

# THEORIES ON ELECTRON PRODUCTION AND RECOMBINATION IN THE D AND E LAYERS

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## 1. IONOSPHERIC PROCESSES

IONIZATION is caused normally in the terrestrial atmosphere by the effect of solar radiations photoionizing various constituents. The most important part is due to solar radiations of  $\lambda < 1026 \text{ \AA}$ , which are able to ionize oxygen and nitrogen. Primary cosmic rays can play a certain role, and other corpuscular radiations may be important but their effects should be introduced only when it is necessary to consider periods of solar disturbances. The radiations of  $\lambda > 1050 \text{ \AA}$  may have an ionization effect when minor constituents are involved.

The removal of electrons depends on various recombination processes and is subject to processes produced by collisions between specific particles (electrons, negative and positive ions, atoms and molecules of different kinds).

The first step is the study of the absorption characteristics of various atmospheric constituents which are dependent on the wavelength, and of the spectral distribution of the solar energy, and it is necessary to consider the numbers of solar photons which are available in those spectral ranges which cause the ionization of the principal atmospheric constituents. It is important to find how oxygen and nitrogen may be ionized. Furthermore, an analysis of the solar spectrum must give some indication of the variations produced by solar activity in the range of X-ray spectrum. But, the number of collision processes involved in the removal of electrons is so large that the recombination coefficient  $\alpha$  needs a special analysis in each case; it is not possible, however, to consider all processes together. For this reason, it is necessary to analyze the physical parameters one after another before trying to find an explanation of the origin of the ionospheric layers. In other words: production of the ionization in the D region at altitudes less than 85 km, formation of the E layer below 130 km, and the origin of the F region above 150 km.

## 2. PRODUCTION OF THE NORMAL IONIZATION

### 2.1. *Atmospheric Absorptions*

Since the diurnal variation of the ionization and its variation during solar eclipses show that the electron production is due to electromagnetic radiation,

the first step is the determination of the penetration of various radiations into the different ionospheric regions.

When the atmospheric density and the values of the absorption cross-sections are compared, a clear picture can be given for the three ionospheric regions:

(i) *D region*, where the atomic cross-section is less than  $10^{-19}$  cm<sup>2</sup>. Solar radiations of wavelengths less than 10 Å and of wavelengths greater than 1750 Å are absorbed in this region. An exception must be made for Lyman- $\alpha$  and a few other radiations, of less importance, in the same spectral range. Therefore, X-rays ionize oxygen and nitrogen, and Lyman- $\alpha$  is able to ionize a constituent with low ionization potential such as nitric oxide.

(ii) *E region*, where the cross-section is less than  $5 \times 10^{-18}$  cm<sup>2</sup>. Solar radiations of wavelengths greater than 800 Å with X-rays of wavelength less than 100 Å must be considered together. Ultraviolet radiations leading to the ionization of molecular oxygen from Lyman- $\beta$  at 1025 Å, and from C III at 977 Å, and to that of atomic oxygen from the Lyman continuum at 910 Å, play a role in the E layer. The spectrum between 100 Å and 31 Å corresponds to the essential part of the X-ray contributions in the E layer.

(iii) *F region*, where the absorption cross-sections are not less than  $10^{-17}$  cm<sup>2</sup>. Ultraviolet radiations of wavelengths less than 800 Å, from the first ionization potential of molecular nitrogen at 796 Å, correspond to efficient radiations leading to ionization in the F layers.

Since primary cosmic rays are involved in the atmospheric ionization, it is necessary to ascertain the region where they are sufficiently important. In mean latitudes the ionization rate coefficient is of the order of  $10^{-17}$  sec<sup>-1</sup>/molecule. In considering the various values of the ionization rate coefficients, the effect of cosmic rays must occur only in the lower part of D region.

## 2.2. Vertical Distribution of the Absorption

If we consider the number of photons  $dq(\nu)$  of frequency  $\nu$  absorbed per unit of time and volume in an elementary vertical layer  $dz$ , we may write

$$dq(\nu) = q(\nu) nK(\nu) dz \sec \chi \quad (1)$$

where  $q(\nu)$  is the number of photons available,  $K(\nu)$  is the monochromatic absorption cross-section and  $\chi$  is the solar zenith distance.  $\sec \chi$ , which is the function for a horizontal layer, must be replaced<sup>1</sup> by another function when  $\chi > 75^\circ$ .

In order to determine the variation of  $q(\nu)$  with height, we write:

$$\frac{dp}{p} = -\frac{1}{\beta} \frac{dH}{H} \quad (2)$$

and

$$\beta = dH/dz \quad (3)$$

Therefore,

$$\frac{p}{p_0} = \frac{n_0 g_0 H_0}{ngH} = e^{-\xi} \quad (4)$$

since

$$\frac{dH}{H} = \beta d\xi = \zeta d\beta + \beta d\zeta \quad (5)$$

if

$$H/H_0 = e^{\beta\zeta} \quad (6)$$

when  $\beta$  is equal to a constant,  $\xi = \zeta$ .

It should be pointed out that the laws are essentially different in an atmosphere with constant scale height compared with the thermosphere where the gradient  $\beta$  is very large.

### 2.3. Vertical Distribution of Electrons

Using for the recombination the following relation

$$\alpha = \alpha_{M}^* (n/n_M^*)^\eta = \alpha_{M}^* e^{-\eta(1+\beta)\zeta} \quad (16)$$

the equilibrium value for  $n_e = (\mathfrak{N}/\alpha)^{1/2}$  is, (14),

$$n_e = \left( \frac{\mathfrak{N}_{M}^*}{\alpha_{M}^*} \right)^{1/2} \exp \left\{ \frac{1+\beta}{2} [1 - \zeta(1-\eta) - \sec \chi e^{-\zeta}] \right\} \quad (17)$$

The condition for a peak in the electronic concentration is obtained from (17), and it is

$$e^{-\zeta_M} = (1-\eta) \cos \chi \quad (18)$$

A real maximum occurs when  $\eta < 1$ . When  $\eta = 0$ , i.e. when the recombination is constant, there is a peak of the electron concentration at the peak of the electron production. Any value between 0 and 1 leads to a maximum above the production peak. For example, a recombination which would be proportional to the pressure leads to the following condition for a peak of the electron concentration

$$e^{-\zeta_M} = \frac{\beta}{1+\beta} \cos \chi \quad (19)$$

showing that the difference in height between the production peak and that of the electron concentration increases when the gradient of the scale height decreases.

In order to show how the vertical structure of an ionospheric layer is modified by a variable recombination compared with a constant recombination the integration of (17) is necessary.

If we write

$$y \equiv \frac{1}{2}(1+\beta)e^{-\zeta} \sec \chi \quad (20)$$

we obtain at the peak

$$y_M = \frac{1}{2}(1+\beta)(1-\eta) \quad (21)$$

and the integration of (17), to obtain the total content  $N_e$ , gives

$$N_e = (n_e)_M^* \frac{e^{(1+\beta)/2}}{[\frac{1}{2}(1+\beta)]^{y_M}} \left[ \int_{y_M}^{\infty} y^{y_M-1} e^{-y} dy + \int_0^{y_M} y^{y_M-1} e^{-y} dy \right] (\cos \chi)^{y_M} \quad (22)$$

The two integrals in (22) are, respectively,

$$N_e = N_1 + N_2 = \int_{-\infty}^{+\infty} n_e dz = \int_{-\infty}^{z_M} n_e dz + \int_{z_M}^{\infty} n_e dz \quad (23)$$

A calculation shows that the ratio  $N_e/N_1$ , i.e. the ratio of the total content of electrons of the layer to the content below the peak varies between 6 and 3 if  $y_M$  varies between 0.1 and 0.6, respectively. The effect of the scale height

Therefore, (28) and (29) lead to the equation expressing the ratio  $\lambda$  of the concentration of negative ions and electrons

$$\frac{1}{\lambda(1+\lambda)} \frac{d\lambda}{dt} = \left[ \frac{an}{\lambda} - (d+fn) \right] - \left[ \frac{nI}{(1+\lambda)n_e} + (\alpha_i - \alpha_D)n_e \right] \quad (30)$$

Formula (30) is a Riccati equation. The stationary value of  $\lambda$  is as follows:

(i) in a sunlit atmosphere,  $\lambda_{sd}$ ,

$$\lambda_{sd} = \frac{an - [\lambda/(1+\lambda)](nI/n_e)}{d+fn + (\alpha_i - \alpha_D)n_e} \quad (31)$$

(ii) in twilight conditions,  $\lambda_{st}$ ,

$$\lambda_{st} = \frac{an}{d+fn + (\alpha_i - \alpha_D)n_e} \quad (32)$$

since ultraviolet radiation is not involved

(iii) in a dark atmosphere,  $\lambda_{sm}$ ,

$$\lambda_{sm} = \frac{an}{fn + (\alpha_i - \alpha_D)n_e} \quad (33)$$

since photo-detachment does not exist.

Values of  $\lambda$  given by (31), (32) and (33) correspond to the following condition:

$$\frac{dn^+}{n^+} = \frac{dn^-}{n^-} = \frac{dn_e}{n_e} \quad (34)$$

If we write the formula (31) in the following form

$$\lambda_{s,d} = \frac{an}{d+fn} \left/ \left[ 1 + \frac{nI}{(1+\lambda)n_e(d+fn)} + \frac{(\alpha_i - \alpha_D)n_e}{d+fn} \right] \right. \quad (35)$$

it is possible to see that the 2<sup>nd</sup> and 3<sup>rd</sup> terms of the denominator are small compared with 1. Numerical values computed in preceding chapters show that they may be neglected in normal conditions. The stationary value of  $\lambda_s = n^-/n_e$  is therefore

$$\lambda_s = \frac{an}{d+fn} \quad (36)$$

and can be used for the determination of the ratio of the concentrations of negative ions and electrons. This ratio depends on the attachment of electrons to neutral particles and on the detachment by solar radiation and by collision. Instead of the general equation (30), it is possible to use the following expression:

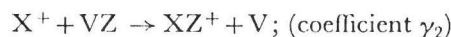
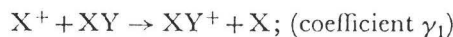
$$\frac{d\lambda}{dt} = (1+\lambda)an - (1+\lambda)\lambda(d+fn) \quad (37)$$

where  $\lambda$  is still given by (43) since molecular oxygen is the negative ion. Equation (45) corresponds to conditions of the D region and must be applied to the E layer if  $\lambda$  is neglected. However, in this region the ion-atom interchange begins to play an important role.

#### 4. ELECTRONS AND ION-ATOM INTERCHANGE

When negative ions are neglected, it appears that atomic ions become important. The recombination of atomic ions is generally very slow since radiative recombination is involved. The principal processes leading to the removal of atomic ions is the ion-atom interchange, giving molecular ions subject to dissociative recombination.

In order to present the situation in a general way, let us consider an atomic ion  $X^+$  and two different molecules VZ and XY leading to the following processes



The various equations are as follows:

$$\frac{dn^+(XY)}{dt} = n(XY) I_{XY} - \alpha_{XY} n^+(XY) n_e + \gamma_1 n(XY) n^+(X) - \gamma_3 n(V) n^+(XY) \quad (46)$$

$$\frac{dn^+(X)}{dt} = n(X) I_X + \gamma_3 n(V) n^+(XY) - [\gamma_1 n(XY) + \gamma_2 n(VZ)] n^+(X) \quad (47)$$

$$\frac{dn^+(XZ)}{dt} = \gamma_2 n(VZ) n^+(X) - \alpha_{XZ} n^+(XZ) n_e \quad (48)$$

and, therefore,

$$\frac{dn_e}{dt} = \frac{dn^+}{dt} = n(XY) I_{XY} + n(X) I_X - n_e [\alpha_{XZ} n^+(XZ) + \alpha_{XY} n^+(XY)] \quad (49)$$

It is clear that the electron concentration depends on the direct production of ions  $XY^+$ , but it is also related to the transformation of  $X^+$  into  $XZ^+$ , even if such a molecule,  $XZ$ , does not exist in the ionosphere. In fact, the atom-ion interchange is a function of the molecular concentrations XY and VZ and of the value of the rate coefficients  $\gamma$ . Since  $n^+(X)$  depends also on the effect of  $\gamma_3 n(V) n^+(XY)$ , it is necessary to consider which values such a term can reach. In the E layer, it is certainly negligible. In such conditions (47) leads, after integration, to the following expression

$$n^+(X) = n_0^+(X) e^{-\gamma n t} + \frac{n(X) I_X}{\gamma n} [1 - e^{-\gamma n t}] \quad (50)$$

in which  $n_0^+(X)$  denotes  $n^+(X)$  at  $t = 0$  and  $\gamma n = \gamma_1 n(XY) + \gamma_2 n(VZ)$ .

The time  $\tau[n^+(X)]$  necessary to reach 50 per cent of the equilibrium value is as follows

$$\tau[n^+(X)] = 0.7/\gamma n \quad (51)$$

beginning of the night. An exact analysis cannot be made when rate coefficients are not well known, since the law of recombination

$$\frac{dn_e}{dt} = -\alpha_{XY} n^+(XY) + \alpha_{VZ} n^+(VZ) n_e \quad (60)$$

is very sensitive to the ratio of the recombinances.

In any case, (60) represents the law which must be applied in the E and F<sub>1</sub> regions, since the transformation is as follows

$$n_e = [n^+(XZ) + n^+(XY) + n^+(X)] \rightarrow [n^+(XZ) + n^+(XY)] \rightarrow n^+(XZ) \quad (61)$$

leading finally to

$$\frac{dn_e}{dt} = -\alpha_{XZ} n_e^2 \quad (62)$$

At sufficiently high altitudes, where

$$n^+(XY) < n^+(X) \leq n_e \quad (63)$$

the time  $\tau[n^+(XY)]$  required to reach equilibrium conditions (50 per cent) is given by expression such as

$$\tau[n^+(XY)] = 0.7/[\alpha_{XY} n_e + \gamma_3 n(V)] \quad (64)$$

Recombination coefficients between  $3 \times 10^{-9} \text{ cm}^3 \text{ sec}^{-1}$  and  $3 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$  lead to

$$\tau[n^+(XY)] < 2.3 \times 10^6/n_e \text{ to } 2.3 \times 10^7/n_e \quad (65)$$

i.e. very short times, not greater than 500 sec when the electron concentration is not less than  $5 \times 10^5 \text{ cm}^{-3}$ . The law of loss of positive atomic ions will have the following form

$$n^+(X) = n_0^+(X) e^{-\gamma n(XZ)t} \quad (66)$$

when

$$n^+(XZ)/n_e = \gamma n(XZ)/\alpha_{XZ} \quad (67)$$

The recombination, therefore, changes from the D region, where electron attachment is involved, to the E layer where dissociative recombination is the essential process, and to the F<sub>2</sub> layer where ion-atom interchange is necessary before the recombination of electrons.

##### 5. ORIGIN OF THE IONIZATION IN THE D REGION

An analysis of the conditions for absorption of the solar radiation (Table 1) shows that X-rays of wavelengths less than 10 Å are involved in the production of the ions O<sub>2</sub><sup>+</sup> and N<sub>2</sub><sup>+</sup>. Furthermore, the penetration of Lyman-α at λ1215.7 Å (see Table 2) leads to the ionization of nitric oxide, produced near the mesopause by an indirect effect of X-rays. Finally, primary cosmic rays produce an ionization which is directly dependent on the total concentration in the mesosphere. In a preliminary analysis, the ionization due to radiations of λ > 1750 Å and to the ionization of atomic oxygen by X-rays are neglected. The effect of the ionization of argon is also neglected when considering that charge transfers are involved.

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A calculation was made<sup>5</sup> adopting the following values:

$$\alpha_i = 10^{-7} \text{ cm}^3 \text{ sec}^{-1} \quad (70)$$

$$\alpha_D(\text{N}_2) = 5 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1} \quad (71)$$

$$\alpha_D(\text{O}_2) = 3 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1} \quad (72)$$

$$\alpha_D(\text{NO}) = 3 \times 10^{-9} \text{ cm}^3 \text{ sec}^{-1} \quad (73)$$

The ratio of the concentrations of negative ions and electrons in a sunlit atmosphere decreases with height and is negligible at the mesopause. Comparison of the ionization rate of  $\text{O}_2$  and  $\text{N}_2$  produced by cosmic rays and X-rays with that of  $\text{NO}$  by Lyman- $\alpha$  shows that the normal ionization in the lower part of the D region must be due to cosmic rays. However, when  $\text{NO}^+$  is produced, the resulting concentration of electrons depends on the recombination of each ion. The final effect of each radiation in the ionization budget of the D region shows that for a quiet sun both cosmic rays and Lyman- $\alpha$  are involved. When

Table 3. Ionization Rate Coefficients ( $\text{sec}^{-1}$ ) at 2, 4 and 6 Å

Solar Conditions	2Å	4Å	6Å
Completely quiet	$1.6 \times 10^{-19}$	$9.8 \times 10^{-18}$	$2.8 \times 10^{-16}$
Quiet	$1.6 \times 10^{-18}$	$9.8 \times 10^{-17}$	$2.8 \times 10^{-15}$
Lightly disturbed	$1.6 \times 10^{-17}$	$9.8 \times 10^{-16}$	$2.8 \times 10^{-14}$
Disturbed	$1.6 \times 10^{-16}$	$9.8 \times 10^{-15}$	$2.8 \times 10^{-13}$
Special events	$1.6 \times 10^{-15}$	$9.8 \times 10^{-14}$	$2.8 \times 10^{-12}$
Strong flares	$1.6 \times 10^{-14}$	$9.8 \times 10^{-13}$	$2.8 \times 10^{-11}$

the sun is disturbed, the effect of X-rays of  $\lambda < 10 \text{ Å}$  begins to be apparent, and Table 3 gives the ionization rate coefficients for various solar conditions. The effect of solar flares is very important.

Consequently, the ionization of the normal D region is essentially due to the ionization of nitric oxide by Lyman- $\alpha$  in the upper part and to the ionization of  $\text{O}_2$  and  $\text{N}_2$  by primary cosmic rays in the lower part. The remarkable increase during solar flares is due to X-rays. If there is some increase of  $\text{NO}^+$ , it must be due to an increase of  $\text{NO}$  and not necessarily to an increase of the intensity of Lyman- $\alpha$ .

It is clear that the preceding theoretical results must be used only as an illustration of the physical behaviour of the D region. First, the rate coefficients which have been used, and particularly those given by (70), are only possible orders of magnitude. Then, it is not possible to introduce the effect of minor constituents such as Na and Ca, since we have no knowledge of the reactions in which neutral and charged particles are involved. Furthermore, various processes such as effects of solar activity and mesospheric mixing lead to variations of the nitric oxide concentration. The variation in the primary cosmic rays of a factor of ten between the equator and  $60^\circ$  is also an important

much greater than  $n(\text{NO})$ . Other reactions involving interchange of ions are neglected in the formation of the E layer and (52) leads to

$$n^+(\text{O}) = \frac{n(\text{O}) I(\text{O})}{\gamma_{\text{O}_2} n(\text{O}_2) + \gamma_{\text{N}_2} n(\text{N}_2)} \quad (76)$$

and to

$$\frac{n^+(\text{N})}{n^+(\text{N}_2)} \propto \frac{n(\text{N})}{n(\text{O}_2)} < 1 \quad (77)$$

In other words, since  $\gamma_{\text{O}_2} n(\text{O}_2)$  in the E layer is greater than 1,  $n^+(\text{O})$  should be a minor ion,  $n^+(\text{O}) < 10^3 \text{ cm}^{-3}$ . In the same way,  $n^+(\text{N})$  is negligible.

The recombination of molecular ions must be given in the E layer by dissociative recombination



and the following ions must be considered



The rate coefficients adopted for the D region i.e. (71), (72) and (73) are adopted to provide an example for calculation. (49) will be the typical law for the variation of the electron concentration. But, in equilibrium conditions, we may write, when (74) is neglected compared with (75),

$$n_e = \frac{n(\text{O}_2) I(\text{O}_2)}{\alpha_D(\text{O}_2) n^+(\text{O}_2)} = \frac{n(\text{N}_2) I(\text{N}_2)}{\alpha_D(\text{N}_2) n^+(\text{N}_2)} = \frac{n(\text{O}) I(\text{O})}{\alpha_D(\text{NO}) n^+(\text{NO})} \quad (82)$$

The first step is to show how the effect of ionization by X-rays is involved in the region where Lyman- $\beta$  ionizes only molecular oxygen. If we adopt the absorption conditions given by Table 4 and the ratios 8:4:1 for the ratios of energy in the spectral ranges 70 Å, 50 Å and 35 Å, the production rates of electrons can be represented by curves such as those of Fig. 1. It is clear that Lyman- $\beta$  causes the first peak of the E layer since its ionization effect is superposed on that by X-rays. Since the absorption cross-section of CIII

Table 4. Absorption Cross-sections of X-rays between 10 Å and 100 Å

Wavelength Spectral Range	70 Å 90-55 Å	50 Å 55-40 Å	35 Å 40-31 Å
Cross sections;			
Total (cm <sup>2</sup> )	$6.2 \times 10^{-19}$	$3.0 \times 10^{-19}$	$1.3 \times 10^{-19}$
N <sub>2</sub> (cm <sup>2</sup> )	$5.5 \times 10^{-19}$	$2.4 \times 10^{-19}$	$9.7 \times 10^{-20}$
O <sub>2</sub> (cm <sup>2</sup> )	$9.3 \times 10^{-19}$	$4.0 \times 10^{-19}$	$1.6 \times 10^{-19}$
$\lambda$	20.5 Å	15.5 Å	11.5 Å
Spectral range	31-16.5 Å	16.5-12.8 Å	12.8-10.3 Å



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Such a relation between  $n^+(\text{O}_2)$  and  $n^+(\text{NO})$  in the E layer shows the difficulty of obtaining numerical values without a complete knowledge of all parameters. It is clear that the effective recombination  $\alpha_E$  of the E layer will be

$$\frac{dn_e}{dt} = -[\alpha_D(\text{N}_2) n^+(\text{N}_2) + \alpha_D(\text{O}_2) n^+(\text{O}_2) + \alpha_D(\text{NO}) n^+(\text{NO})] n_e = -\alpha_E n_e^2 \quad (84)$$

and will be a function of the ratios  $n^+(\text{NO}) : n^+(\text{O}_2) : n^+(\text{N}_2)$ . After sunset the successive disappearance of ions with high recombination coefficients should lead to the presence of the ion with the smallest value, i.e. in our analysis  $\text{NO}^+$  compared with  $\text{N}_2^+$  and  $\text{O}_2^+$ .

It should be pointed out that during solar flares the ratio  $n^+(\text{O}_2)/n^+(\text{NO})$  will change since  $\text{O}_2^+$  is particularly affected. As an example, the effect of X-ray of  $\lambda < 10 \text{ \AA}$  is important, even if there is an increase of a factor of 4 in the region of  $\lambda > 31 \text{ \AA}$ . At 90 km, an increase of a factor of 100 at  $\lambda > 31 \text{ \AA}$

*Table 5. Example of Possible Percentages of Ion Concentrations in the E layer. Sunlit Atmosphere*

Altitude (km)	$\text{O}_2^+$	$\text{NO}^+$	$\text{N}_2^+$
85	36	59	5
90	65	27	8
95	78	20	2
100	68	31	1
105	66	32	2
110	53	44	2
115	43	54	2
120	28	69	2

is needed to produce a sufficiently large effect. At 95 km, a factor of 10 is still needed. Such a result shows that the effect of solar flares, which is chiefly due to an increase of X-rays of  $\lambda < 10 \text{ \AA}$  affecting the D region, will modify the shape of the lower E layer more than the radiation of  $\lambda > 31 \text{ \AA}$ .

Finally, observational night-time results are explained by a sufficiently low recombination for  $\text{NO}^+$  as compared with that of  $\text{O}_2^+$ . A value of  $3 \times 10^{-9} \text{ cm}^3 \text{ sec}^{-1}$  which has been adopted for  $\alpha(\text{NO})$  is not outside of possible values, but is not necessarily the exact value.  $10^{-8} \text{ cm}^3 \text{ sec}^{-1}$  is still acceptable.

An example of a computation is given in Table 5 in order to show how the ions may be distributed.  $\text{O}_2^+$  and  $\text{NO}^+$  are the principal ions while  $\text{N}_2^+$  is a minor ion because of its high recombination. The presence of  $\text{NO}^+$  in the lower part of the E layer is essentially due to the transformation into  $\text{NO}^+$  of  $\text{O}^+$  produced by X-rays. In the region above 100 km,  $\text{NO}^+$  results from  $\text{O}^+$  produced by ultraviolet radiation of  $\lambda \leq 910 \text{ \AA}$ . The exact ratio  $\text{O}_2^+/\text{NO}^+$  is not known since the ratio of  $\gamma_{\text{O}_2}/\gamma_{\text{N}_2}$  of (74) and (75) has not yet been determined.

p. 116 in *Electron Density Profiles in the Ionosphere and Exosphere*, edited by B. Maehlum, Pergamon Press, London, 1962.

### PAPER 3

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The removal of electrons depends on various recombination processes and is subject to processes produced by collisions between specific particles (electrons, negative and positive ions, atoms and molecules of different kinds).

The first step is the study of the absorption characteristics of various atmospheric constituents which are dependent on the wavelength, and of the spectral distribution of the solar energy, and it is necessary to consider the numbers of solar photons which are available in those spectral ranges which cause the ionization of the principal atmospheric constituents. It is important to find how oxygen and nitrogen may be ionized. Furthermore, an analysis of the solar spectrum must give some indication of the variations produced by solar activity in the range of X-ray spectrum. But, the number of collision processes involved in the removal of electrons is so large that the recombination coefficient  $\alpha$  needs a special analysis in each case; it is not possible, however, to consider all processes together. For this reason, it is necessary to analyze the physical parameters one after another before trying to find an explanation of the origin of the ionospheric layers. In other words: production of the ionization in the D region at altitudes less than 85 km, formation of the E layer below 130 km, and the origin of the F region above 150 km.

### 2. PRODUCTION OF THE NORMAL IONIZATION

#### 2.1. *Atmospheric Absorptions*

Since the diurnal variation of the ionization and its variation during solar eclipses show that the electron production is due to electromagnetic radiation,

The variation of  $q(\nu)$  with height is obtained by integration of (3) with the help of (4), and

$$Q = Q_\infty \exp[-n_0 KH_0(g_0/\bar{g}) \sec \chi e^{-\xi}] \quad (7)$$

if  $Q$  replaces  $q(\nu)$  when a constant value is used in a certain spectral range.  $Q_\infty$  is the number of photons available at the top of the earth's atmosphere.

The number of ionization processes per unit of time and volume  $\mathfrak{N} = nKQ$  can be written with (4) and (7)

$$\mathfrak{N} = n_0 H_0(g_0/\bar{g}) K Q_\infty (e^{-\xi}/H) \exp[-n_0 KH_0(g_0/\bar{g}) \sec \chi e^{-\xi}] \quad (8)$$

Introducing the condition for a maximum of  $\mathfrak{N}$  in (8), one obtains in neglecting the variation of  $g$ ,

$$n_M KH_M \sec \chi = 1 + \beta \quad (9)$$

in which  $M$  corresponds to the altitude where there is an absorption peak for the production of electrons,  $\mathfrak{N}_M$

$$\mathfrak{N}_M = \frac{(1 + \beta) Q_\infty \cos \chi}{H_M \exp(1 + \beta)} \quad (10)$$

For an overhead sun,  $\chi = 0$ , and (9) and (10) become

$$n_M^* KH_M^* = 1 + \beta \quad (11)$$

and

$$\mathfrak{N}_M^* = \frac{(1 + \beta) Q_\infty}{H_M^* \exp(1 + \beta)} \quad (12)$$

The formulas (11) and (12) represent conditions which can lead to a preliminary knowledge of the origin of the atmospheric ionization. From (11), it is possible when the absorption cross-section is known, to determine the atmospheric region where the absorption peak occurs since  $nH$  is the total number of molecules in a vertical column. The maximum production of electrons can be obtained for a certain region when the number of photons available is known.

The vertical distribution of the absorption rate (or the electronic production if the absorption cross-section corresponds to the ionization cross-section) from (8) and (12)

$$\mathfrak{N} = \mathfrak{N}_M^* e^{\beta \xi} (H_M^*/H) \exp[(1 + \beta)(1 - \xi - \sec \chi e^{-\xi})] \quad (13)$$

When  $\beta = \text{constant}$ , (6) can be used and (13) becomes

$$\mathfrak{N} = \mathfrak{N}_M^* \exp[(1 + \beta)(1 - \zeta - \sec \chi e^{-\zeta})] \quad (14)$$

and, (10) and (12)

$$\mathfrak{N}_M = \mathfrak{N}_M^* (\cos \chi)^{1 + \beta} \quad (15)$$

which shows how the maximum rate varies with the solar zenith distance when  $\beta = \text{constant}$ .

We note that Chapman's formulas for a constant scale height are given by (9) to (15) when there is no gradient of the scale height,  $\beta = 0$ , and

$$\zeta = (z - z_M^*)/H$$

gradient  $\beta$  is not very important when the recombination is constant, since  $N_e/N_1 \leq 3$ . But, if  $\alpha$  is proportional to the pressure, the effect of the scale height gradient is important. When two different constituents are involved of mass  $m_1$  for the ionization and of mass  $m$  for the recombination, the ratio  $N_e/N_1$  is modified. A decreasing mass ratio  $m_1/m$  leads to diminutions in the ratio  $N_e/N_1$ . For example, if  $m_1/m = 0.5$ , the ratio for an ionization equilibrium  $N_e/N_1 = 4$ .

It is clear that the vertical distribution of the electron concentration has various forms when the recombination is not constant with height. Since several parameters are involved it is very difficult to find the total content even in a steady state. Observational data *in situ* are required to obtain the information which is needed.

### 3. ELECTRONS AND NEGATIVE IONS

In order to determine the laws of the electron recombination it is necessary to consider all processes in which electrons and ions are involved. But, the analysis is simplified when a distinction is made between the processes for which negative ions are essential and those for which atom-ion interchange plays a role. With such a subdivision, one implicitly assumes that atomic ions are not important in the lowest region where negative ions are efficient.

If only one constituent is involved, the following equations must be considered:

$$\frac{dn^+}{dt} = nI - \alpha_D n^+ n_e - \alpha_i n^+ n^- \quad (24)$$

$$\frac{dn^-}{dt} = ann_e - n^-(d + fn + \alpha_i n^+) \quad (25)$$

$$\frac{dn_e}{dt} = nI - \alpha_D n^+ n_e - ann_e + n^-(d + fn) \quad (26)$$

in which the rate coefficients are as follows:

- $\alpha_D$  = dissociative recombination;
- $\alpha_i$  = mutual neutralization of ions;
- $a$  = electron attachment;
- $d$  = detachment by solar radiation;
- $f$  = detachment by collision (molecular formation);
- $I$  = ionization by solar radiation.

If we write

$$n^+ = n^- + n_e = (1 + \lambda) n_e, \quad (27)$$

(24) and (25) lead to

$$\frac{dn_e}{dt} = \frac{nI}{1 + \lambda} - (\alpha_D + \lambda\alpha_i) n_e^2 - \frac{n_e}{1 + \lambda} \frac{d\lambda}{dt} \quad (28)$$

$$\frac{dn_e}{dt} = \frac{ann_e}{\lambda} - n_e [d + fn + (1 + \lambda) \alpha_i n_e] - \frac{n_e}{\lambda} \frac{d\lambda}{dt} \quad (29)$$

with the particular solution  $\lambda = -1$ . Its general solution is written as follows

$$\lambda = \frac{an}{d+fn} \frac{1 - \{[an - (d+fn)\lambda_0]/[an(1+\lambda_0)]\} \exp\{-[d+(a+fn)t]\}}{1 + \{[an - (d+fn)\lambda_0]/[(d+fn)(1+\lambda_0)]\} \exp\{-[d+(a+f)n]t\}} \quad (38)$$

if  $\lambda_0$  denotes the value of  $\lambda$  when  $t = 0$ .

The time necessary  $\tau(\lambda_s)$  to reach the equilibrium value (at least 50 per cent) is given by

$$\tau(\lambda_{sd}) = 0.7/[d+(a+f)n] \quad (39)$$

According to Burch, Smith and Branscomb<sup>2</sup> giving the photo-detachment rate coefficients of  $O_2^-$  and  $O^-$ , it is clear that the time to reach the equilibrium between negative ions and electrons in a sunlit atmosphere is

$$\tau(\lambda_{sd}) \leq 2 \text{ sec} \quad (39a)$$

i.e. a time of the order of a second.

In such circumstances, equilibrium is normal in a sunlit atmosphere. Under night conditions, the attachment must be considered first. When  $O_2^-$  is the principal ion<sup>3</sup>, (39a) leads, for  $\tau(\lambda_{sn})$ , to

$$\tau(\lambda_{sn}) = 5 \times 10^{29}/n^2(O_2) \quad (39b)$$

With (39a),  $\tau(\lambda_{sn})$  increases from 3 sec at 70 km to 60 sec at 80 km, and reaches 2000 sec near 90 km. It is therefore possible to claim that the equilibrium conditions between negative ions and electrons are almost immediately reached in the D region. However, since the detachment by collision could be due to atomic oxygen the stationary value of  $\lambda_{sn}$ , where there is no oxygen atom, should be<sup>4</sup>

$$\lambda_{sn} = 4 \times 10^{-11} n(O_2) \quad (40)$$

i.e. in the stratosphere and in the lower mesosphere. However, near or below the mesopause where atomic oxygen is not completely transformed into ozone,

$$\lambda_{sn} = \frac{1.5 \times 10^{-30} n^2(O_2)}{f n(O)} \quad (41)$$

represents the stationary value for night-time conditions.

Thus, in the D region, (28) can be written

$$\frac{dn_e}{dt} = \frac{nI}{1+\lambda} - (\alpha_D + \lambda\alpha_i) n_e^2 \quad (42)$$

where

$$\lambda = \frac{an}{d+fn} \quad (43)$$

But, in the E layer,

$$\frac{dn_e}{dt} = nI - (\alpha_D + \lambda\alpha_i) n_e^2 \quad (44)$$

in which  $\lambda\alpha_i$  is neglected compared with  $\alpha_D$ . Since the ionization is due to several constituents, (43) must be replaced by a more complicated equation:

$$\frac{dn_e}{dt} = \frac{n_j I_j}{1+\lambda} - \frac{n_e}{1+\lambda} \sum (\alpha_{D,j} + \lambda\alpha_{ij}) n_j^+ \quad (45)$$

Even for values of  $\gamma$  of the order of  $10^{-13} \text{ cm}^3 \text{ sec}^{-1}$ , the time needed to reach equilibrium conditions is short in the E layer and the concentration of  $n^+(X)$  is small compared with the electron concentration. Thus, the equilibrium value of  $n^+(X)$  which is, (47),

$$n^+(X) = \frac{n(X) I_X + \gamma_3 n(V) n^+(XY)}{\gamma_1 n(XY) + \gamma_2 n(VZ)} \quad (52)$$

can be introduced in (46) and (48) to give

$$\frac{dn^+(XY)}{dt} = n(XY) I_{XY} + n(X) I_X - \gamma_2 n(VZ) n^+(X) - \alpha_{XY} n^+(XY) n_e \quad (53)$$

and

$$\begin{aligned} \frac{dn^+(XY)}{dt} + \frac{dn^+(XZ)}{dt} = & n(XY) I_{XY} + n(X) I_X - n_e [\alpha_{XY} n^+(XY) + \\ & + \alpha_{XZ} n^+(XZ)] \end{aligned} \quad (54)$$

which is identical to (49).

When  $X^+$  is a minor ion, (54) represents the law of the variation of the electron concentration, i.e. for the E layer.

When the molecular concentration becomes sufficiently low, it is impossible to reach equilibrium conditions for atomic ions; (51) would take too long. Consequently, electron concentration cannot reach an equilibrium value in a sufficiently short time and the use of (52) is not possible.

The nocturnal recombination, where the molecular ions are more important than the atomic ions, is obtained from the preceding equations in which the photo-ionization processes are neglected. In an ionospheric region, after sunset, where

$$n^+(X) = n_0^+(X) \exp \{ - [\gamma_1 n(XY) + \gamma_2 n(VZ)] t \} \quad (55)$$

leads rapidly to a negligible concentration of  $n^+(X)$ , the laws of recombination of molecular ions become

$$\frac{dn^+(XY)}{dt} = -\alpha_{XY} n^+(XY) n_e \quad (56)$$

$$\frac{dn^+(XZ)}{dt} = -\alpha_{XZ} n^+(XZ) n_e \quad (57)$$

If  $n^+(XY) < n^+(XZ)$ , (56) leads to

$$n^+(XY) = n_0^+(XY) \exp (-\alpha_{XY} n_e t) \quad (58)$$

showing that

$$\frac{dn_e}{dt} = -\alpha_{XZ} n^+(XZ) n_e \quad (59)$$

The recombination depends after a certain time on the molecular ion having the smallest recombination. However, it must be sufficiently abundant at the

Table 1. Absorption Cross-sections and Altitude of the Unit Optical Depth of X-rays between 0.01 Å and 10 Å

$\lambda$ (Å)	$K(N_2)$ ( $cm^2$ )	$K(O_2)$ ( $cm^2$ )	$K(A)$ ( $cm^2$ )	$K(Air)$ ( $cm^2$ )	Altitude $\tau_{air}=1$ (km)
0.01	$2.66 \times 10^{-24}$	$3.03 \times 10^{-24}$	$3.42 \times 10^{-24}$	$2.74 \times 10^{-24}$	27
0.02	$3.69 \times 10^{-24}$	$4.22 \times 10^{-24}$	$4.77 \times 10^{-24}$	$3.81 \times 10^{-24}$	30
0.05	$5.28 \times 10^{-24}$	$6.05 \times 10^{-24}$	$7.11 \times 10^{-24}$	$5.46 \times 10^{-24}$	32
0.10	$6.64 \times 10^{-24}$	$7.65 \times 10^{-24}$	$1.09 \times 10^{-23}$	$6.89 \times 10^{-24}$	34
0.20	$8.40 \times 10^{-24}$	$1.01 \times 10^{-23}$	$2.96 \times 10^{-23}$	$8.95 \times 10^{-24}$	36
0.40	$1.45 \times 10^{-23}$	$2.03 \times 10^{-23}$	$1.66 \times 10^{-22}$	$1.71 \times 10^{-23}$	41
0.60	$2.91 \times 10^{-23}$	$4.59 \times 10^{-23}$	$5.23 \times 10^{-22}$	$3.72 \times 10^{-23}$	47
0.80	$5.71 \times 10^{-23}$	$9.51 \times 10^{-23}$	$1.20 \times 10^{-21}$	$7.56 \times 10^{-23}$	53
1.00	$1.03 \times 10^{-22}$	$1.76 \times 10^{-22}$	$2.27 \times 10^{-21}$	$1.38 \times 10^{-22}$	58
1.20	$1.71 \times 10^{-22}$	$2.95 \times 10^{-22}$	$3.83 \times 10^{-21}$	$2.31 \times 10^{-22}$	62
1.50	$3.23 \times 10^{-22}$	$5.63 \times 10^{-22}$	$7.18 \times 10^{-21}$	$4.37 \times 10^{-22}$	66
2.00	$7.47 \times 10^{-22}$	$1.31 \times 10^{-21}$	$1.59 \times 10^{-20}$	$1.01 \times 10^{-21}$	72
2.50	$1.44 \times 10^{-21}$	$2.57 \times 10^{-21}$	$2.90 \times 10^{-20}$	$1.92 \times 10^{-21}$	76
3.00	$2.46 \times 10^{-21}$	$4.29 \times 10^{-21}$	$4.67 \times 10^{-20}$	$3.26 \times 10^{-21}$	79
4.00	$5.73 \times 10^{-21}$	$9.93 \times 10^{-21}$	$1.10 \times 10^{-20}$	$6.55 \times 10^{-21}$	83
5.00	$1.10 \times 10^{-20}$	$1.90 \times 10^{-20}$	$1.93 \times 10^{-20}$	$1.26 \times 10^{-20}$	87
6.00	$1.87 \times 10^{-20}$	$3.20 \times 10^{-20}$	$3.09 \times 10^{-20}$	$2.13 \times 10^{-20}$	90
8.00	$4.27 \times 10^{-20}$	$7.22 \times 10^{-20}$	$6.23 \times 10^{-20}$	$4.85 \times 10^{-20}$	95
10.00	$8.05 \times 10^{-20}$	$1.34 \times 10^{-19}$	$1.05 \times 10^{-19}$	$9.09 \times 10^{-20}$	99

Table 2. Ionization Rate Coefficient of NO by Lyman- $\alpha$

Altitude (km)	$I_{NO}(L\alpha)$ ( $sec^{-1}$ )	Altitude (km)	$I_{NO}(L\alpha)$ ( $sec^{-1}$ )	Altitude (km)	$I_{NO}(L\alpha)$ ( $sec^{-1}$ )
100	$7.0 \times 10^{-7}$	77.5	$3.5 \times 10^{-7}$	67.5	$1.3 \times 10^{-8}$
85	$6.0 \times 10^{-7}$	75	$2.3 \times 10^{-7}$	65	$2.1 \times 10^{-9}$
82.5	$5.4 \times 10^{-7}$	72.5	$1.2 \times 10^{-7}$	62.5	$1.8 \times 10^{-10}$
80	$4.6 \times 10^{-7}$	70	$4.9 \times 10^{-8}$	60	$6.7 \times 10^{-11}$

Since the various reactions are extremely rapid, equilibrium conditions are adopted in (45). Therefore, it is possible to write

$$n_e = \frac{n_1 I_1}{(\alpha_{i1} \lambda + \alpha_{D1}) n_1^+} = \frac{n_2 I_2}{(\alpha_{i2} \lambda + \alpha_{D2}) n_2^+} \quad (68)$$

and for the D region

$$n_e = \frac{n(O_2) I(O_2)}{\alpha_{i(O_2)} \lambda + \alpha_{D(O_2)} n^+(O_2)} = \frac{n(N_2) I(N_2)}{\alpha_{i(N_2)} \lambda + \alpha_{D(N_2)} n^+(N_2)} = \frac{n(NO) I(NO)}{\alpha_{i(NO)} \lambda + \alpha_{D(NO)} n^+(NO)} \quad (69)$$

factor to be introduced in a complete analysis. In the same way, the disturbed conditions caused, when increases of corpuscular radiation are observed, must be considered and lead to an important modification in the problem of ionization in the D region.

Night conditions in the D region are completely different from those of a sunlit atmosphere. The electron concentration is reduced to a very small value, because the attachment of electrons is an important process when the concentration of atomic oxygen is sufficiently small. However, the night-time conditions should be studied when it is possible to deduce the time variation of the concentration of atomic oxygen. The removal of oxygen atoms in the mesosphere is related to reactions dealing with the formation of ozone, and it is clear that oxygen atoms have a very short lifetime after twilight in the lower mesosphere. The ratio  $n^-/n_e$  should be related to  $n(\text{O})$ . In any case, it is certain that during the night in the D region electrons disappear by attachment to oxygen molecules. But it is impossible to fix the levels where the collisional detachment begins to play a role, since the rate coefficient of collisional detachment by atomic oxygen is not yet known. However, the transition region from the electron attachment to the dissociative recombination as the loss process of electrons corresponds to the transition from the D region to the nocturnal E layer. Finally, a negative ion such as  $\text{NO}_2^-$  having a large electron affinity is required.

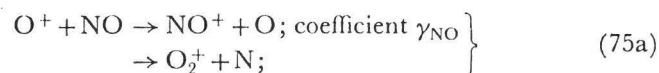
#### 6. ORIGIN OF THE IONIZATION OF THE E REGION

Considering again all ionization processes which may be involved in the E region, one may say that its ionization is due to

- (i) molecular oxygen ionized by X-rays between 100 Å and 31 Å, by ultraviolet radiation of Lyman- $\beta$  type and also by the Lyman continuum, at  $\lambda < 910$  Å;
- (ii) molecular nitrogen ionized only by X-rays between 100 Å and 31 Å;
- (iii) atomic oxygen ionized by ultraviolet radiation of the Lyman continuum at  $\lambda \leq 910$  Å and by X-rays.

One considers that the photo-ionization of NO, N and Ca is negligible compared with other processes in the E layer. Furthermore, the effect of radiations of  $\lambda < 800$  Å ionizing  $\text{N}_2$  occurs in the  $F_1$  layer and can only be of some importance in the transition region between the E and  $F_1$  layers.

In the E region, the effect of negative ions is negligible and the ratio  $n^-/n_e$  is very small. But, another process must be introduced; it deals with the ion-atom interchange since the ion  $\text{O}^+$  is formed in the E layer. Among the various reactions described in another paper the following ones must be considered,



Reaction (75a) will be neglected in the E layer since  $n(\text{O}_2)$  and  $n(\text{N}_2)$  are



( $\lambda 977 \text{ \AA}$ ) is  $3.2 \times 10^{-18} \text{ cm}^2$ , i.e. twice that of Lyman- $\beta$ , the ionization peaks of these two radiations differ by about 5 km. The shape of the vertical distribution of the electron concentration must be ultimately related to the spectral distribution of X-rays. For example, the lower part of the E layer near the mesopause should be associated with the energy of the spectral range 31–40  $\text{\AA}$ .

The production of ions  $\text{O}^+$  leading to  $\text{NO}^+$  depends on the ionization of oxygen atoms by X-rays and by ultraviolet radiations, of  $\lambda < 910 \text{ \AA}$ . Since the absorption cross-section of  $\text{O}_2$  is of the order of  $5 \times 10^{-18} \text{ cm}^2$ , the optical depth between 100 km and 105 km is of the order of 10 and ionization of atomic oxygen is due only to X-rays. Therefore, the presence of  $\text{NO}^+$  at 100 km and below cannot be explained by an effect of ultraviolet radiation and shows that X-rays are certainly effective in the ionization of the E layer. Above 110 km,

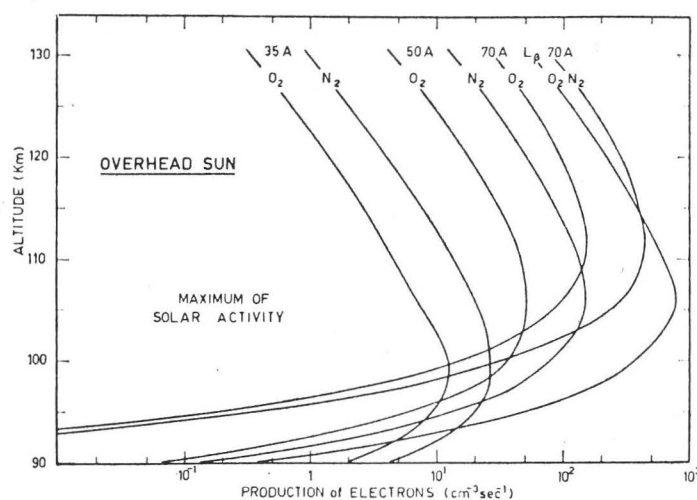


Fig. 1. Production rates of electrons vs. height.

the optical depth of molecular oxygen at  $\lambda \leq 910 \text{ \AA}$  is less than 3, and anion increase of  $\text{NO}^+/\text{O}_2^+$  should be due to the effect of the ionization of atomic oxygen by ultraviolet radiation. Above 115 km additional ionization is caused by radiations of  $\lambda > 150 \text{ \AA}$ . However, a high concentration of the order of  $2 \times 10^5 \text{ electrons cm}^{-3}$  at 110 km does represent maximum conditions since reaction (74) has been neglected. When its effect is introduced, the total electron concentration decreases and also the concentration of  $\text{NO}^+$ . At the present time, it is not useful to try to fit the observations since the parameters are not sufficiently known. The ratio  $n(\text{NO}^+)/n(\text{O}_2^+)$  is a function of the solar energy, of the ratio  $\alpha_{\text{O}_2}/\alpha_{\text{NO}}$  of the recombination coefficients and of the ratio  $\gamma_{\text{O}_2}/\gamma_{\text{N}_2}$  of the ion-atom interchange rate coefficients.

With three unknown parameters, it is always possible to reach an agreement with any observational data. With (74) and (75), an equation such as (82) leads to

$$\frac{n^+(\text{O}_2)}{n^+(\text{NO})} = \frac{\alpha_D(\text{NO}) \gamma(\text{O}_2) n(\text{O}_2)}{\alpha_D(\text{O}_2) \gamma(\text{N}_2) n(\text{N}_2)} \left[ 1 + \frac{n(\text{O}_2) I(\text{O}_2) \{ \gamma(\text{N}_2) n(\text{N}_2) + \gamma(\text{O}_2) n(\text{O}_2) \}}{n(\text{O}) I(\text{O}) \gamma(\text{O}_2) n(\text{O}_2)} \right] \quad (83)$$

For that reason  $n^+(\text{NO})$  in Table 5 should be considered as a maximum and  $n^+(\text{O}_2)$  as a minimum when their recombination is given by (72) and (73).

#### 7. ORIGIN OF THE IONIZATION IN THE F REGION

Due to the exponential decrease of nitrogen and oxygen, solar radiations between 800 Å and 200 Å are absorbed above 120 km and there is an absorption peak for an important fraction of the spectrum peak near 170 km for an overhead sun.

Table 6. Ionization Rate Coefficient ( $\text{sec}^{-1}$ ) by Ultraviolet Radiations

Spectral Range	O <sub>2</sub>	O	N <sub>2</sub>
1026-1000 Å	$(5 \pm 3) \times 10^{-9}$		
1000- 910 Å	$(4 \pm 2) \times 10^{-8}$		
910- 800 Å	$(1 \pm 0.5) \times 10^{-7}$	$(5 \pm 3) \times 10^{-8}$	
800- 500 Å	$(4 \pm 3) \times 10^{-7}$	$(1.5 \pm 1.0) \times 10^{-7}$	$(2.5 \pm 2.0) \times 10^{-7}$
500- 250 Å	$(1.5 \pm 0.8) \times 10^{-7}$	$(1.0 \pm 0.5) \times 10^{-7}$	$(7.5 \pm 5.0) \times 10^{-8}$
Total	$(6 \pm 5) \times 10^{-7}$	$(3.0 \pm 2.5) \times 10^{-7}$	$(3.5 \pm 3.0) \times 10^{-7}$

Since the principal constituents are necessarily nitrogen and oxygen in molecular or atomic form with absorption coefficients of the same order of magnitude ( $\sim 10^{-17} \text{ cm}^2$ ), the problem of the production of electrons is not very different from that of the E region.

When one considers the ionization rate coefficients of Table 6 it is clear that all thermospheric constituents play a role related to their concentration. If the precision of the ionization coefficient is not very high and if there is some uncertainty in the absolute value of the concentrations, it is possible to claim that the final electron concentration must be associated with an atomic ion such as  $\text{O}^+$  since the recombination is the essential process. But the principal difficulty in the determination of the vertical structure of the ionization comes from a lack of knowledge of the absolute values of the ionic reactions.

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