Indian J. Phys. **51A**, 151–162 (1977)

The theoretical night-time NI(5200 Å) emission rate in the F-region under equilibrium conditions

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(*Received* 29 *April* 1975, *revised* 31 *May* 1976)

The overall theory of the night-time F-region emission rate of the atomic nitrogen ^2D–^4S line at 5200 Å is re-developed, including some new terms. Calculations using the derived expression show that the integrated 5200 Å vertical volume emission rate over Nairobi (36°49′ E, 1°16′ S) at 2000 UT on 2/4/1973 ($K_p \leqslant 5_0$) was less than 1 R. Volume emission rates calculated at 2000 UT display maximum values within the 260–290 km. altitude range.

1. INTRODUCTION

The presence of the NI(5200 Å) line in the nightglow spectrum was first mentioned by Courtes (1950) and Dufay (1950), and was further ascertained experimentally within a decade afterwards (Kvassovskii 1958; Dufay 1959; Blackwell *et al* 1960). A lot more other measurements of the night-time emission rate of this line have been reported e.g., Weill *et al* 1968; Weill & Christophe-Glaume 1969); Hernandez & Turtle 1969; etc.). Other workers (Bates 1952; Seaton 1953; Peterson *et al* 1966; etc.) have contributed pieces of theoretical work which have formed a concrete base upon which the theory governing the night sky emission rate of this atomic nitrogen line has been built. Formulative expressions for the NI(5200 Å) emission rates (night-time or otherwise) are always susceptible to expansions and/or modifications in the face of new findings that bear correlation with the density of atmospheric $N(^2D)$. We have incorporated new terms in the formulation developed in this analysis. In particular, we have put emphasis on both the population of the $N(^2D)$ species through cascading from atomic nitrogen energy levels higher than the doublet ^2D levels, and the depopulation of the $N(^2D)$ species through some chemical reactions. Consideration of these processes is essential for very accurate work. A side objective of this paper is to compare samples of night-time theoretical integrated emission rate and (photometric) experimental emission rates of NI(5200 Å) in the tropical atmosphere with the corresponding estimates reported in the current literature.

2. THE INTEGRATED EMISSION RATE OF NI(5200 Å)

The Emission of the 5199·9 Å–5202·3 Å *Line*

The level structure and multiplets of the ground configuration of NI are illustrated in Figure 1. The energy and designation for each level are indicated in the same figure together with the wavelength of each of the possible transitions. The Einstein transition coefficients (given in units of $\sec^{-1}$) are written in parentheses, while the term lifetimes are shown just above or below each level or group

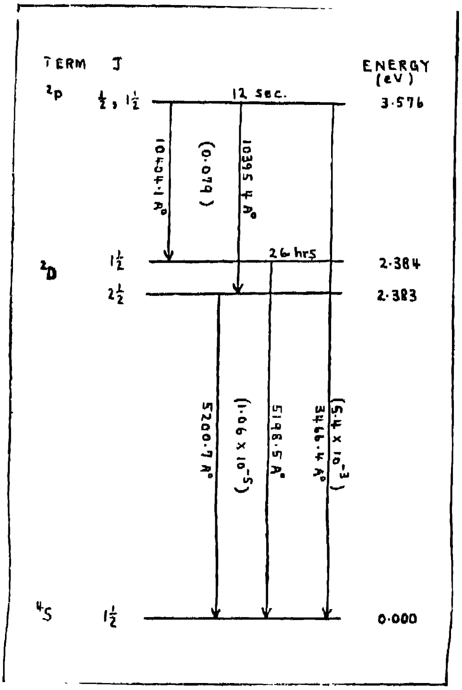

Fig. 1

of levels. The energy and J values for each level are also shown. All these values have been obtained from Chamberlain with an exception of the energy values which have themselves been obtained from Hernandez & Turtle. It is worthwhile noting that although the lifetime of $N(^2D)$ is about 26 hours in the laboratory, its value decreases considerably in the ionosphere e.g., about 15 min. at 175 km, 200 km and 300 km; about 17 to 25 min. during the night; and within the range from 2 to 15 minutes. If we denote the Einstein coefficient for the NI(^2D–^4S) transitinon by A_D and the population density of $N(^2D)$ by $[N(^2D)]$, then the emission rate ϵ_D (emissions cm^{-3} $\sec^{-1}$) of the 5200 Å line is written ais :

$$\epsilon_D = A_D[N(^2D)] \tag{1}$$

Expressions for $\epsilon_D(h)$, where h denotes height above ground level can be obtained through appropriate solution of the continuity equation :

$$\frac{\partial[N(^2D)]}{\partial t} = P_D(h) - L_D(h) - \operatorname{div}([N(^2D)]v_D) \tag{2}$$

where $P_d(h)$ is the rate of production of atoms in state (^2D), $L_D(h)$ is the loss rate of atoms in state (^2D), and v_D is the velocity of the $N(^2D)$ atoms. The integrated emission rate in the vertical direction Q (raleighs) can be written in the form

$$Q\,(\text{raleighs}) = 10^{-6} \int_0^\infty \epsilon_0(h)dh$$

$$= 10^{-6} A_D \int_0^\infty [N(^2D)]dh. \qquad (3)$$

Loss of $N(^2D)$

The ^2D levels of N are depopulated by radiative transitions and also by deactivating collisions. The prominent quenching agents have been identified as $O_2(X^3\Sigma_g^-)$, electrons and $O(^3P)$ (Wallace & McElroy, 1966; Henry & Williams, 1968; etc.). The respective quenching reactions are :

$$N(^2D)+O_2(X^3\Sigma_g^-) \rightarrow N(^4S)+O_2(^1\Delta_g \text{ or } ^1\Sigma_g^+) \qquad (4)$$

$$N(^2D)+e \longrightarrow N(^4S)+e \qquad (5)$$

$$N(^2D)+O(^3P) \longrightarrow N(^4S)+O(^1D) \qquad (6)$$

The corresponding collisional deactivation coefficient, d_D, is

$$d_D = S_1[O_2]+S_2[e]+S_3[O] \qquad (7)$$

where S_1, S_2 and S_3 are the specific reaction rates for reactions (4), (5) and (6), respectively. The ^2D levels of N are also depopulated by the following chemical reactions :

$N(^2D)+O_2 \rightarrow O+NO$ $\qquad k_1 = 6\times 10^{-12}$ cm^{3}sec^{-1}
...Nicolet, 1970.

$N(^2D)+NO \rightarrow N_2+O$ $\qquad k_2 = 1{\cdot}8\times 10^{-10}$ cm^{3}sec^{-1}
...Krasnopol'skiy, 1971.

$N(^2D)+N_2O \rightarrow N_2+NO$ $\qquad k_3 = 4\times 10^{-12}$ cm^{3}sec^{-1}
...Malcolme-Lawes, 1974.

The loss rate L_D is the product of the corresponding coefficients of depopulation and $[N(^2D)]$, i.e.,

$$L_D = (A_D+d_D+k_1[O_2]+k_2[NO]+k_3[N_2O])[N(^2D)] \qquad \ldots (8)$$

The Production of $N(^2D)$

The mechanisms that lead to the excitation of the nitrogen atoms into the ^2D levels during the day and night time have been discussed by a number of authors [e.g., Norton *et al*, 1963; Wallace & McElroy, 1966; Ivanov-Kholodnyy

& *Nikol'skiy*, 1969; and others]. Norton *et al* suggested that one of the sources of $N(^2D)$ at heights above about 90 km is the reaction

$$\mathrm{NO}^+ + e \rightarrow \mathrm{N} + \mathrm{O} + 2{\cdot}76 \text{ eV} \qquad \ldots \quad (9)$$

whose reaction rate is $\alpha_1[\mathrm{NO}^+][e]$, where α_1 is the rate coefficient for the reaction. Energetically, the N and O atoms produced by this reaction can be either the $N(^4S)$ and $\mathrm{O}(^1D)$ terms, or the $N(^2D)$ and $\mathrm{O}(^3P)$ terms. However, since excitation of the O atom into the ^1D level violates conservation of spin [Dalgarno & Walker, 1964], we shall consider the production of $N(^2D)$ and $\mathrm{O}(^3P)$ as being predominant. The formation of $\mathrm{N}(^2D)$ can also be done by oxygen association [Wallace & McElroy, 1966]. Thus the reactions

$$\mathrm{O} + \mathrm{O} + \mathrm{N} \rightarrow \mathrm{O}_2 + \mathrm{N}(^2D) \qquad \ldots \quad (10)$$

and

$$\mathrm{O} + \mathrm{O} + \mathrm{M} \rightarrow \mathrm{O}_2' + \mathrm{M}$$

followed by

$$\mathrm{O}_2' + \mathrm{N} \rightarrow \mathrm{O}_2 + \mathrm{N}(^2D) \qquad \ldots \quad (11)$$

are possible excitation mechanisms. Note that O_2' denotes excited oxygen molecule. However, owing to the low atmospheric concentration of atomic nitrogen, the resultant emission by reactions (10) and (11) would be negligible. Wallace and McElroy consider the ion-atom interchange reaction

$$\mathrm{N}_2^+(X^2\Sigma_g^+) + \mathrm{O}(^3P) \rightarrow \mathrm{NO}^+(^1\Sigma^+) + \mathrm{N}(^2D) + 0{\cdot}71 \text{ eV} \qquad \ldots \quad (12)$$

(with reaction rate $\alpha_2[\mathrm{N}_2^+][\mathrm{O}]$) as one of the mechanisms leading to the formation of $N(^2D)$. It has been agreed [Hernandez & Turtle 1969] that dissociative recombination of NO^+ could be one of the sources of $\mathrm{N}(^2D)$ in the ionosphere although the same authors found the efficiency of the dissociative recombination to be at most 10%. Moreover, according to Wallace & McElroy (1966), agreement with observation has been satisfactory in demonstrating that NO^+ recombination is not a necessary source of $\mathrm{N}(^2D)$. We shall, therefore, take only reactions (9) and (12) into our account. The ^2D level of N is also populated by transitions from the neighbouring higher energy level ^2P ($E = 3{\cdot}5762$ eV) resulting in the emission of 10398 Å and 10407 Å. Let A_{D2} denote the corresponding rate of transition. It is also worthwhile noting that the ^2D level of N can be populated by cascading from higher lying states.

In summary, the production rate, P_D ($\mathrm{cm}^{-3}\mathrm{sec}^{-1}$), is

$$P_D = k_{D1}\alpha_1[\mathrm{NO}^+][e] + k_{D2}\alpha_2[\mathrm{N}_2^+][\mathrm{O}] + A_{D2}[^2P] + \sum_{n,X} Z_n[\mathrm{N}(^nX)] \qquad \ldots \quad (13)$$

where the k's are the numbers of excitations per reaction, and the summation term accounts for cascading from higher lying states. Note that the Z's are the respective transition rates. It would seem that the population rate of $N(^2P)$

is not yet well known (Rees & Jones 1973), although the following expression for $[^2P]$ has been given(:

$$[^2P] = [N_2^+](0{\cdot}0825+0{\cdot}66[e]\alpha_4)$$

where

$$\alpha_4 = 2{\cdot}9\times10^{-7}\left(\frac{300}{T}\right)^{1/3}.$$

Concentration of $N(^2D)$

In arriving at an expression for the $N(^2D)$ concentration, we shall invoke the equilibrium conditions, especially at night-time in the *F*-region. It is known that the ionosphere attains equilibrium (or at least quasi-equilibrium) some hours after sunset e.g. Stubbe (1968) reported that at one height below the maximum, it takes about 5 hours for equilibrium to be attained in the *F*-region. Under equilibrium conditions, therefore, the time-dependent and divergence terms in equation (2) can be neglected. Hence, by combining equations (2), (8) and (13), we get

$$[N(^2D)] = \frac{k_{D_1}\alpha_1[NO^+][e]+k_{D_2}\alpha_2[N_2^+][O]+A_{D_2}[^2P]+\sum\limits_{n,X} Z_n[N(^nX)]}{A_D+d_D+k_1[O_2]+k_2[NO]+k_3[N_2O]} \quad \dots (14)$$

The Concentrations of N_2^+ and NO^+

The concentrations of N_2^+ and NO^+ can be obtained by setting up and solving their continuity equations, if necessary under certain assumptions. The prominent source of N_2^+ in the ionosphere is the reaction

$N_2+h\nu \rightarrow N_2^+ + e$ k_{23} (not yet conclusively known known numerically).

...Danilov 1970.

On the other hand, N_2^+ is lost through the following chemical reactions :

$N_2^+ + e \rightarrow N + N'$ $k_{19} = 3\times10^{-7}(T)^{-3/2}$

...Danilov 1970.

$N_2^+ + O_2 \rightarrow O_2^+ + N_2$ $k_{20} = 10^{-10}cm^3sec^{-1}$

...Danilov 1970

$N_2^+ + O \rightarrow NO^+ + N$ $k_{21} = 2{\cdot}5\times10^{-10}$

...Danilov 1970

$N_2^+ + O \rightarrow N_2 + O^+$ $k_{22} = 3\times10^{-11}$

...Danilov 1970

$N_2^+ + N \rightarrow N_2 + N^+$ k_{24}

...Timothy *et al* 1971.

The continuity equation for N_2^+ can be written as

$$\frac{\partial[N_2^+]}{\partial t} = k_{23}[N_2]-\{k_{19}[e]+k_{20}[O_2]+(k_{21}+k_{22})[O]+k_{24}[N]\}[N_2^+]-\nabla[N_2^+]v \quad \dots (15)$$

The principal sources of NO^+ in the ionosphere are the chemical reactions

$O_2^+ + NO \rightarrow NO^+ + O_2$ $\quad k_{25} = 8\times10^{-10}$
...Nicolet 1965

$N_2^+ + O \rightarrow NO^+ + N$ $\quad k_{26} = 2{\cdot}5\times10^{-10}$
...Forgson *et al* 1965

$O^+ + N_2 \rightarrow NO^+ + N$ $\quad k_{27} = 3\times10^{-12}$
...Fergson *et al* 1965

$N^+ + O_2 \rightarrow NO^+ + O$ $\quad k_{28} = 3\times10^{-10}$
...Danilov 1960.

The major reaction that depopulates NO^+ is

$NO^+ + e \rightarrow N + O$ $\quad k_{29} = 4{\cdot}4\times10^{-7}\left(\frac{300}{T}\right)$

...Krasnopol'skiy 1971.

Hence the continuity equation for NO^+ is

$$\frac{\partial(NO^+]}{\partial t} = -k_{29}[e][NO^+]+k_{27}[O^+][N_2]+k_{26}[N_2^+][O]+k_{25}[O_2^+][NO]$$
$$+k_{28}[N^+]O_2]-\nabla(NO^+]v. \quad \dots (16)$$

Since NO^+ and N_2^+ are two of the main constituents of the lower part of the F-layer [Ruster 1971], the divergence terms in equations (15) and (16) are not very important. Under equilibrium conditions, the time-dependent and divergence terms in equations (15) and (16) can be ignored. Therefore,

$$[N_2^+] = \frac{k_{23}[N_2]}{k_{19}[e]+k_{20}[O_2]+(k_{20}+k_{22})[O[+k_{24}[N]} \quad \dots (17)$$

and

$$[NO^+] = \frac{k_{27}[O^+][N_2]+k_{26}[N_2^+][O]+k_{25}[O_2^+][NO]+k_{28}[N^+][O_2]}{k_{29}[e]} \quad \dots (18)$$

The integrated emission rate of NI(5200 Å)

By combining equations (3), (14) and (17) the following expression for the integrated emission rate, Q_D, are arrived at :

$$Q_D(\text{raleighs}) = 10^{-6}\int_0^\infty \frac{k_{D1}\alpha_1[NO^+][e]+(k_{D2}\alpha_2k_{23}[N_2][O])/B+A_{D2}[^2P]+\sum\limits_{n,X} W_n}{1+(d_D+k_1[O_2]+k_2[NO][+k_3[N_2O])/A_D}dh \quad \dots (19)$$

where

$$W_n = Z_n[\mathrm{N}(^n\mathrm{X})]$$

and

$$B = k_{19}[e]+k_{20}[\mathrm{O}_2]+(k_{21}+k_{22})[\mathrm{O}]+k_{24}[\mathrm{N}].$$

Equation (19) can be written in the equivalent form :

$$Q_D(R) = 10^{-6}\int_{H0}^{H} \frac{k_{D_1}\alpha_1[\mathrm{NO}^+][e]+(k_{D_2}\alpha_2k_{23}[\mathrm{N}_2][\mathrm{O}])/B+A_{D_2}[^2P]+\sum\limits_{n,X} Z_n[\mathrm{N}(^n\mathrm{X})]}{1+(d_D+k_1[\mathrm{O}_2]+k_2[\mathrm{NO}]+k_3[\mathrm{N}_2\mathrm{O}])/A_D}\,dh \qquad \ldots \quad (20)$$

where H_0 and H are the lower and upper altitude limits of the emitting layer, respectively. It has been shown [Peterson *et al* 1966] that the value of the steady state [NO$^+$] at night-time can be expressed in terms of dissociative recombination of molecular ions reactions charge neutrality arguments, and atomic-to-molecular-ion conversion reactions. Thus

$$[\mathrm{NO}^+] = \frac{k_{30}[\mathrm{N}_2]}{\alpha_1(1+(k_{30}\mathrm{N}_2/\alpha_0e)+(k_{31}\mathrm{O}_2/\alpha_3e))} \qquad \ldots \quad (21)$$

where k_{30}, k_{31} and α_3 are the rate coefficients of the following reactions :

$$\mathrm{O}^++\mathrm{N}_2 \rightarrow \mathrm{NO}^++\mathrm{N}+1{\cdot}09\ \mathrm{eV} \qquad k_{30}$$

$$\mathrm{O}^++\mathrm{O}_2 \rightarrow \mathrm{O}_2^++\mathrm{O}\quad 1{\cdot}53\ \mathrm{eV} \qquad k_{31}$$

$$\mathrm{O}_2^++e \rightarrow \mathrm{O}+\mathrm{O}+6{\cdot}96\ \mathrm{eV} \qquad \alpha_3$$

The value of [NO] can be written in the following approximation expression [Mitra 1968] :

$$[\mathrm{NO}] = 0{\cdot}4\exp\left(-\frac{3{\cdot}00}{T}\right)[\mathrm{O}_2]+5\times10^{-7}[\mathrm{O}] \qquad \ldots \quad (22)$$

Hernandez & Turtle [1969] have associated the production of N(^2D) by the reaction (9) with an efficiency factor. Likewise, we associate an efficiency factor ρ with the production of N(^2D) by the reaction (9), so that a combination of equations (20), (21) and (22) gives

$$Q_D(R) = 10^{-6}\int_{H_0}^{H} \frac{(\rho k_{30}k_{D_1}[\mathrm{N}_2][e]/F+(k_{D_2}\alpha_2k_{23}[\mathrm{N}_2][\mathrm{O}])/B+A_{D_2}[^2P]+\sum\limits_{n,X} W_n}{1+(d_D+k_1[\mathrm{O}_2]+k_3[\mathrm{N}_2\mathrm{O}]+k_2(0{\cdot}4\exp\left(\frac{3700}{T}\right)[\mathrm{O}_2]+5\times10^{-7}[\mathrm{O}]))/A_c}\,dk \qquad \ldots \quad (23)$$

where $F = 1+(k_{30}\mathrm{N}_2/\alpha_1e)+(k_{31}\mathrm{O}_2/\alpha_3e)$.

The last equation has been used in computing theoretical values of the volume and integrated emission rates of NI(5200 Å) over Nairobi (36°49′ E, 1°16′ S) during the night of 2/3 April 1973 at 2000 UT, 2100 UT and 2300 UT for both $T_\infty = 1200°K$ and $T_\infty = 1000°K$. The latter has been chosen because the year 1973 was within the sunspot minimum, thus implying that the ionosphere might not have been at its maximum temperature during the time in question. The 2/3 April 1973 night was fairly magnetically quite with K_p values between 3_- and 5_0. Apart from the availability of ionosonde data, Nairobi has been chosen because it is a tropical area. It is no doubt that the theoretical values so obtained have served to give at least a rough picture of the sort of emission rate values to expect, assuming, of course, that the whole basis of the theoretical analysis is valid at the times and place in question. For the computations we have extracted the densities of N_2, O_2 and O as functions of altitude from CIRA 1972, while the electron density values over Nairobi have been deduced from ionosonde data (N. J. Skinner, Private Communication).

We have incorporated the following approximations in our calculations :

$k_{23} \approx 0$ since it is assumed that there is negligible (solar) radiation during the night under equilibrium conditions.

$k_3[N_2O] \approx 0$ since N_2O is not one of the prominent molecular constituents of the ionosphere.

$S_3 \approx 0$ since reaction (6) can at most provide a minor source of $O(^1D)$ in the undisturbed night-time ionosphere, it can be considered as having negligible effect on the density of $N(^2D)$.

$F \approx 1$ since the terms $((k_{30}N_2/\alpha_1(e)+(k_{31}O_2/\alpha_3 e))$ are known to be fairly small in the upper atmosphere at night(7).

$A_{D2}[^2P]+\Sigma Z_n[N(^1X)] \approx 0$ since there is negligible quantity of sunlight at night-time. Note that absorption of sunlight at λ3466Å (^4S–^2P) followed by cascading to ^2D with emission of λ10400 Å is a more important way of populating $N(^2D)$ than direct absorption at n5199 Å.

Moreover, the following numerical values for the constant in equation (23) have been used in the calculations :

Numerical Value	*Source of Numerical Value*
$A_D = 7{\cdot}0 \times 10^{-6}$ sec^{-1}	Chamberlain
$pk_{30} = 2{\cdot}7 \times 10^{-14}$ cm^3 sec^{-}	Hernandez & Turtle
$k_{31} = 10^{-11}$ cm^3 sec^{-1}	,,
$S_1 = 1{\cdot}9 \times 10^{-12}$ cm^3 sec^{-1}	Wallace & McElroy
$S_2 = 8 \times 10^{-10}$ cm^3 sec^{-1}	Seaton
$k_1 = 6 \times 10^{-12}$ cm^3 sec^{-1}	Nicolet
$k_2 = 1{\cdot}8 \times 10^{-10}$ cm^3 sec^{-1}	Krasnopol'skiy
$k_{D1} = 1$	See text.

4. RESULTS AND CONCLUSION

Tables 1, 2 and 3 show the electron densities at 2000 UT, 2100 UT and 2300 UT, respectively. Figure 2 shows the calculated volume emission rates of NI(5200 A) at different altitudes for $T_\infty = 1200^\circ\mathrm{K}$ at 2000 UT, 2100 UT and 2300 UT. Careful numerical calculation of the area bounded by the 2000 UT curve and the horizontal axis (Fig. 2) shows that

$$Q_D(R) \approx 0{\cdot}41\ R. \qquad \ldots \quad (24)$$

Table 1. Electron densities (numbers per cm^3) at 2000 UT

Height (km)	Electron Density
187·5	$0{\cdot}087 \times 10^6$
200	0·100
212·5	0·04
225	0·082
237·5	0·139
250	0·195
262·5	0·260
275	0·340
287·5	0·592
300	0·720
312·5	0·090
325	0·0486
337	0·0337
350	0·0234

Table 2. Electron densities (numbers per cm^3) at 2100 UT

Height (km)	Electron Density
237·5	$0{\cdot}08 \times 10^6$
250	0·195
262·5	0·350
275	0·510
287·5	0·630
300	0·730
312·5	0·850

Table 3. Electron densities (numbers per cm^3) at 2300 UT

Height (km)	Electron Density
250	$0{\cdot}491 \times 10^6$
270	0·010
280	0·280
290	0·525
300	0·705
310	0·630

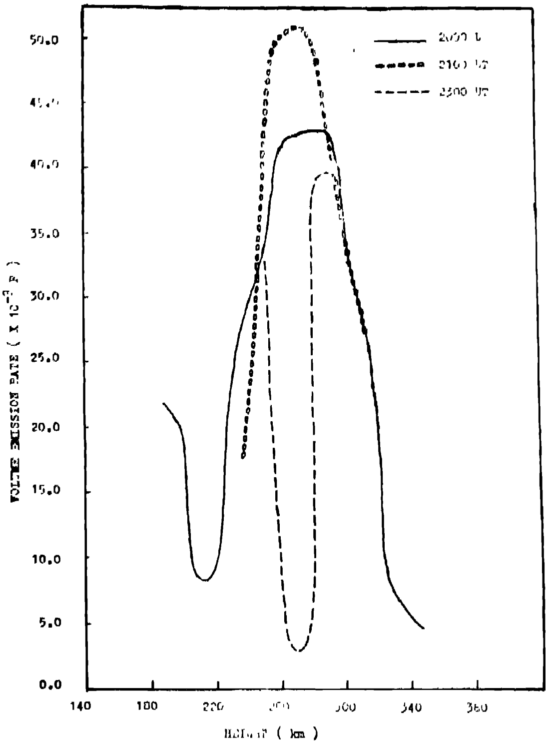

Fig. 2.

Figure 3 shows a plot of the volume emission rates versus altitude for T_∞ = 1000°K at 2000 UT, 2100 UT and 2300 UT. By means of a numerical analysis technique, it is found that at 2000 UT (and for T_∞ = 1000°K)

$$Q_D(R) \approx 0{\cdot}35\ R. \tag{25}$$

It is shown in the literature [e.g. McCormac 1971] that Q_D $(R) \leqslant 1R$ during the night, in consistence with equations (24) and (25). However, it has been confirmed through a series of photometric measurements of the night sky NI(5200 Å) emission rate [Njau *et al* 1976] that the night sky values of $Q_D(R)$ at Dar es Salaam (6°46′ S, 39°14′ E) are at times far greater than 1 R. Experimental measurements made at Dar es Salaam from July to October 1974 have shown [Njau 1975] that night-sky emission rates of NI(5200 Å) varied from a lower limit of about 0 R to an upper limit of about 28 R. The apparent discrepancy between (theoretical) estimates reported in the literature and experimental (photometric) values may probably be accounted for by taking into account factors like OH(9, 2) contamination, possible errors in calculating ionospheric electron densities, and the degree of accuracy with which the constants for the processes that effect the density of N(^2D) in the ionosphere are assigned numerical values.

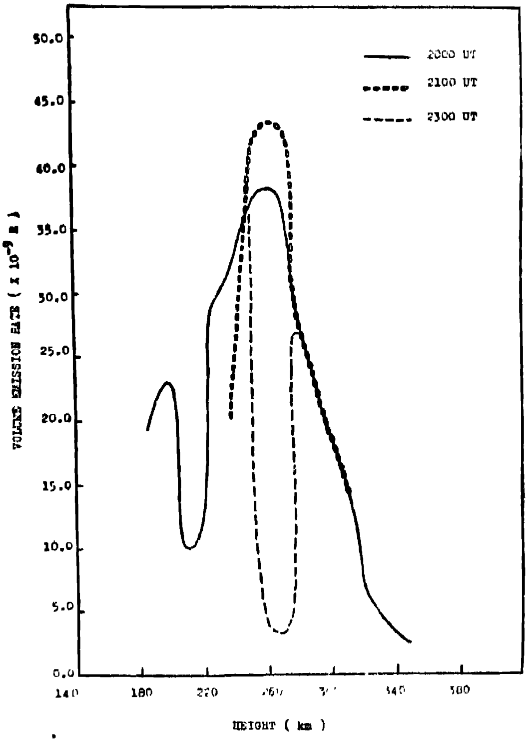

Fig. 3

5. Acknowledgments

The author wishes to thank Prof. E. H. Carman for assisting in checking this work. Thanks are also due to Prof. N. J. Skinner for supplying the electron density data and also to Prof. P. B. Vitta for offering to discuss this paper.

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