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La formation de la région D de l'ionosphère

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RESUME :

Les radiations solaires qui peuvent pénétrer jusqu'à des altitudes inférieures à 85 km sont les suivantes :

- (1) Rayons X de longueurs d'onde inférieures à 12 Å c'est-à-dire d'énergies supérieures à KeV.
- (2) La radiation Lyman-alpha de l'hydrogène à 1216 Å émise dans la chromosphère solaire
- (3) Les radiations de longueurs d'onde supérieures à 1800 Å

Ces diverses radiations peuvent ioniser respectivement :

- (1) Les molécules d'azote (N_2) et d'oxygène (O_2)
- (2) L'oxyde d'azote (NO)
- (3) Les ions métalliques (Na, Ca, Si, ...)

L'azote et l'oxygène moléculaire sont également ionisés par le rayonnement cosmique.

Le rapport des concentrations des ions négatifs aux électrons est important au-dessous de 70 km et influence la distribution verticale de la concentration électronique dans le domaine inférieur de la région D.

On montre comment les conditions normales d'ionisation s'expliquent par les rayons cosmiques et la radiation Lyman-alpha de l'hydrogène et comment les conditions au cours des éruptions solaires dépendent des rayons X observés au moyen de fusées. Au dessus de 85 km, le comportement de l'ionisation se rattache à celui de l'ionisation de la Région E.

I. Introduction

The complexity of studies pertaining to the D region of the ionosphere is due to difficulties in interpreting the observational data and to the fact that several sources of ionization are effective with regards to the different atmospheric constituents involved in region formation.

The ionization of the principal constituents, such as molecular nitrogen and oxygen, cannot be produced by ultraviolet radiation, since their ionization cross-sections, not less than 10^{-18} cm^2 , do not permit the penetration of such ionizing radiation below 100 km. The only ultraviolet radiations which can penetrate below 85 km must have a wave length greater than 1026.5 \AA , corresponding to the first ionization potential of O_2 . Furthermore, since the absorption cross section of O_2 in the Schumann-Runge Continuum beginning at 1750 \AA is more than 10^{-19} cm^2 between 1700 \AA and 1220 \AA , the penetration of solar radiation to sufficiently low altitudes can occur only in the atmospheric windows near 1216 \AA , 1187 \AA , 1167 \AA , 1157 \AA , 1143 \AA , and 1108 \AA for which unit optical depth is reached at about $10^{20} \text{ molecules cm}^{-2}$ of vertical column. This corresponds to an altitude of about 75 km for an overhead sun.

In the spectral range $2000-1800 \text{ \AA}$, the penetration of solar radiation is also possible between the bands of the Schumann-Runge system of O_2 . However, ionization by solar radiation for wave lengths longer than 1800 \AA requires constituents for which the ionization potential is very low,

such as sodium ($\lambda \leq 2413 \text{ \AA}$) and calcium ($\lambda \leq 2028 \text{ \AA}$). In the region $\lambda < 1220 \text{ \AA}$ only nitric oxide and metallic atoms have an ionization potential sufficiently low (9.25 eV) to be ionized by ultraviolet solar radiation. Since the absorption cross section of X-rays shorter than 10 \AA decreases rapidly from 10^{-19} cm^2 at 10 \AA to about 10^{-22} cm^2 at 1 \AA , this spectral range penetrates over the entire atmospheric region between 90 km and 60 km. In view of this, in addition to photons capable of ionizing nitric oxide and metallic atoms, X-rays in the range 1 to 10 \AA can contribute to the production of the ionization in the D region.

The lower part of the E layer, furthermore, can overlap with the ionization of the D region. It is known that X-rays of wave length of the order of 35 \AA , for which the absorption cross section is $1.3 \times 10^{-19} \text{ cm}^2$, can produce ionization down to 85 km. However, it can be shown that such radiations are not important below the mesopause level and need only be considered above 85 km. In fact, the ionospheric regions above 85 km must be associated with the formation of the E layer by radiations ionizing constituents for which the ionization cross-section is not less than 10^{-19} cm^2 .

In addition to the above mentioned sources of ionization in Region D, it is shown in this work that it is necessary to consider the effects of cosmic rays. Since the ionization produced by cosmic ray primaries corresponds to a production of between 100 and 300 ion pairs $\text{cm}^{-3} \text{ sec}^{-1}$ for

2.5×10^{19} molecules, between geomagnetic latitudes 40° and 60° , the cosmic ray ionization production is effective below 75 km.

It is the purpose of this work to discuss the ionization processes in Region D during both normal solar conditions and during solar flares.

II. The Ionization by Cosmic Rays

The ionization produced by normal cosmic ray primaries was considered by Nicolet (1958) using the ionization rates given by Van Allen (1952).

Let us designate $q_0(\Phi)$ as the ionization rate arising from cosmic ray primaries in the atmosphere of number density $n_0 = 2.5 \times 10^{19}$ molecules cm^{-3} at geomagnetic latitude Φ . Above 40km the ionization rate ($\text{sec}^{-1} \text{cm}^{-3}$) $q(\Phi)$ is given by

$$q(\Phi) = q_0(\Phi) \frac{n}{n_0} \quad (1)$$

in which n is the molecular concentration at the altitude z .

In order to determine the electron production due to cosmic rays, it is necessary to consider the variation of the effect with latitude and to assume that molecular oxygen and nitrogen have the same ionization coefficient. For example, assuming a mean production rate of 250 ion pairs $\text{cm}^{-3} \text{sec}^{-1}$ at 760 mm of Hg and 20°C , the production rate by cosmic ray primaries according to (1) is

$$q(\Phi = 50^\circ) = 10^{-17} n \text{ cm}^{-3} \text{sec}^{-1} \quad (2)$$

The variation with latitude (between $\Phi = 0^\circ$ and $\Phi = 60^\circ$) involves a variation of a factor of 10 in q ; namely between $1.2 \times 10^{-18} \text{ n cm}^{-3} \text{ sec}^{-1}$ and $1.2 \times 10^{-17} \text{ n cm}^{-3} \text{ sec}^{-1}$, that is to say a variation of a factor of 3 in the electron concentration. It should be remembered that conditions ought to be completely different in the auroral zone and "abnormal" ionization should be discussed in the same way that Bailey (1957, 1959) determined the effects of cosmic-ray flux enhancements in these latitudes. Even at intermediate latitudes some variation can be expected according to variations which have been detected by balloon observations of cosmic ray intensities. However, it is clear that, for normal conditions, we can use the ionization rate given by (2) on keeping in mind that the latitude effect will give a decrease of a factor of 3 from $\Phi (60^\circ)$ to the magnetic equator and an increase which will be of importance in the auroral zone.

The recombination, α , must result from different processes of electron loss, and it is necessary to determine all processes which are involved in the variation of electron and ion densities. Since there are multiple processes of electron production and different loss mechanisms with differing recombination coefficients, the recombination must be determined when all ionized constituents and processes are known.

III. The Ionization by X-Rays

The principal atmospheric constituents which can be involved in ionization by x-rays of $\lambda < 10 \text{ \AA}$ are N_2 , O_2 , and A . Atomic oxygen need not be considered in the mesosphere

since it corresponds to a small fraction of O_2 , but may play a particular role in the lower thermosphere. The ionization cross sections can be deduced from the experimental data of Woernle (1930), Messner (1933), Lindh and Nilloson (1945), and Victoreen (1949). Table I gives the absorption cross sections corresponding to a photoelectric absorption to which is associated the scattering effect. The production of electrons by X-rays is due to two different processes. The first is the normal photoelectric effect in which a photon of energy $h\nu$ is absorbed by an atom which then releases an electron with a certain kinetic energy depending on the ionization potential. In such a process the entire energy of the photon is involved in the ionization process. In addition, the use of the K radiation lines inside the atom can remove other electrons from the same atom (Auger effect) or from another atom (additional photoelectrons of low energy). Several photoelectrons can be produced by a direct photoelectric effect, but the production per photon is limited to a few electrons.

The other ionization process is due to the Compton effect in which the recoil electron comes from the upper levels of the atoms. Since the ratio of photoelectrons and recoil electrons must be, as a first approximation, equal to the ratio of the absorption and scattering cross sections, it is certain that for $\lambda > 1 \text{ \AA}$ the scattered electrons can be neglected in comparison with the photo-electrons. But at $\lambda = 0.1 \text{ \AA}$, the ratio in nitrogen is of the order of 120.

Table I Absorption Cross-Sections (cm^2) between 0.1 $\overset{\circ}{\text{A}}$ and 10 $\overset{\circ}{\text{A}}$

λ	N_2	O_2	A	Air
0.1	6.64×10^{-24}	7.65×10^{-24}	1.09×10^{-23}	6.89×10^{-24}
0.12	7.02	8.12	1.31	7.30
0.15	7.54	8.81	1.77	7.90
0.20	8.40	1.01×10^{-23}	2.96	8.45
0.25	9.36	1.16	4.86	1.02×10^{-23}
0.3	1.07×10^{-23}	1.39	7.66	1.20
0.4	1.45	2.03	1.66×10^{-22}	1.71
0.5	2.04	3.06	3.10	2.52
0.6	2.91	4.59	5.23	3.72
0.8	5.71	9.51	1.20×10^{-21}	7.56
1.0	1.03×10^{-22}	1.76×10^{-22}	2.27	1.38×10^{-22}
1.2	1.71	2.95	3.83	2.31
1.5	3.23	5.63	7.18	4.37
2.0	7.47	1.31	1.59×10^{-20}	1.01×10^{-21}
2.5	1.44×10^{-21}	2.51	2.90	1.92
3.0	2.46	4.29	4.67	3.26
3.8			9.71×10^{-20}	
4.0	5.73	9.93	1.10×10^{-20}	6.55
5.0	1.10×10^{-20}	1.90×10^{-20}	1.93	1.26×10^{-20}
6.0	1.87	3.20	3.09	2.13
8.0	4.27	7.22	6.23	4.85
10	8.05×10^{-20}	1.34×10^{-19}	8.37×10^{-20}	9.09×10^{-20}

In order to compute the efficiency of the ionization by X-rays of $\lambda < 10 \text{ \AA}$, we consider the average energy W required to produce one ion pair. Since the thresholds of ionization of O_2 and N_2 are about 530 eV and 400 eV, respectively, the average energy removed from the photo-electron is taken as 500 eV and the kinetic energy of the electron as $1/2 mv^2 = X - 500$, where X denotes the energy of the incident photon; namely 2 KeV at 6.2 \AA , 3 KeV at 4.13 \AA and 6 KeV at 2.06 \AA . It is clear that the limiting value of W is infinite at zero energy. Dalgarno and Griffing (1958) have shown that the average energy per ion pair for electrons in atomic hydrogen is constant for energies above 200 eV and increases rapidly as the energy falls below 60 eV. Therefore, an average energy expenditure can be taken for air as determined by experimental methods. The value adopted is 35 eV (see J. M. Valentine and S. C. Curran, 1958). Consequently, the following approximate numbers have been adopted for the number of electrons produced per photon (ionization efficiency).

λ $\overset{\circ}{\text{\AA}}$	λ $\overset{\circ}{\text{\AA}}$	λ $\overset{\circ}{\text{\AA}}$
Efficiency 45	75	165

Data on solar X-rays have been obtained by Friedman and his collaborators (1958) from rocket measurements during solar flares and during normal solar conditions. Their results show that solar X-ray radiation must contribute to the ionization of the D region; particularly during solar flares. In

fact, the effect of solar X-rays was considered as a possibility 25 years ago, for instance by Müller (1935), but it was necessary to have rocket observations in order to show that an adequate intensity of such radiations was available for the production of ionization below 85 km. Considering the published data (Friedman and Chubb, 1955 ; Byram, Chubb and Friedman, 1956; Chubb, Friedman, Kreplin and Kupperian, 1957), it is possible to determine the energy available in the X-ray spectrum for various solar conditions. Results of an analysis of observational data are shown in Table II for three, approximate, wave lengths. The spectral range between 10 Å and 1 Å has been subdivided into three ranges for which the absorption cross sections (see Table I) are $1.0 \times 10^{-21} \text{ cm}^2$ at 2 Å, $6.6 \times 10^{-21} \text{ cm}^2$ at 4 Å and $2.1 \times 10^{-20} \text{ cm}^2$ at 6 Å. Such

Table II Variations in the X-ray intensities according to various solar conditions. Energies in $\text{erg-cm}^{-2}\text{-sec}^{-1}$.

	2 Å	4 Å	6 Å
Completely quiet sun	10^{-8}	10^{-7}	10^{-6}
Quiet sun	10^{-7}	10^{-6}	10^{-5}
Lightly disturbed	10^{-6}	10^{-5}	10^{-4}
Disturbed	10^{-5}	10^{-4}	10^{-3}
Special events (flares)	10^{-4}	10^{-3}	10^{-2}
Strong flares	10^{-3}	10^{-2}	10^{-1}

a simplification is acceptable in that it corresponds to a variation of a factor of 10 in the energy and to a sufficient approximation to cover the entire spectral range between 1.5 Å and 8 Å. However, it is also necessary to

consider emissions of $\lambda \leq 1 \text{ \AA}$, which are particularly important during strongly disturbed conditions, (Chubb and Friedman, private communication 1959; Peterson and Winckler, 1959). For example, an observation of Peterson and Winckler (1959) during a solar flare leads to a production of the order of 0.1 to 0.5 electrons $\text{cm}^{-3} \text{ sec}^{-1}$ near 30 km. High ionization rates at such short wave lengths do not correspond to the radiation deduced from the ionization of the solar corona, for Elwert's computation (1956) deals only with the emission of coronal lines.

The effective ionization rate coefficient can be determined by using the data of Table II together with the absorption cross section and the efficiency of ionization. Table III shows the various ionization coefficients for zero optical depth according to various solar conditions. They represent relative ionization rates per unit of energy in the spectral ranges 1.5 to 3.3 \AA , 3.3 to 5 \AA , 5 to 8 \AA of 1, 2.5×10^2 and 10^4 ; respectively. Values of Table II will be used to compute the ionization rates by X-ray radiation versus altitudes above 60 km.

	Ionization Coefficients (per molecule sec^{-1})		
	2 \AA	4 \AA	6 \AA
Completely quiet sun	1.6×10^{-19}	9.8×10^{-18}	2.8×10^{-16}
Quiet sun	1.6×10^{-18}	9.8×10^{-17}	2.8×10^{-15}
Lightly disturbed	1.6×10^{-17}	9.8×10^{-16}	2.8×10^{-14}
Disturbed	1.6×10^{-16}	9.8×10^{-15}	2.8×10^{-13}
Special events	1.6×10^{-15}	9.8×10^{-14}	2.8×10^{-12}
Strong flares	1.6×10^{-14}	9.8×10^{-13}	2.8×10^{-11}

IV. The Ionisation by Lyman-Alpha

The chromospheric radiation Lyman-Alpha at 1215.7 Å is an important solar emission which was proposed by Nicolet (1945) as leading to the ionization of nitric oxide.. Lyman-alpha is in the spectral range (9.25 eV - 12 eV) situated between the ionization and dissociation continua of molecular oxygen and, in particular, in an atmospheric window for which the absorption cross section is $1 \times 10^{-20} \text{ cm}^2$ for molecular oxygen; according to Watanabe, Inn and Zelikoff (1953). Other experimental determinations, such as those made earlier by Preston (1940), lead to the same value while others like those of Lee (1955) and Ditchburn, Bradley, Cannon and Munday (1954) give $8.5 \times 10^{-21} \text{ cm}^2$. In any event, due to such a low value, Lyman-alpha can penetrate to 75km as was observed by Byram, Chubb, Friedman and Gailar (1953). Its energy now appears to have been determined with an acceptable precision and is between 3 and 6 ergs $\text{cm}^{-2} \text{ sec}^{-1}$. In fact, in measurements before 1955 (see Byram, Chubb, Friedman, Kupperian 1958), values as low as 0.1 erg $\text{cm}^{-2} \text{ sec}^{-1}$ were given. In spite of low solar activity, it should be accepted that values greater than 1 erg $\text{cm}^{-2} \text{ sec}^{-1}$ correspond to the real incident flux. Recent spectroscopic observations by Tousey (private communications) and by Rense (private communication) lead to 5 and 3 erg $\text{cm}^{-2} \text{ sec}^{-1}$. A value of 3 erg $\text{cm}^{-2} \text{ sec}^{-1}$ will be considered in our computations.

Since the mechanism was proposed by Nicolet (1945), Bates and Seaton (1950) have set forth reasons indicating why it is difficult to consider other alternative ionizations due to ultraviolet solar radiation. The experimental values of the absorption and ionization cross sections of NO have been determined by Watanabe (1954). At Lyman-alpha, the ionization cross section of nitric oxide is $2 \times 10^{-18} \text{ cm}^2$ while the absorption cross section is $2.4 \times 10^{-18} \text{ cm}^2$.

Negative results of nitric oxide absorption measurements in the atmosphere set upper limits to its concentration. A recent analysis by Jursa, Tanaka and LeBlanc (1959) of the solar spectrum leads to the conclusion that the concentration of nitric oxide in the altitude interval 63 to 87 km cannot exceed $10^8 \text{ molecules cm}^{-3}$, since the bands of its electronic system are not observed. Such a low value shows that the determination by Mitra (1954) of $10^{12} \text{ molecules cm}^{-3}$ is not acceptable by a factor of more than 10^4 , and consequently his resulting D layer model likewise cannot be accepted. The estimation made by Nicolet (1955), which was based on the then available, low, published value of $0.1 \text{ erg cm}^{-2} \text{ sec}^{-1}$ for Lyman-alpha led to a high value of the order of $10^8 \text{ molecules cm}^{-3}$ at 80 km. A recent analysis of the photochemistry of nitric oxide made by Nicolet (1958) shows that the concentration of nitric oxide at 85 km is about 10^{-10} of the total concentration; namely $10^4 \text{ molecules cm}^{-3}$.

Such a low concentration is far below the value which can possibly be detected by spectrographic methods. The vertical distributions of nitric oxide will not be discussed here but the values obtained by Nicolet (unpublished) will be used for the computation of the ionization by Lyman-alpha. In the computations this radiation will be kept constant even though it is possible that it can vary by a factor 2 with solar activity. Consequently, the photo-ionization rate coefficient of nitric oxide at zero optical depth is taken as $3.6 \times 10^{-7} \text{ sec}^{-1}$.

V. The Ionization by Radiation of $\lambda > 1750 \text{ \AA}$

From laboratory measurements, absorption in cross sections near the threshold can be obtained for Na (Ditchburn, Jutsum and Marr, 1953) and for Ca (Jutsum, 1954). At zero optical depth, the photo-ionization rate coefficients (Nicolet 1955) are $1.1 \times 10^{-5} \text{ sec}^{-1}$ and 10^{-6} sec^{-1} for Na and Ca; respectively. These high ionization rate coefficients show that very small concentrations are needed to produce appreciable electron densities at low levels by radiation of $\lambda < 2413 \text{ \AA}$ or $\lambda < 2018 \text{ \AA}$.

VI. The Ionization of Atomic Oxygen

Atomic oxygen cannot be ionized in the D region by solar radiation of $\lambda < 910 \text{ \AA}$, corresponding to its threshold, since molecular oxygen essentially absorbs all of this radiation above 100 km. However, the peak concentration of atomic oxygen is below 100 km and its concentration in the

mesosphere is associated with the ozone concentration. Above 50 km, $n(O) > n(O_3)$, increases with altitude and is not less than 10^{11} atoms cm^{-3} above 65 km in a sunlit atmosphere. At 80 km, a concentration of more than 10^{11} cm^{-3} is maintained even in a dark atmosphere (Nicolet, 1958). Therefore, x-rays can ionize atomic oxygen and its ionization rate coefficient is $3/4$ of the values which are given in Table III. The importance of the ionization of atomic oxygen in the present connection is that it leads to the production of NO^+ by the ion interchange reaction between O^+ and N_2 . Constituents such as Na and Ca, and also O, are possibly important with regards to sporadic effects and nocturnal ionization above 85 km.

VII. The Vertical Distribution of Constituents and Absorption Peaks

In order to study the behavior of the ionization in the D region it is necessary to adopt an atmospheric model. The atmospheric data are taken from tables computed by Nicolet (1959) on the basis of rocket observations. Table IV shows the height variation of the numbers of molecules cm^{-3} and molecules cm^{-2} of a vertical column. These data permit the computation of the ionization rate for various radiations by using the following formula:

$$n_j I_j \infty e^{-Z n_j K_j H \sec \chi} \quad (3)$$

Table IV Atmospheric Data Between 50 and 90 km

Altitude (km)	Temp (°K)	n(O ₂) (cm ⁻³)	n(NO) (cm ⁻³)	n(N ₂)* (cm ⁻³)	n(M)H (cm ⁻²)
50	274	4.93x10 ¹⁵	2.35x10 ⁶	1.83x10 ¹⁶	1.9x10 ²²
52.5	274	3.63	1.73	1.35	1.4
55	274	2.68	1.28	9.97x10 ¹⁵	1.0
57.5	263	2.04	9.72x10 ⁵	7.58	7.6x10 ²¹
60	253	1.53	7.31	5.70	5.5
62.5	242	1.14	5.43	4.24	3.9
65	232	8.35x10 ¹⁴	3.99	3.11	2.8
67.5	221	6.05	2.89	2.25	1.9
70	210	4.31	2.06	1.61	1.3
72.5	207	2.94	1.40	1.09	8.7x10 ²⁰
75	203	1.99	9.48x10 ⁴	7.40x10 ¹⁴	5.8
77.5	200	1.34	6.38	4.98	3.8
80	197	8.93x10 ¹³	4.26	3.24	2.5
82.5	193	5.93	2.83	2.21	1.6
85	190	3.90	1.86	1.45	1.1
87.5	191	2.48	1.83	9.24x10 ¹³	6.9x10 ¹⁹
90	192	1.59x10 ¹³	1.39x10 ⁴	5.93x10 ¹³	4.5x10 ¹⁹

* n(N₂) = 0.7808, of the total concentration n(M)

where the indice j denotes the constituents of species j , $I_{j\infty}$ is the ionization rate coefficient for the zero unit optical depth and the exponential term corresponds to the fraction which is not yet absorbed at the altitude considered; it is the optical depth τ_λ for an overhead sun multiplied by the solar zenith distance χ .

X-rays are absorbed by N_2 and O_2 and the optical depth τ_λ is

$$\tau_\lambda = n(M) K_\lambda(M) H \quad (4)$$

in which $n(M)$ is the total number of particles, $K_\lambda(M)$ the absorption cross section for air, and H the atmospheric scale height. Lyman-alpha is absorbed by O_2 and the optical depth

τ_λ is

$$\tau_\lambda = n(O_2) K_\lambda(O_2) H$$

in which $n(O_2)$ is the concentration of molecular oxygen, and $K_\lambda(O_2)$ the absorption cross sections of O_2 . The unit optical depths for an overhead sun are as follows:

	°	°	°	°
λ	2 Å	4 Å	6 Å	1216 Å
Altitude	70 km	80 km	87 km	75 km

The electron production peak is obtained by differentiating (3) and corresponds to the condition

$$\sum n_j K_j H = (1 + \beta) \sec \chi \quad (5)$$

in which $\beta = dH/dz$ is the gradient of the scale height H . Since β is small, at the height levels of interest, the altitude of the electronic production peak is approximately the

altitude of unit optical depth. From these data it is clear that the ionization by Lyman-alpha occurs in the range of altitudes where the ionization by X-rays between 2 and 4 A is produced.

VIII. Equation of Ionization

The conventional equation of ionization is

$$\frac{dn_e}{dt} = q - \alpha n_e^2 \quad (6)$$

in which q is an equivalent production of electrons, n_e , and α denotes an equivalent recombination coefficient or recombination. Since the recombination is very high in the D region the ionization conditions can be found by determining the ionization equilibrium given as

$$n_e^2 = q/\alpha \quad (7)$$

Furthermore, since various constituents and various spectral ranges are involved in the electron production, q must be written

$$q = \sum q_j \quad (8)$$

in which q_j represents one of the n contributions, $j = 0, 1, \dots, n$, to the electron production. Also, the recombination α is due to all effects of recombination and it is necessary to define a specific recombination, α_j ,

$$q_j = \alpha_j n_j^+ n_e \quad (9)$$

in which n_j^+ is the positive ion of the constituent j .
According to (9), equation (7) must be replaced by

$$\frac{q_1}{\alpha_1 n_1^+} = \frac{q_2}{\alpha_2 n_2^+} = \dots = \frac{q_n}{\alpha_n n_n^+} = n_e \quad (10)$$

or

$$Z \frac{q_j}{\alpha_j} = n_e Z n_j^+ \quad (11)$$

Since $n^+ = n^- + n_e$ (12)

and writing $\frac{n^-}{n_e} \equiv \lambda$ and $n^+ = (1 + \lambda) n_e$ (12')

equation (11) can be written as follows:

$$(1+\lambda) n_e^2 = Z \frac{q_j}{\alpha_j} \quad (13)$$

instead of the conventional equation (7). It will be noted that the recombination α is different ($\lambda > 1$) from a recombination α_e between positive ions and electrons

$$\alpha n_e^2 \equiv \alpha_e (1+\lambda) n_e^2 \equiv Z q_j \quad (14)$$

α_e corresponds to an equivalent production function, $Zq_j/(1+\lambda)$.

IX. Negative Ions

The determination of the value of λ , the ratio of negative ions to electrons, has been the subject of many papers. Recently Mitra (1959) deduced a general expression for the recombination. However, his determination must be rejected in that it leads to wrong values for λ .

It is necessary to consider the physical parameters which ~~has~~ been determined in the laboratory. First, Branscomb, Busch, Smith and Geltman (1958) determined the photodetachment cross section of electrons from the negative ion of atomic oxygen and the radiative attachment of electrons to oxygen atoms. At the low values of electron energies corresponding to the atmospheric temperatures in Region D, the attachment coefficient $a(0)$, is

$$a(0) = 1.3 \times 10^{-15} \text{ cm}^3 \text{ sec}^{-1} \quad (15)$$

The photodetachment rate coefficient, $d(0)$, is

$$d(0^-) = 1.4 \text{ sec}^{-1} \quad (16)$$

according to the value for the threshold equal to $1.465 \pm 0.05 \text{ eV}$; corresponding to a wave length of $0.846 \pm 0.003 \mu$. According to (15) and (16), and since $n(0) \leq 10^{13} \text{ cm}^{-3}$ in the D region, it is clear that

$$\lambda(0^-) < 10^{-2} \quad (17)$$

and that negative ions of atomic oxygen can be neglected.

The photodetachment of electrons from O_2^- was studied by Burch, Smith and Branscomb (1958) and leads to a photodetachment rate coefficient, $d(O_2)$,

$$d(O_2) = 0.44 \text{ sec}^{-1} \quad (18)$$

The attachment of slow electrons in molecular oxygen is a three-body attachment according to Chanin, Phelps and Biondi (1959). Since the third body in the atmosphere is also molecular oxygen, and temperature variations can be neglected, the attachment coefficient of electrons to molecular oxygen is taken as

$$a(O_2) = 1.5 \times 10^{-30} n(O_2) \text{ cm}^3 \text{ sec}^{-1} \quad (19)$$

From (18) and (19), the ratio λ is given by

$$\lambda = \frac{1.5 \times 10^{-30}}{0.44} n^2(O_2) \quad (20)$$

Such a value of λ can be used down to 60km, even if collisional detachment reaches a value of $4 \times 10^{-17} \text{ cm}^3 \text{ sec}^{-1}$ and (20) therefore represents the equilibrium ratio between negative ions and electrons in a sunlit atmosphere. Its value between 60km and 90km varies as follows:

Altitude (km)	60	70	80	90
λ	7.5	0.63	0.03	8.6×10^{-4}

Figure 1 shows the variation of $\lambda = n^-/n_e$ and $(1+\lambda) = n^+/n_e$ between 60km and 90km.

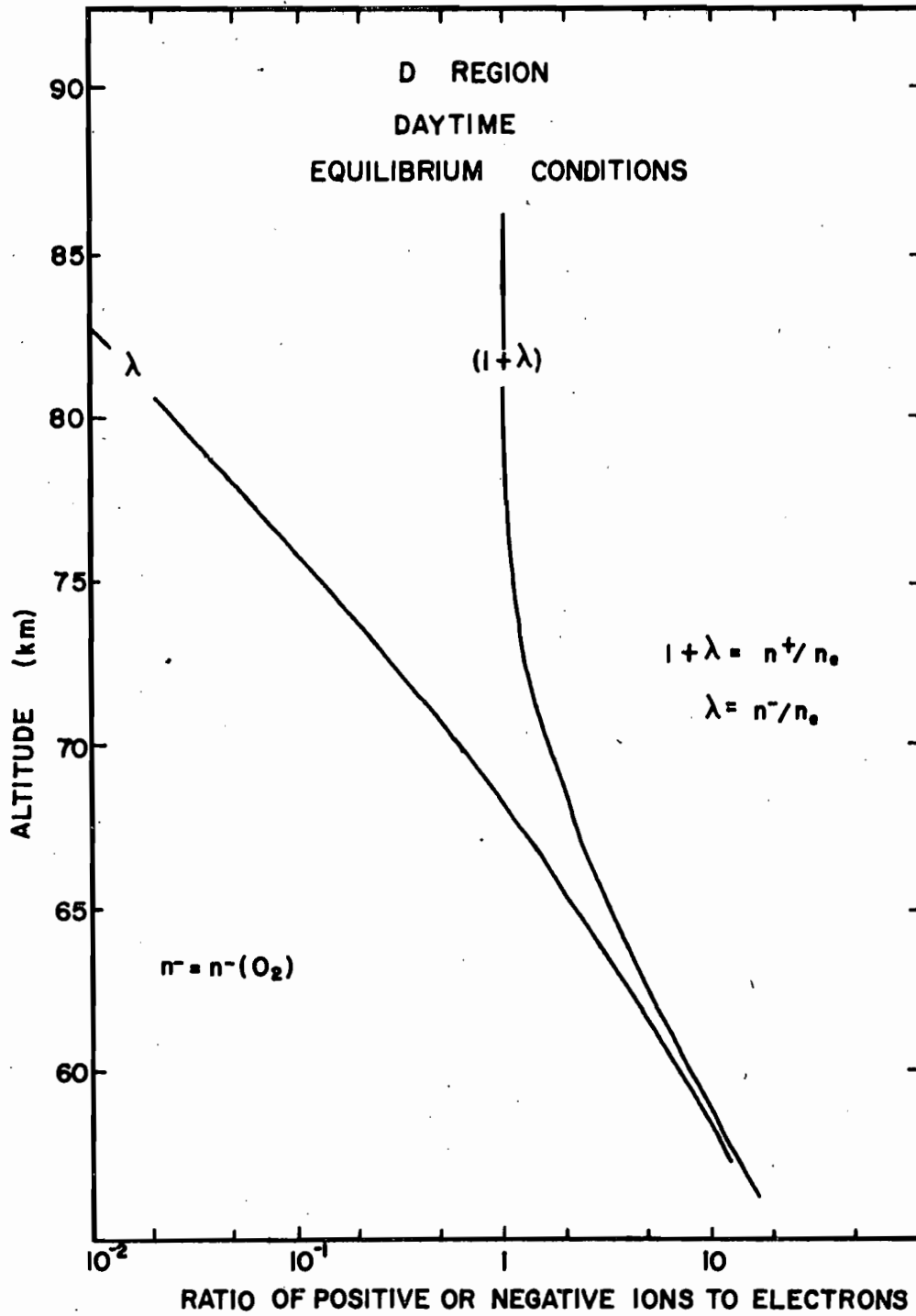


FIGURE 1

Since the value of $\lambda \leq 0.03$ above 80km, it is clear that the conventional equation (6) can be written

$$\frac{dn_e}{dt} = q - \alpha_e n_e^2 = \Sigma q_1 - \alpha_e n_e^2 \quad (21)$$

in which q is the real production function of electrons. α_e now becomes the real recombination since $n^+ \simeq n_e$. But, below 80km the conventional equation must be written

$$\frac{dn_e}{dt} = \frac{\Sigma q_1}{1+\lambda} - \alpha_e n_e^2 - \frac{n_e}{1+\lambda} \frac{d\lambda}{dt} \quad (22)$$

If it is assumed that processes dealing with attachment and detachment of electrons are very rapid, $d\lambda/dt$ equals zero. Under such conditions,

$$\frac{dn}{n} = \frac{dn_e}{n_e} \quad (23)$$

and, therefore, (22) can be written as follows:

$$\frac{dn_e}{dt} = \frac{\Sigma q_1}{1+\lambda} - \alpha_e n_e^2 \quad (24)$$

and (24) is the practical equation for the variation of the electron concentration.

X. The Recombination Coefficient

The equivalent recombination, α_e , of equation (24) cannot be determined without a complete analysis of all processes, since several radiations produce the ionization of various constituents in the D region. An adoption of empirical values deduced from radio data cannot be used since such values currently deal with estimates which are very uncertain. The values of α_e are not necessarily constant throughout the day nor should they vary according to the modifications of the layer shape with time. An average curve, such as that of Mitra (1959), is not acceptable since the difference between the observational data quoted and the mean values adopted are too large.

The calculations made by Houston (1958) using, for nitric oxide, a varying recombination from about $5 \times 10^{-6} \text{ cm}^3 \text{ sec}^{-1}$ at 60km to $10^{-6} \text{ cm}^3 \text{ sec}^{-1}$ near 70km and $10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ near 90km leads to an artificial distribution of the ionization. In fact, such a vertical distribution of the electron density corresponds to any arbitrary minor constituent for which the optical depth is given by the absorption distribution of O_2 and N_2 subject to the law of recombination which has been assumed.

In order to determine the recombination we may consider the ionization of a constituent, the total ionization being given by equation (13).

The equation for positive ions of species j is

$$\frac{dn_j^+}{dt} = q_j - \alpha_{D,j} n_j^+ n_e - \alpha_{i,j} n_j^+ n^- \quad (25)$$

in which $\alpha_{D,j}$ denotes the recombination coefficient of positive ions with electrons and $\alpha_{i,j}$ is the recombination coefficient of positive ions with negative ions. Equation (25) can be written in the following form since there is only one negative ion to be considered (see Section IX).

$$\frac{dn_j^+}{dt} = q_j - (\alpha_{D,j} + \lambda \alpha_{i,j}) n_j^+ n_e \quad (26)$$

However, (26) cannot be written in the practical form of (24) since $n_j^+ < n^+$. In fact, (24) must be equivalent to

$$Z \frac{dn_j^+}{dt} = Z q_j - n_e Z (\alpha_{D,j} + \lambda \alpha_{i,j}) n_j^+ \quad (27)$$

or

$$\frac{dn_e}{dt} = \frac{Z q_j}{1+\lambda} - \frac{n_e}{1+\lambda} Z (\alpha_{D,j} + \lambda \alpha_{i,j}) n_j^+ \quad (28)$$

Bates (1950) has shown that dissociative recombination is a process occurring at a much faster rate than other recombination processes involving electrons. Experimental determinations have been made and the recombination of the molecular ion of nitrogen has been recently studied by Bialecke

and Dougal (1958) and Faire and Champion (1959). Such determinations lead to a coefficient as high as $5 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ for N_2 in D region. As far as molecular oxygen is concerned the experimental analysis is not yet complete. However, Sayers (1956) gave a value of the order of $4 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$. Nitric oxide ions are certainly an important ionospheric constituent, but their dissociative recombination coefficient is not known. Considering that such an ion should have a long lifetime, its recombination will be considered to be 10 times lower than that of molecular oxygen. Therefore, we have adopted for a quantitative treatment the following values:

$$\alpha_D(\text{N}_2) = 5 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}; \quad \alpha_D(\text{O}_2) = 3 \times 10^{-8}; \quad \alpha_D(\text{NO}) = 3 \times 10^{-9}$$

It is not possible to estimate the value of the coefficients with assurance since they are temperature dependent. However, we believe that the ratios for N_2 , O_2 and NO are not far from 100:10:1.

Ionic recombination, α_i , has been considered as an important process since Bates and Massey (1946) gave potent arguments for its inclusion. It can have a value as high as $10^{-7} \text{ cm}^3 \text{ sec}^{-1}$. Such a value has been adopted as a working value for all constituents.

With the adoption of numerical values for α_i and α_D all the information required to complete the resulting distribution of the electron concentration has been obtained.

Equation (10) has been used as follows:

$$\frac{q(N_2)}{(10^{-7}\lambda + 5 \times 10^{-7})n^+(N_2)} = \frac{q(O_2)}{(10^{-7}\lambda + 3 \times 10^{-8})n^+(O_2)} = \frac{q(NO)}{(10^{-7}\lambda + 3 \times 10^{-9})n^+(NO)}$$

$$= n_e \quad (30)$$

and together with equation (13), leads to the determination of the electron concentration. However, it must be pointed out that the values which have been adopted, for example for NO, may be too high and, therefore, some inconsistency may occur in our results owing to the fact that only one value has been adopted for α_1 . But, even a value such as $\alpha_1(NO) = 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$ will not change our arguments.

XI. Ionization for a Quiet Sun

We have determined all values of the various quantities in equation (13) assuming that O_2 , N_2 and NO are the constituents ionized by cosmic radiation, x-rays and Lyman-alpha. Figure 2 shows the vertical distribution of the electron concentration n_e from 60km to 90km for an overhead sun; n_e increases from about 100 electrons cm^{-3} at 60km to a peak of about 1500 electrons cm^{-3} at 80km. Above 85km, the electron concentration would decrease if the tail of the E layer were not involved. It will be shown in another publication that the ionization of the E layer by x-rays of wavelength 30-35 Å

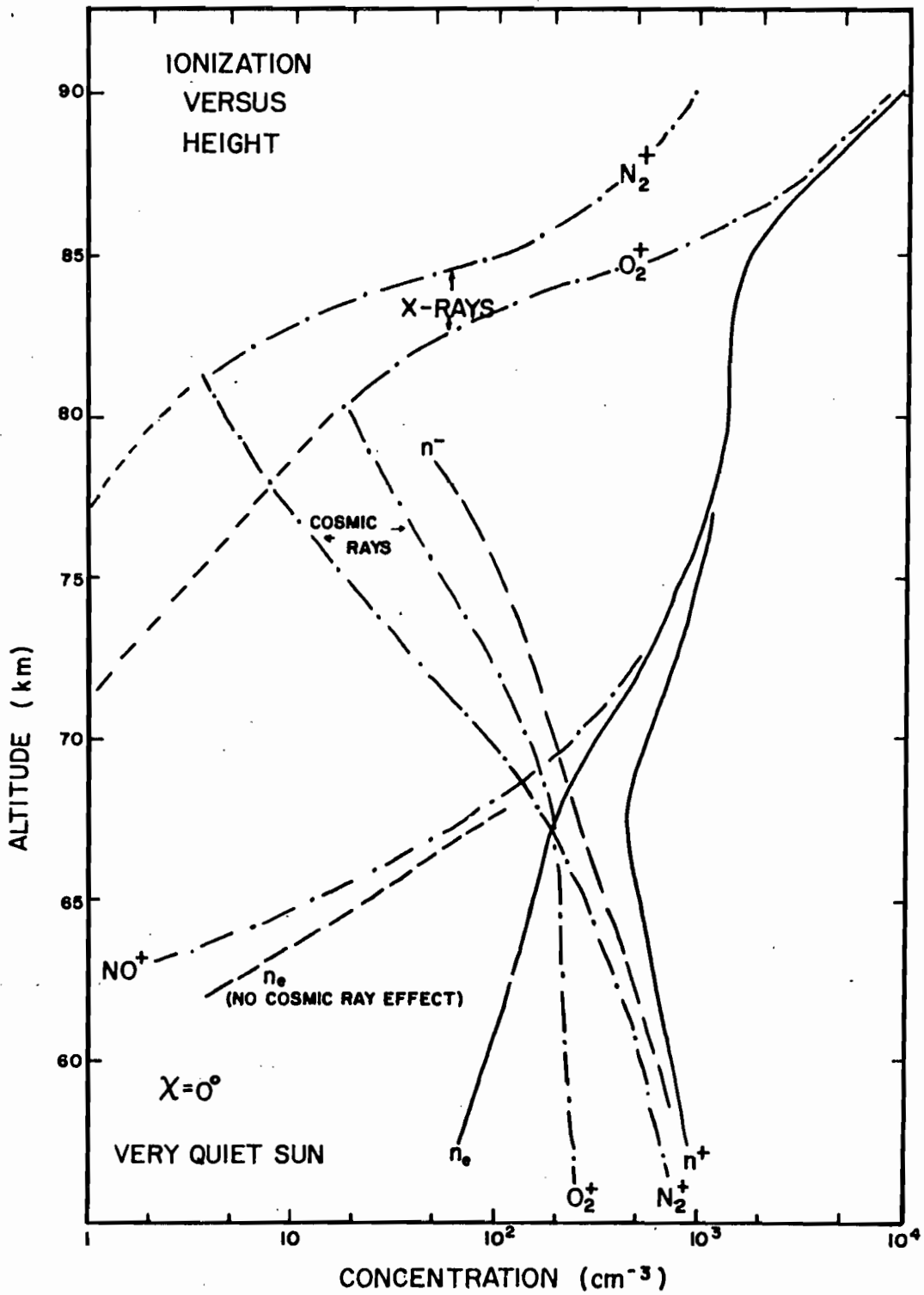


FIGURE 2

is effective downwards to 85km for an overhead sun. In order to show the effect of the electron attachment, two curves giving the vertical distributions of positive ions and of the negative ion of molecular oxygen are given. Negative ions in a sunlit atmosphere are important in the lower part of the D region up to 70km and are negligible at 80km. The simultaneous effect of cosmic rays, x-rays and Lyman-alpha is shown by curves giving the vertical distribution of N_2^+ , O_2^+ and NO^+ .

Below 65km, due to the adaption of the same ionic recombination coefficient for all constituents, N_2^+ is the most important ion as N_2 is the most important constituent. Above 70km, $n^+(O_2) > n^+(N_2)$, since the dissociative recombination coefficient, $\alpha_D(O_2)$, is less than $\alpha_D(N_2)$. It is also clear that ionization by X-rays does not play a role below 80km when the sun is quiet. The number of positive ions N_2^+ and O_2^+ due to X-rays is negligible. Table V shows values of the product n^+n_e at three particular altitudes; namely 60km, 70km and 80km. From this table it is clear that cosmic rays are the principal radiations causing ionization at 60km and that Lyman-alpha plays the important role at 80km.

As far as the altitude of 70km is concerned, the ionization production is contributed by NO^+ , ionized by Lyman-alpha, and O_2^+ and N_2^+ , due to cosmic rays. Since the cosmic ray production rate in our computation corresponds to a geomagnetic latitude of about 50° , there will be a variation

with latitude near 70km where the total ionization is very sensitive to fluctuations of the nitric oxide concentration and the intensity of cosmic rays. It is easy to obtain latitude corrections by taking into account the variation of the production function which varies by a factor 10 between the equator and $\Phi = 60^\circ$.

Table V. n^+n_e at 60, 70 and 80 km

Altitude: 60 km	Cosmic Rays	X-rays	Lyman α
$n^+(O_2)n_e$	2.1×10^4	1.8×10^1	
$n^+(N_2)n_e$	4.7×10^4	2.3×10^1	
$n^+(NO)n_e$			3.6×10^4
Totals	6.8×10^4	4.1×10^1	3.6×10^4
Total	$6.8 \times 10^4 \text{ cm}^{-6} = (1+\lambda)n_e^2$		
Altitude: 70 km	Cosmic Rays	X-rays	Lyman α
$n^+(O_2)n_e$	4.6×10^4	2.8×10^2	
$n^+(N_2)n_e$	2.9×10^4	9.9×10^1	
$n^+(NO)n_e$			7.9×10^4
Totals	7.5×10^4	3.8×10^1	7.9×10^4
Total	$1.54 \times 10^5 \text{ cm}^{-6} = (1+\lambda)n_e^2$		
Altitude: 80 km	Cosmic Rays	X-rays	Lyman α
$n^+(O_2)n_e$	2.7×10^4	2.1×10^4	
$n^+(N_2)n_e$	6.6×10^3	2.9×10^3	
$n^+(NO)n_e$			1.8×10^6
Totals	3.4×10^4	2.4×10^3	1.8×10^6
Total	$1.8 \times 10^6 \text{ cm}^{-6} = (1+\lambda)n_e^2$		

The effect of cosmic rays is shown in Figure 3 by the difference between the curves representing electrons concentrated below 70km. The minimum electron concentrations should be due the ionization of Lyman-alpha alone, considering that there is a negligible effect due to cosmic rays. Nevertheless, the gradient of 100 electrons cm^{-3} per km between 70km and 75km is due only to the effect of nitric oxide and it is not affected by the cosmic ray effect.

An essential part of the result is also the fact that there is a peak in the electron concentration between 80km and 85km. This peak, deduced for an overhead sun, will very nearly remain in the same range of altitudes when the solar zenith angle is between $\chi=0$ and $\chi=75^\circ$. The vertical distributions of the ionization is shown in Figure 3 and it is clear that the reflection level for 75 kc/s radio waves, corresponding to 300 electrons cm^{-3} which is at 70km for an overhead sun, goes up to about 75km for $\chi=70^\circ$. Near sunrise, equilibrium conditions for $\chi \geq 80^\circ$ must be studied in considering the time-variation due to the rapid change of production after sunrise and the value of the effective recombination before sunset.

XII. Ionization During Solar Flares

Considering that the variation of Lyman α cannot be more than a factor of 4, and that of cosmic rays not more than a factor of 2, except for exceptional events, it is only necessary to study the variations of X-rays in determining solar flare effects. As is easily seen, there is

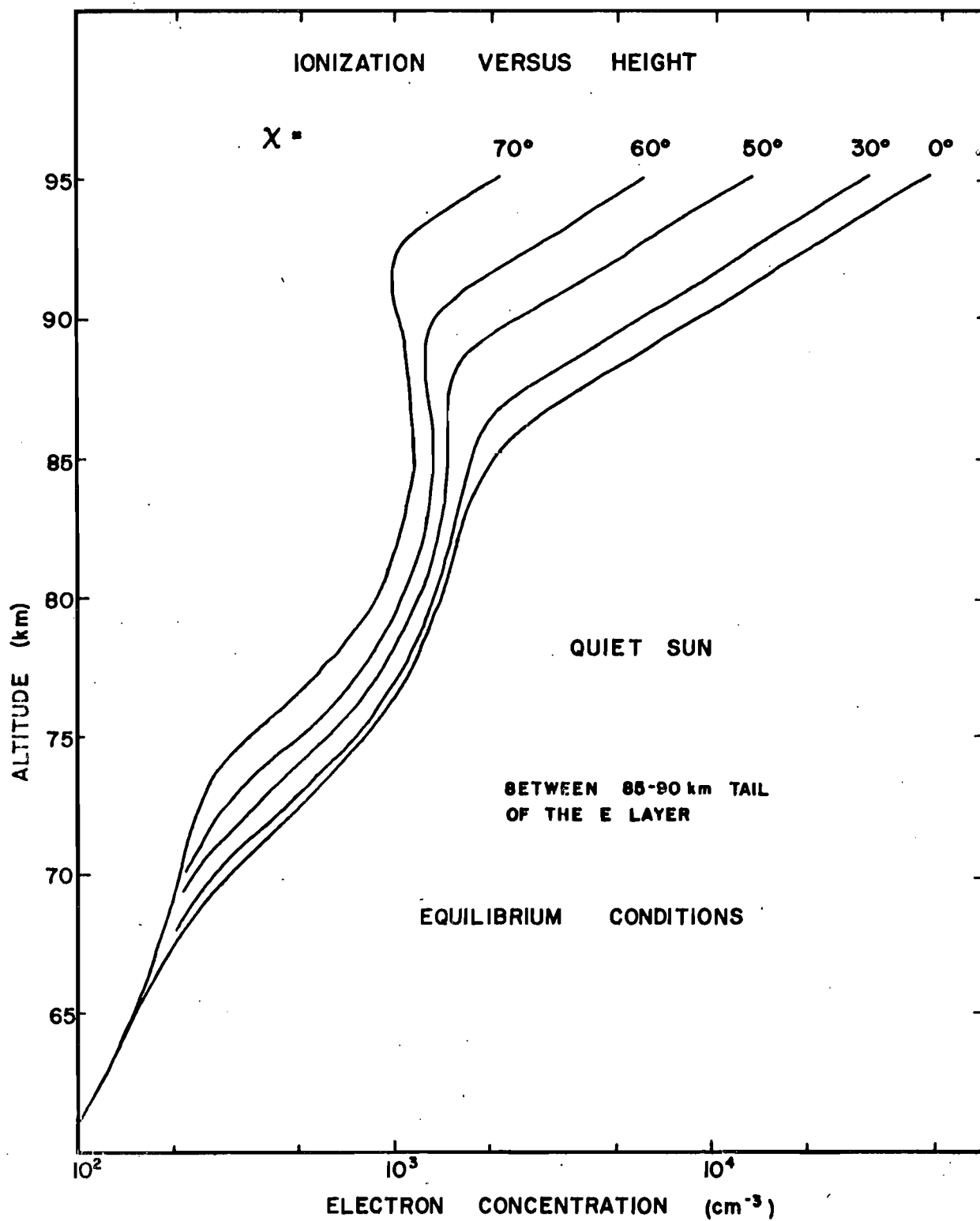


FIGURE 3

practically no difference in the electron concentration of the D region, if the sun is considered completely quiet or quiet from the values given in Table II. The conditions, for a lightly disturbed sun, for which the X-ray energies are 10^{-6} , 10^{-5} and 10^{-4} ergs $\text{cm}^{-2}\text{sec}^{-1}$ at 2, 4 and 6 Å, respectively, result in a small effect on the vertical distributions of the ionization below 80 km.

Figure 4 shows how these effects occur when the sun is overhead. The activity of X-rays becomes readily apparent when energies are between 10^{-6} and 10^{-3} erg $\text{cm}^{-2}\text{sec}^{-1}$ for the wave length range 2 to 6 Å. For energies greater than these values, flare conditions become more and more important. Strong flares lead to a very large increase of the ionization.

Evidence that solar X-ray emission produces the necessary ionization, as demonstrated by Friedman and Chubb (1955), is shown by the various curves of Figure 4. There is a general lowering of the layer due to the increase of the intensity of X-rays. When the sun is well disturbed, the average lowering is about 2 km. When there is flare activity, the lowering easily reaches 5 km, and during the largest flares, the same electron concentrations are found 10 km below the quieter sun level.

Therefore, X-rays are certainly responsible for the ionization during disturbed solar conditions beginning with conditions efficient for solar flare activity. The rapid increase of the ionization when the energy is greater than

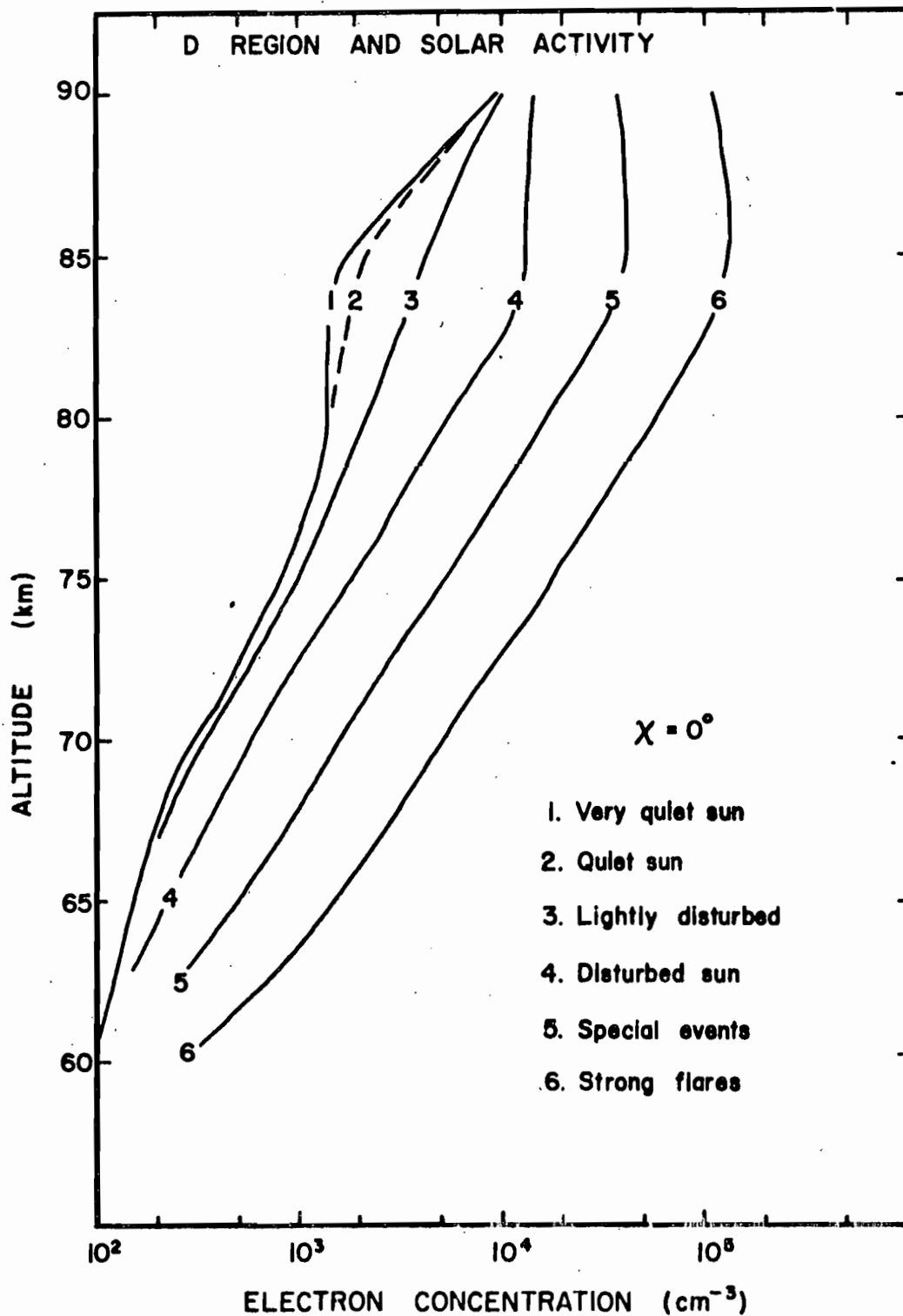


FIGURE 4

10^{-6} erg cm^{-2} sec^{-1} at 2 \AA and 10^{-4} erg cm^{-2} sec^{-1} at 6 \AA does not permit the involvement of Lyman-alpha in solar flare effects. On the other hand, it is not possible to account for the formation of the normal D layer with X-rays; this must be explained by the ionization of nitric oxide.

The radiations of wave lengths of the order of 6 \AA can produce a large increase in the ionization near 85 km. The values shown in Figure 4 indicate that an energy of 0.1 erg $\text{cm}^{-2}\text{sec}^{-1}$ leads to an electron peak of the order of 10^5 cm^{-3} ; not too different from the peak of the normal E layer.

Such variations in the ionization of the D layer indicate that radio absorption effects are under solar control and sudden or short-duration events in the absorption are directly correlated with solar flares. Since the ratio of the intensities of effective radiations is not necessarily constant, as given in Table II, the vertical distributions can be distorted from the average curves shown in Figure 4 and the manner in which absorption depends upon the height will be affected according to the variations of the intensities in the spectral range, 1 to 10 \AA .

Below 60 km, the ionization must be explained by cosmic rays and X-rays of $\lambda < 1 \text{ \AA}$. Observations are needed in order to compute the ionization rate at such low altitudes.

XIII. Conclusions

This theoretical study of the D region of the ionosphere shows that the ionization processes correspond to a normal ionization of nitric oxide by Lyman-alpha with a resultant electronic peak near 85km, to cosmic ray ionization which can be effective below 70km, and to ionization by X-rays of 2 keV or more varying with solar conditions. No effort has been made to follow the observational studies of the D region. Such an analysis would require an interpretation of certain observational data and also the addition of other possible sources of ionization such as meteor effects. In fact, it has been shown (Nicolet, 1955) how meteor atoms may be involved in the ionization and it is clear that sporadic effects can result from the ionized meteor atoms. An ionization of sodium atoms must exist and near 80-85 km, the production could be of the order of $10^{-1} \text{cm}^{-3} \text{sec}^{-1}$. But, the final electron concentration depends on the recombination of sodium which is not known.

The term "D region" is generally used to consider that portion of the ionosphere below the E region. From our analysis it is clear that the separation between these two regions occurs near 85km at the mesopause level. The tail of the E layer is due to the ionization by X-rays of $\lambda > 31 \overset{\circ}{\text{A}}$ and, therefore, is formed by other processes than those which create the D region. At night, such behavior will also be apparent since there will be negligible electron concentrations below 85km.

According to our theoretical results, normal conditions lead to three subdivisions of the D region. Between 80-85 km, there is an electron peak which remains stable until solar activity has increased above a certain level. Between 70-75 km, a reflection level can occur since the electron concentration increases with a gradient of the order of 100 electrons cm^{-3} per km. It must be pointed out that these two persistent regions are subject to variations due to latitude effects and to fluctuations of the solar activity. For example, when the effect of cosmic rays is small, the electron concentrations at 65km and 70km are 30 and 300 electrons cm^{-3} . At $\Phi = 50^\circ$, the value at 65km could increase to 150 electrons cm^{-3} . Finally, the effect due to solar flares is a complete transformation of the shape of the normal D layer, since concentrations of more than 1000 electrons cm^{-3} occur at and below 70km. This corresponds to an increase of not less 10 times the initial concentration for a strong flare. In the region of 85km, a complex situation results from the variations of solar activity. The ionization peak disappears in moderate solar activity, but may become important when solar flares occur. Concentrations greater than 10^4 electrons cm^{-3} near 85km will completely distort the shape of the tail of the E layer.

Because of the uncertainties in the rate coefficients involved, the electron concentrations inferred from our theoretical analysis may require certain later modifications.

Nevertheless, they give a picture from which it will be possible to find an adequate physical representation of the D region when more detailed data become available.

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