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OGO-4 OBSERVATIONS OF THE ULTRAVIOLET AURORAL SPECTRUM

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Abstract—Auroral ultraviolet spectra in the range 1200–3200 A have been obtained by the spectrometer onboard the OGO-4 satellite. Emissions of N_2, H, O and N are readily identified. Atomic and molecular intensities are deduced from the comparison with a synthetic spectrum and compare reasonably well with some previous measurements and calculations. A feature at 2150 A is assigned to the (1-0) NO γ band. Taking into consideration the various excitation mechanisms of $NO(A^2\Sigma)$ we propose that the energy transfer from N_2 metastable molecules to oxygen accounts for the excitation of the NO γ bands. In particular, we suggest that the resonant reaction between O_2 and highly metastable $N_2(W^3\Delta)$ molecules may be a major source of $NO(A^2\Sigma)$.

INTRODUCTION

From the polar orbit of OGO-4 the ultraviolet spectrometer experiment made a large number of observations of nighttime auroral spectra. During the period 26 October–2 November 1968, the OGO-4 satellite made observations of the high latitude aurora and airglow. The downward viewing ultraviolet spectrometer repeatedly scanned the spectral region 1100–3400 A at a resolution of 20 A with a scan period of 37 seconds (Barth and Mackey, 1967). This period of time corresponds to a satellite displacement of approximately 2.5° of latitude. The field of view of the instrument is $16.8° \times 11.9°$, intercepting an area of 120×85 km at 100 km for a satellite altitude of 500 km. Consequently, different regions of the sky are observed between the beginning and the end of the scans. The spectral range is covered by two channels with different spectral responses. The short wavelength channel (G) uses an EMR 541-08 photomultiplier sensitive to radiation between 1100 and 2000 A. The long wavelength channel (F) is equipped with an EMR 541F-05 photomultiplier responding to wavelengths between 1700 and 3400 A. The second order of the G channel is also observed.

RESULTS

About 20 night-time auroral spectra selected among the data recorded during the storm period were summed to improve the signal-to-noise ratio and to compensate for the satellite motion. Only scans showing a measureable signal in the F channel were included in the sum. The sharp noise spikes often present on the top of bright features were removed during the data processing. The F and G channel average spectra were connected near 1900 A where sensitivity is nearly equal in both channels. The average spectrum obtained using the G channel data between 1200 and 1800 A is displayed in Fig. 1(a). The brightest features are readily identified as Lyman α (1216 A), O I λ1304 and 1356 A, N_2 Lyman–Birge–Hopfield (LBH) bands, N I λ1493 and 1743 A. Figure 2(a) shows the 1400–3200 A spectral region on a larger intensity scale. Several emission features between 2100 and 2500 A coincide with the position of nitric oxide gamma bands. This assignment will be discussed in detail in the next section. At longer wavelengths, the N_2 Vegard–Kaplan (VK), second positive (2P) bands, and the [O I] λ2972 A line are also observed. A synthetic spectrum at the instrumental resolution ($\simeq$20 A) is plotted in Figs. 1(b) and 2(b). It includes the N_2 LBH, VK and 2P systems, the NO γ bands, and the atomic lines at 1200, 1216, 1304, 1356, 1493, 1743 and 2972 A. The overall brightness of a given molecular system is normalized to the observed intensity, whereas the relative intensity of the individual bands is given by:

$$I_{v'v''} = N_{v'} A_{v'v''} \simeq q_{v',0} \frac{A_{v'v''}}{\sum_{v''} A_{v'v''}},$$

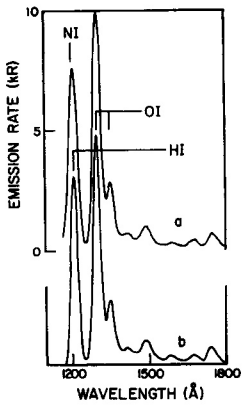

FIG. 1. (a) AURORAL ULTRAVIOLET SPECTRUM RECORDED BY THE OGO-4 SPECTROMETER IN THE 1100–1800 A REGION. (b) SYNTHETIC SPECTRUM AT THE INSTRUMENT RESOLUTION (20 A).

where $N_{v'}$ is the population of the v' level when excited by electron impact, $q_{v',0}$ and $A_{v'v''}$ are the Franck–Condon factors and Einstein coefficients, respectively. These relative intensities were taken from Barth (1965) for the N_2 a $^1\Pi$ and C $^3\Pi$ states. The $N_2(A \rightarrow X)$ band intensities were calculated using the effective excitation cross sections of Borst and Chang (1973), and Shemansky's (1969) transition probabilities. A relatively good match is obtained by this method and allows the atomic lines' intensity to be obtained by simple subtraction. Table 1 lists the observed features and their emission rates. The brightness of this average spectrum can be compared to a visible emission reference. This can be done in several ways. The 2P(1–0) band represents 16% of the total system intensity; consequently, the overall 2P emission rate is about 3.5 kR. The OI λ2972 A represents $\frac{1}{20}$ of the λ5577 intensity, thus corresponding to an emission rate of 4 kR for the green line. Finally, the electron excitation cross section of NI(^{2}P) has a shape similar to the N_2^+(IN) system. Using the cross section for λ3914 A of Borst and Zipf (1970) and Ajello's (1970) NI(^{2}P) cross section, a λ3914 A emission rate of 4.4 kR is deduced. Consequently, the intensity of this average aurora is on the order of 5 kR at 5577 or 3914 A, and the auroral brightness coefficient ranges between I and II. For comparison, the intensities measured previously with ultraviolet spectrometers on rockets or satellites are listed in Column 4. They have been normalized to an intensity of 5 kR for the (0–0) first negative band of N_2^+ at 3914 A. The scatter between the various experimental results is attributed to variations of the spectrum of precipitated electrons, different corrections for the absorption by O_2, inaccurate measurement of the total intensity of molecular systems and calibration errors. Previous estimates of the OI 1304 and 1356 A intensities tend to give relatively smaller values than the OGO-4 derivations. The 1304/1356 intensity ratio measured here is also lower than most other experimental results. These differences are probably due to different viewing geometries. A wider field of view allows the optically thick 1304 A radiation to be almost entirely detected, whereas a small field will only detect a fraction of the total λ1304 A radiation. The NI λ1493/λ1743 ratio of nearly 2 observed in the OGO spectrum compares favorably with the theoretical branching ratio of 2.25 (Wiese *et al.*, 1966). The last column of Table 1 gives intensities calculated for different electron precipitation spectra. Unless otherwise mentioned, they are taken from Vallance-Jones (1974). The intensities are normalized to I(3914 A) = 5 kR. The agreement may be considered as satisfactory, since the OGO-4 spectrum is an average of different auroras with different intensities and characteristic electron energies. Uncertainties in the magnitude of the cross sections, deactivation rates, and electron spectrum must also be taken into account. The only emission features not satisfactorily predicted by the theory are the NO γ bands. Possible excitation mechanisms are discussed in the next section.

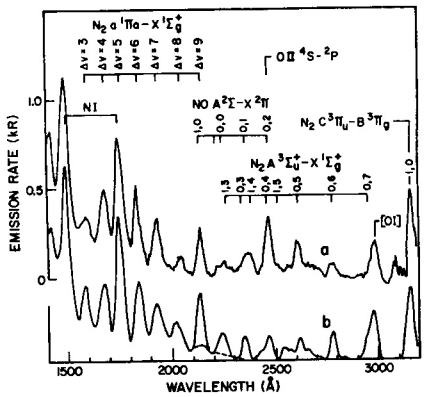

FIG. 2. (a) AURORAL ULTRAVIOLET SPECTRUM RECORDED BY THE OGO-4 SPECTROMETER IN THE 1400–3200 A REGION. (b) SYNTHETIC SPECTRUM AT THE INSTRUMENT RESOLUTION (20 A).

The dotted line shows the contribution of the N_2 LBH bands above 2100 A.

NO γ EMISSION AND EXCITATION

The presence of a 300 R emission near 2150 A, possibly due to the NO γ (1–0) band, is clearly seen

TABLE 1. INTENSITIES OF THE ULTRAVIOLET AURORAL SPECTRUM FOR I(3914 A) = 5 kR

Transition	λ(A)	Emission rate (kR)		
		Present observations	Previous observations	Theory
O I 2^3P–3^3S^0	1304	10.0	3[d], 3.5[b], 6[a], 10[e], 12[c]	5[k]
O I 2^3P–3^5S^0	1356	2.3	0.4[a], 0.7[b], 1.3[c]	0.8[k]
O I ^3P–^1S	2972	0.2	0.2[f]	0.1–0.3
N I 2^4S–3^4P	1200	2.3	0.3[a,d], 0.8[b]	
N I 2^2D–3^2P	1493	0.7	0.4[b], 0.7[c]	
	1793	0.35	0.2[b,f], 0.3[c,f]	
N_2 LBH	1200–2200	14.0	4[a], 8[b], 11[c], 13[e], 19[g]	10–13[b]
N_2 2P	3000–4200	3.5	5.5[h]	6
N_2 VK ($v'=0$)	2000–3600	~2.0	2.2[i], 2.7[b], 3.5[j]	4.6
NO γ	2150	0.3	0.6[b]	

a. Miller *et al.* (1968)
b. Sharp and Rees (1972)
c. Theobald and Peek (1969)
d. Peek (1970)
e. Opal *et al.* (1970)
f. based on ratio of transition probabilities
g. Vreux (1971)
h. Vallance-Jones (1974)
i. Vallance-Jones and Gattinger (1976)
j. Sharp (1971)
k. Strickland and Rees (1974)

on the spectrum of Fig. 2(a). The $\Delta v = 9$ sequence of the N_2 LBH bands, the only other emission identified in this spectral vicinity, is much weaker than the observed emission rate. The intensity of the underlying LBH bands near 2150 A is indicated in the synthetic spectrum by a dotted line. There are also possibly contributions from the NO γ bands near 2260 A (0–0), 2380 A (0–1) and 2470 A (0–2). However, the weak signal-to-noise ratio and the residual temporal fluctuation makes it impossible to determine the relative contribution from the NO γ and N_2 VK systems. Spectra with a 5 A resolution recently obtained from a rocket by Feldman (1976) also show the 2150 A feature. They indicate that the emissions between 2200 and 2500 A can be assigned to the $v'=0$ and 1 progressions of the nitric oxide system. Remarkably, no band from the $v'=2$ level is observed in our, or in Feldman's, spectrum. Earlier, there have been reports of observations of the (1, 0) gamma band at 2150 A in aurorae from rockets (Duysinx and Monfils, 1972) and from the OGO-4 ultraviolet spectrometer (Sharp and Rees, 1972). In summary, an emission feature tentatively attributed to the (1–0) NO γ band is observed in the ultraviolet auroral spectrum. All the available evidence suggests that no contribution from the $v'=2$ and possibly only a weak contribution from $v'=0$ vibrational levels are present.

So far, two mechanisms have been proposed to explain the presence of the NO gamma bands in the aurora; namely electron impact excitation of nitric oxide:

$$NO + e \rightarrow NO(A^2\Sigma) + e, \qquad (1)$$

and the reaction of metastable $N_2(A^3\Sigma_u^+)$ with NO (Sharp and Rees, 1972):

$$NO + N_2(A^3\Sigma) \rightarrow NO(A^2\Sigma) + N_2(X^1\Sigma). \qquad (2)$$

The electron impact cross section of nitric oxide for the excitation of the gamma bands is very small (Imami and Borst, 1975), while the cross section for the $N_2(A^3\Sigma_u^+)$–NO reaction is large (Young and St. John, 1968). However, the amount of nitric oxide necessary to produce the observed gamma band emission from the $N_2(A^3\Sigma_u^+)$ reactions would require that the auroral atmosphere be composed of more than 1% nitric oxide (Sharp and Rees, 1972). Observations of the amount of nitric oxide is on the order of 10^{-4} of the atmospheric density (Rusch and Barth, 1975). In particular, OGO-4 twilight observations were made during the same period, 26 October–5 November 1968, in order to determine the amount of nitric oxide in the auroral oval. These observations showed that during the period of high auroral activity, the nitric oxide density increased only by a factor 8 over the mid-latitude densities (Gerard and Barth, to be published) and not the factor of 100 that is necessary for the $N_2(A^3\Sigma_u^+)$ reaction to account for the observations. The observed vibrational distribution is also incompatible with excitation by direct electron impact on NO which would give a (2–0) band intensity slightly higher than the (1–0) band. Laboratory spectra of the NO γ bands excited by Reaction (2) show vibrational population ratios $N_0:N_1:N_2$ of 1:0.25:0.05, also drastically different from the auroral spectrum.

We suggest an alternative excitation mechanism, namely, the energy transfer from metastable N_2 molecules to atomic or molecular oxygen to produce excited NO:

$$N_2(a'^1\Sigma, w^1\Delta_u, W^3\Delta) + O \rightarrow NO(A^2\Sigma) + N \quad (3)$$

or

$$N_2(a'^1\Sigma, w^1\Delta_u, W^3\Delta, A^3\Sigma) + O_2 \rightarrow NO(A^2\Sigma) + NO. \quad (4)$$

The excitation energy required to produce $NO(A^2\Sigma)$ in the $v = 1$ level is 9.02 eV for Reaction (3) and 7.63 eV for Reaction (4). Since Reaction (4) requires the breaking of two chemical bonds, the reaction of N_2 metastable with atomic oxygen is probably faster. Table 2 lists the N_2 vibrational quanta required to make excitation of the $NO(A^2\Sigma)$, $v = 1$ level by the energy transfer reactions possible. The density of these N_2 metastables in the aurora is not known. They are populated by direct excitation by secondary electrons and by cascading from higher levels. The radiative lifetimes are 13×10^{-3} sec (Tilford and Benesch 1976), 17 sec (Covey *et al.*, 1973), and 2 sec (Shemansky, 1969), respectively, for the $a'^1\Sigma$, $W^3\Delta$ and $A^3\Sigma$ vibrational ground levels. A lifetime of 5×10^{-4} sec can be deduced for the $w^1\Delta$ state from the f value measured by Ching *et al.* (1967). However, a recent analysis by Tilford and Benesch (1976) indicates that the $w^1\Delta$ lifetime is much longer than this value. The lifetime of N_2 molecules in the $W^3\Delta$ state against the $W \rightarrow B$ transition depends critically on the vibrational quantum: it decreases from 16.7 sec for $v = 0$ to 2×10^{-3} sec for $v = 1$ (Covey *et al.*, 1973). Consequently, the reaction between $N_2(W^3\Delta)$ and O_2 molecules may be an efficient source of $NO(^2\Sigma)$. Furthermore, the reaction of $N_2(W^3\Delta, v = 0)$ with $O_2(X^3\Sigma, v = 0)$ is resonant for an ambient temperature of about 400 K, which prevails at altitudes of 120 km. Consequently, the enhanced rate of this reaction combined with the long radiative lifetime of the $N_2(W^3\Delta, v = 0)$ level argue in favor of this process as a candidate for the excitation of the NO γ bands.

TABLE 2. VIBRATION QUANTA REQUIRED TO EXCITE THE NO γ BANDS BY ENERGY TRANSFER REACTIONS

Reaction	$N_2(w^1\Delta)$ (v)	$N_2(a'^1\Sigma)$ (v)	$N_2(W^3\Delta)$ (v)	$N_2(A^3\Sigma)$ (v)
$N_2^* + O$	0	4	10	20
$N_2^* + O_2$	0	0	0	9

The principal unknowns to calculate the NO γ intensity expected from Reactions (3) and (4) are: (1) the effective cross section for excitation of the singlet and triplet states including contributions from cascading; (2) the rate of all of the processes that deactivate these states; and (3) the reaction rate of N_2^* with atomic and molecular oxygen to prouduce nitric oxide in the $A^2\Sigma^+$ state.

CONCLUSION

Auroral spectra taken by the ultraviolet spectrometer have been added to provide a 20 A resolution spectrum between 1100 and 3200 A. The observed spectrum can be satisfactorily matched by a synthetic spectrum including emissions from O, N, O^+, N_2 and NO. Comparison of the intensities with other previous measurements indicates some discrepancies, but theoretical calculations predict correctly most of the emission rates. The only outstanding problem is the identification and excitation mechanisms of a feature near 2150 A previously observed. If it is assigned to the NO γ (1–0) band, a possible source of $NO(A^2\Sigma)$ excitation is the reaction between N_2 metastable singlets or triplets and atomic or molecular oxygen.

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