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SHORT PAPER

Secondary electron excitation in the aurora

J. C. GÉRARD
Institut d'Astrophysique, Université de Liège, 4200-Cointe-Ougrée-Belgique

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Abstract—A calculation of emission rates of a few important auroral features is made, based on recent cross-section data and measured secondary electron spectra. A comparison of values obtained with observations shows a satisfactory agreement for most emissions. However it appears that direct impact of secondary electrons on oxygen atoms (^3P–^1S transition) contributes to about 10 per cent of the green line intensity. The same percentage is reached for secondary ionization of N_2 ($X^1\Sigma_g$–$B^2\Sigma_u^+$ transition) giving rise to the First Negative bands.

INTRODUCTION

THE ROLE played by secondary electrons ejected after ionization of the target (N_2, O_2 or O) by primary auroral electrons is dominant in the excitation of forbidden low energy transitions.

FELDMAN *et al.* (1971) recorded secondary spectra between 95 and 155 km in the energy range 5–50 eV. These showed little variation in the shape as altitude varied.

These observations are in good agreement with theoretical calculations (REES *et al.*, 1969) except for the presence of a dip in the calculated spectrum between 10 and 20 eV corresponding to the excitation of N_2 Second Positive System.

REES *et al.* used their calculated spectrum to deduce the intensity of the 5577 Å oxygen line due to electron impact on ground-state atomic oxygen. The values obtained were largely below experimental determinations. PARKINSON *et al.* (1970) reached the same conclusion but their analysis was based on a preliminary estimation of the experimental flux, radically different in number and shape from the final spectrum of Feldman *et al.* It is thus of interest to re-examine this conclusion and to compare emission rates for various transitions and to examine whether they are compatible with secondary excitation hypothesis.

CALCULATIONS

The secondary electron flux measured by Feldman *et al.* can be written as a good approximation as a power-law distribution:

$$F_S(E) = kE^{-\alpha}$$

where $F_S(E)$ is the differential secondary flux (cm^{-2} sec^{-1} ster^{-1} eV^{-1}), k the normalisation factor dependent on primary flux and altitude and α a spectral index whose average value is 3·17. The production rate per particle of an excited state through electron impact is:

$$\eta = 4\pi \int_S^\infty F_S(E) \,.\, \sigma(E) \,.\, \mathrm{d}E$$

assuming isotropy in the secondary flux; S denoting the excitation threshold, $\sigma(E)$ the differential cross-section for electron impact. The cross-sections used here are chosen among recent determinations. OI(^{3}P–^{1}S) and (^{3}P–^{1}D) values were calculated by HENRY *et al.* (1969) and ((2p^4)^{3}P–(2p^3)3s ^{5}S) by STEWART (1965).

As to N_2 they were measured in laboratory by BRINKMANN and TRAJMAR (1970) ($A_u{}^{3+}$ state) and STANTON and ST. JOHN (1969) ($B^3\pi_g$, $C^3\pi_u$ and $B^2 \sum\limits_u^+$ states). Data relative to $B^3\pi_g$ and $C^3\pi_u$ are apparent values, including cascading effects from upper levels if they occur.

DISCUSSION

Two basic experimental results may be cited to facilitate comparison of intensities discussed hereunder: the (O–O) band at 3914 Å represents 60 per cent of the 1. Neg. emission rate (CHAMBERLAIN, 1961). The ratios $\dfrac{\mathrm{I}(5577)}{\mathrm{I}(3914)}$ as well as $\dfrac{\eta(5577)}{\eta(3914)}$ vary between 1 and 2 according to the various measurements made (EATHER, 1969; PARKINSON *et al.*, 1970; DUYSINX, 1971; VREUX, 1971a).

N_2 *First positive system*

The overall intensity of the 1 Pos. system is estimated as being of the order of that of the oxygen green line by BROADFOOT and HUNTEN (1964). BENESCH *et al.* (1967) analysing photographic spectra of IBC III aurora give a unit for I(1. Pos)/I(3914). HARRISON (1969) has measured in several auroras the intensity of the infrared (O–O) band, from which can be deduced:

$$R_1 = \frac{\mathrm{I(1\ Pos)}}{\mathrm{I(1\ Neg)}} \simeq 4{\cdot}5.$$

The only local measurement allowing direct comparison of emission rates was performed by means of rocket by PARKINSON and ZIPF (1970). They recorded with photometers the (5–2) 1 Pos. and (O–O) 1 Neg. emission profile. Their observations lead to $R_1 \simeq 4$. This value will be adopted for the following discussion.

Second positive system

HUNTEN and BROADFOOT (1965) give $R_2 = \dfrac{\mathrm{I(1\ Pos)}}{\mathrm{I(2\ Pos)}} = 6$. HARANG and GÉRARD (1971) have determined $\dfrac{\mathrm{I(2\text{–}6,\ 2\ Pos)}}{\mathrm{I(0\text{–}1,\ 1\ Neg)}} = 0{\cdot}02$ which gives I(2 Pos) $\simeq$ 0·9 I(3914), in good agreement with the conclusion of BENESCH *et al.* (1967) who mention

I(2 Pos) $\simeq$ I(3914). VREUX (1971b) using a rocket-borne film spectrograph recorded the (O–O) band of both 1. Neg. and 2. Pos. systems. He obtained

$$\frac{\mathrm{I(O\text{–}O,\ 2\ Pos)}}{\mathrm{I(O\text{–}O,\ 1\ Neg)}} = 0{\cdot}30, \text{ thus } \frac{\mathrm{I(2\ Pos)}}{\mathrm{I(1\ Neg)}} = 0{\cdot}7.$$

These results would mean $R_2 \simeq 6$.

Vegard–Kaplan System

Analysis of Franck–Condon factors for transition $X\,^1\Sigma_g^+ - A\,^3\Sigma_u^+$ shows that electron impact on nitrogen molecules populates mainly $v > 4$ vibration levels. These contribute negligibly to the system intensity. The state $A\,^3\Sigma_u^+$ is thus mainly populated by cascading through 1. Positive system. AMHED (1966) has calculated that among cascades from 1. Pos, the proportion of transitions to $v = 0$ and 1 levels of $A\,^3\Sigma_u^+$ is nearly 40 per cent. SHARP (1971) has shown that at high altitude (negligible deactivation):

$$\frac{\eta(\mathrm{0\text{–}0,\ 2\ Pos})}{\eta(v = 0,\ \mathrm{V\text{–}K})} = 0{\cdot}135$$

$$\frac{\eta(\mathrm{O\text{–}O,\ 2\ Pos})}{\eta(v' = 1,\ \mathrm{V\text{–}K})} = 0{\cdot}175, \text{ which gives an experimental ratio:}$$

$$R_3 = \frac{\eta(\mathrm{2\ Pos})}{\eta(\mathrm{V\text{–}K},\ v = 0, 1)} \simeq 0{\cdot}3.$$

1356 Å *oxygen line*

Its production rate has been measured with a rocket-borne spectrometer (STRICKLAND and DONAHUE, 1970). The emission rate per particle, compared to 3914 Å shows strong variations between 120 and 140 km, with a sharp maximum around 140 km. At these altitudes:

$$R_4 = \frac{\eta(1356)}{\eta(3914)} \text{ varies between } 0{\cdot}2 \text{ and less than } 0{\cdot}02.$$

6300 *oxygen line*

Measurements of the red line emission rate are almost inexistent and the measurements existing comprise certain experimental errors. PARKINSON and ZIPF (1971) give for $R_5 = \dfrac{\eta(6300)}{(5577)}$ an upper limit between 24 and 45, depending on the model atmosphere adopted.

N_2^+ *first negative system*

It must be noted that as a consequence of σ(E) shape, 10 per cent of B $^2\Sigma_u^+$ production is due to secondary impact, the remaining being the effect of higher energy primary electrons (FELDMAN *et al.*, 1971). The summary of this discussion is indicated in the following table where theoretical $\eta(5577)$ is chosen as the unit and η(1. Pos) is taken as a comparison element. To allow valuable comparison between O and N_2 emissions a concentration ratio $[N_2]/[0] = 5$, characterizing atmospheric conditions at 120 km has been adopted.

Table 1

Transition	Calculations (using $[N_2]/[0] = 5$)	Observations
N_2 1. Pos	40	40
N_2 2. Pos	10	7
N_2 V–K ($v = 0, 1$)	13 (electron impact) / 16 (40 per cent cascade of 1 Pos)	23
OI 5577 Å	1	10
OI 1356 Å	1·3	3 to less than 0·015
OI 6300 Å	55*	less than 240–450
N_2^+ 1. Neg.	(1·4) / 14 (if primary flux included)	10 (with respect to N_2 systems) 8–16 (with respect to λ5577)

* Mechanisms other than electron impact contribute to populating this level.

CONCLUSIONS

The results given in Table 1 show that, within experimental uncertainties, the agreement is good between 'predicted' and observed values, within the exception of ^{1}D and ^{1}S of oxygen. This tends to validate secondary flux and cross-sections used and clearly shows the existence of a specific problem for OI ^{1}S. The main disagreement comes from an underestimation of $\eta(5577)$ calculated by means of process (1). A reaction, 10-times more efficient, must be involved such as O_2 dissociative excitation whose cross-section is unfortunately unknown. A similar conclusion can be drawn for ^{1}D but it is expected that other processes efficiently populate such a low-energy level (hot thermal electrons, electric field). The present results also suggest the possible role of vibrational energy transfer between N_2 A $^3\sum$ to B $^3\pi$ increasing 1 Pos and V–K emission rate, thus approaching the result of the observations. They also confirm the importance of primaries in excitation of N_2 First Negative bands. An improved accuracy in the measurements of intensities and particularly of emission rates would be required to permit a more detailed discussion of processes involved.

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