$ band should be a useful measure of incident electron energy (Pendleton et al., 1989).

4.2.5. Ratio of $I(5577)$ to $I(4278)$

This ratio was predicted by Rees and Luckey (1974) to be sensitive to primary electron energy and their results have been used by McEwen et al. (1981) and recently by Kaila and Rasinkangas (1989) in studies of pulsating aurora energy variations. Other references to work with this ratio is to be found in the paper by Vallance Jones et al. (1987). Certainly, quenching should produce decreases in the ratio for higher energy electrons reinforced by decreases in the $[O]/[N_2]$ ratio below 100 km. However, there is
still some uncertainty on the relative importance of different suggested excitation mechanisms for \textit{O}(^{1}\text{S})\text{,} so that the quantitative relation between electron energy and the ratio is less well predicted.

4.3 Variations in rotational and Doppler temperature

A somewhat different variable quantity in the spectrum is that of the rotational temperatures of molecular bands and thermal Doppler broadening of atomic lines. The intensity distribution in the rotational structure of many bands depends on the local kinetic temperature and in the particular case of the \textit{N}^{2}_{2} \textit{IN} bands, the variation may be measured conveniently with a pair of suitable interference filters together with a third background filter (e.g. HUN TEN et al., 1963). Because the kinetic temperature of the neutral atmosphere is a strong function of height above 100 km, the measured rotational temperature of such a band is also a function of the height of emission which is in turn a function of the energy of the incident exciting particles. Tests of this method have been carried out by SHEPHERD and EATHER (1976) and \textit{VALLANCE JONES et al.} (1987).

The profiles of atomic lines, measured by a Fabry-Perot or Michelson interferometer, may also be analyzed to yield the local kinetic temperature in the case of forbidden emissions which attain thermal equilibrium before emitting. In this case a similar derivation of incident particle energy may be carried out. Such measurements have been widely made with the 6300 \AA \textit{[OI]} line and to a smaller extent with other lines such as the 5577 \AA \textit{[OI]} line or the 7320 \AA \textit{O}^{+} line.
Figure 16 shows the variation of atmospheric temperature plotted against equivalent height together with the three $N_2^+$ height profiles. Figure 17 shows quantitative results from the model. It is clear that the average temperature from the rotational structure of $N_2^+$ bands will also be sensitive to the energy of the exciting electrons. It is also clear that the temperature-energy relation is highly sensitive to the exospheric temperature and consequently this quantity must be known either from an atmospheric model or preferably from an independent measurement from the Doppler profile of the red line (SICA et al., 1986; MCCORMAC et al., 1987; HEDIN and THUILLIER, 1988).

The rotational temperature method is somewhat suspect in the case of aurora excited by protons for which the rotational distribution may be perturbed by lower energy exciting collisions. For excitation by heavy ions such as $O^+$, the rotational distribution of the $N_2^+$ bands is strongly perturbed and serves instead as an indicator of the presence of these exciting ions. High altitude aurora, such as sunlit rays, and strong excitation by soft electrons, such as in Type-A red aurora, may also produce abnormal non-thermal rotational distributions. Of course, under such unusual conditions, other optical techniques, as discussed above, may also be unreliable.

4.4 Variations due to changes in atmospheric transmittance

For aurora, observed by satellite from outside the atmosphere, the height distribution of emission within the atmosphere can lead to energy sensitive variations in the observed intensity of spectral features in the ultraviolet. Features absorbed by molecular oxygen
Fig. 14. Similar to Fig. 7 for modelled values of the ratio \( \frac{I(VK)}{I(4278)} \). In this case the quenching rate constant and lifetime apply to the \( \nu'=0 \) vibrational level of \( N_2(A) \) so that some adjustment would be necessary to predict the intensity ratio for a particular VK band.

will be weaker when produced deeper in the atmosphere. The modelling of such effects involves many of the principles discussed above. In addition, the upward escape of radiation may be modified by resonance scattering under optically thick conditions. We will not attempt to discuss these matters in detail here. Good discussions may be found in the studies of PRASAD et al. (1985), MONCHIK et al. (1985) and REES et al. (1988).

5. Precautions and Limitations in the Application of Optical Methods of Energy Determination

The methods described have several limitations which must be considered.

5.1 Effect of protons and other ions in the primary flux

In the presence of significant ion flux, the results given by the intensity ratios discussed above must be treated with caution. Proton flux may be detected from the appearance of Doppler broadened or shifted HI emissions. Under these conditions optical energy estimates become unreliable.

5.2 Measurements away from the magnetic zenith

The discussion in the previous section tacitly assumes that height integrated emission intensity ratios can be measured. This is possible in the direction of the magnetic zenith.
In other directions, the observed ratios cannot be directly related to energy in the simple way described. EATHER et al. (1976) and MENDE et al. (1984) have described a technique applicable to isolated auroral forms observed away from the zenith. The temperature and composition ratio methods may likewise be applicable to uniform extended layers of emission. Over a limited range of latitude, it is possible to derive height distributions by tomographic methods which can produce two-dimensional plots of volume emission rates from observations with two or three separate scanning photometers or cameras. Such methods may indeed provide an extremely valuable optical technique, applicable in support of other ground-based facilities. Multi-station techniques may of course be used to determine the energies of incident particles from the height distribution of one spectral component. This method has been applied recently by KAILA (1989) and KAILA and RASINKANGAS (1989).

5.3 Scattering effects

An additional limitation arises from the situation depicted in Fig. 18 where observations are made of ratios from a form, A, in the magnetic zenith with a brighter form, B, outside the field of view. It is clear that light from the bright form, B, can be scattered into the field of the zenith photometer and can lead to false ratio values for the latter, in two ways. First, the emission being scattered may have a different ratio from that from the weaker feature, A, in the zenith. (Figure 18 was prepared using the two lower energy height profiles of Fig. 5.) Secondly, the scattering itself may be stronger for the shorter wavelength component of the pair of emissions. The first effect would occur
Fig. 16. Similar to Fig. 6 except that the abscissa quantity plotted is the atmospheric neutral temperature for the four different geophysical conditions.

even for closely spaced pairs of emission features or for scattering from cloud which may be wavelength independent, while the second would occur for Rayleigh or aerosol scattering.

A useful diagnostic tool for such scattering effects has been suggested by one of us (R.L.G.). The ratio of a pair of emissions of the N\textsubscript{2} First Positive system in the red and a Second Positive Band in the ultraviolet is monitored. Observations and models provide support for the view that such a ratio should remain constant (except possibly for very low altitude aurora). However, if the observed light has been scattered as depicted in Fig. 18, the short wavelength member of the pair is enhanced. In the presence of such abnormal 2PG/1PG ratios, the results for the energy estimate may simply be discarded although in some cases an empirical correction is possible. The value of this procedure is illustrated in Fig. 19 which is similar to Fig. 15 except that all the observed ratios have been included. The elimination of the points, shown by the 2P/1P ratio to be suspect, is obviously critical in obtaining useable results.

5.4 Remote sensing by satellite from above

Optical estimates of particle energy from satellite instruments suffer from some of the problems discussed above, in particular those associated with ion fluxes, oblique viewing and scattering. The last factor enters in two ways. First, for resonantly scattered
features, radiation may be scattered away from the original source somewhat as described above. Secondly, in the region where the atmosphere is transparent, scatter from the ground complicates the analysis.

5.5 Instrumental effects

The energy sensitive ratios and measurements, discussed in Section 4, are subject to the accuracy with which the ratios can be measured. For strong emission pairs, in the visible region, such as 6300 Å OI and 4278 Å N₂, the intensity ratio can be measured with good accuracy except in the high energy range where as noted above the 6300 Å emission becomes very weak. This is because the measured signals are strong even in weaker aurora and reliable measurements can be made of the background to be subtracted. The 8446 Å OI can also be measured well (although with more difficulty) if a GaAs photomultiplier is used. Somewhat more difficult are measurements in the near UV of the VK and 2P N₂ bands because of the greater difficulty of obtaining ideal filters to separate the desired features and to subtract the background. The measurements of ratios of the O₂ and N₂ 1N bands also present instrumental problems. The results shown in Fig. 10 were obtained with a scanning spectrometer capable of measuring and partially separating the blended N₂ and O₂ bands in bright and medium intensity aurora. It may be that a specialized multichannel filter photometer will succeed with these emissions or alternatively a dedicated spectrograph with a linear or area detector. The application of the temperature method is likewise possible but subject to some signal strength
Fig. 18. Schematic diagram showing the mechanism by which false ratios may be measured when emission from a brighter, more energetic form is scattered in the lower atmosphere into the direct path from a weaker less energetic form. Form A has the height distribution of the $E_0=0.38$ keV curve of Fig. 5 while Form B corresponds to $E_0=1.9$ keV.

limitations with conventional filter photometer techniques. For these reasons, the most widely used technique has been the simple $6300\ \AA/N_2$ ratio while the other methods have until now been restricted to special studies designed to evaluate the technique rather than for routine use.

6. Energy Flux and Auroral Emission

The overall brightness of aurora is related to the flux of particle energy deposited in the atmosphere from the magnetosphere. The theoretical models make exact predictions of the absolute intensity of different auroral emission features for a given particle flux. The best explored relation and one of the most convenient for observation is that for the intensity of the various $N_2$ bands. The relation will clearly be somewhat dependent on atmospheric conditions (composition profile) and on the average particle energy because of the variation of $[O]/[N_2]$ with height. Theoretical values arise from the models and observational studies have been carried out by KASTING and HAYS (1977) and MCEWEN and VENKATARANGAN (1978). Values of about $200R/(\text{erg}\cdot\text{cm}^{-2}\cdot\text{s}^{-1})$ are typical for $N_2^+$.
Fig. 19. Similar to Fig. 15 except that all data points observed have been included. It may be concluded that the higher values of the ratio which appear in the low energy region result from scattering into the beam as illustrated in Fig. 18.

4278 Å in normal electron excited aurora. This provides an important tool for estimating total particle energy input. If the methods discussed above can be used to estimate the average particle energy, a more exact estimate of the energy flux is possible.

7. Conclusions

1) Optical spectral ratio and intensity techniques provide a relatively inexpensive method of monitoring input energy flux and average particle energy in electron aurora. When networks of suitable photometers are used such as in the Canadian CANOPUS system (VALLANCE JONES, 1986), valuable information for magnetospheric studies can be obtained in real time.

2) For accurate absolute measurements of primary electron energy, double ratio methods are necessary to correct for the effects of changing atmospheric composition or alternatively composition changes must be reliably modelled. Accurate measurements are difficult in the presence of significant proton fluxes although the presence of such fluxes can be monitored optically. Significant ion fluxes would also constitute a problem although these are probably uncommon in most conditions at auroral latitudes.

3) For accurate absolute measurements it is also necessary to avoid conditions where scattering could give spurious spectral ratios. Such conditions can usually be recognized when meridian scan records are available or better still all-sky images. A technique involving simultaneous measurements of N₂ 1P and 2P bands appears to be useful in discarding contaminated data.

4) For low intensity levels, optical ratios may be affected by nightglow contamina-
tion and consequently care in subtracting background radiation is necessary. Steps must be taken to exclude data contaminated by moonlight or affected by cloud conditions.

5) Accurate calibration of the sensitivity and instrumental profiles of optical instruments is necessary.

6) Optical methods based on the measurement of rotational temperatures of bands and the Doppler profiles of forbidden atomic lines also provide a means to estimate primary electron energies. These are less sensitive to atmospheric composition but do require measurement or modelling of the exospheric temperature.

7) Observations from multi-channel satellite imagers can provide wide coverage over the auroral oval and should in the future become an important application of optical techniques in magnetospheric studies. Already work has been published (Rees et al., 1988) in which input energy fluxes and particle energies have been estimated from satellite images and applied to the global mapping of ionospheric conductances to provide better modelling of magnetospheric electric fields and field aligned currents.

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