# IV. IONOSPHERE AND RADIO PHYSICS

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# *D* REGION FORMATION*

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## I. INTRODUCTION

That part of the terrestrial ionosphere which lies below 85 km is termed the "*D* region." Observations of ion and electron densities have been made at altitudes as low as 40 km so that this altitude can be taken as the lower boundary of the region. The mean molecular mass of the neutral atmosphere is essentially constant throughout the *D* layer and the distribution of the principal constituents, molecular oxygen and nitrogen, can be described by the hydrostatic equations relating density, pressure, and temperature. There are also several minor constituents of importance such as atomic oxygen, which reaches its peak concentration above 85 km, ozone and various oxides of nitrogen.

One of these minor constituents nitric oxide has an ionization potential such that it will be ionized by the strong hydrogen Lyman alpha line of the solar spectrum at 1216A. Lyman alpha together with short wavelength X-rays and galactic cosmic radiation are considered to be the ionizing sources of the undisturbed *D* region. Enhancement of 2 to 8A X-rays during solar flares causes large increases of electron density. These increases are termed sudden ionospheric disturbances or "SID's." Other equivalent terms in common use are cosmic noise anomaly (CNA) and sudden phase anomaly (SPA), although these terms refer to the effect on a specific type of measurement.

Electrons in the energy range 10 to 200 kev are precipitated in the auroral zone, which extends between 60° and 70° geomagnetic latitude. These electrons are the primary source of the aurora and cause large increases in *D* and lower *E* region ionization. Protons of 10 to 100 Mev produced in the course of large solar flares arrive at the earth a few hours after onset of the flare. The resultant increases in ionization occurring over the entire polar cap and extending south to a geomagnetic latitude of 65° are termed "Polar Cap Absorption" events or PCA. After the sudden commencement of a magnetic storm, which occurs about 20 hours after a strong flare, the polar cap radio wave absorbing region is extended to a geomagnetic latitude of 55°. Some sudden commencement events are accompanied by dumping of electrons in the auroral zone.

Electron density distributions, observed during some of the ionizing events discussed here, are illustrated elsewhere in this book (Electron Density Distribution by R. E. Bourdeau). A description of the ionization and recombination processes taking place in the homosphere under the influence of different radiations is given in the following sections.

## II. ATMOSPHERIC ABSORPTION OF PHOTONS AND CHARGED PARTICLES

In order for radiation to penetrate to the *D* region it must have an absorption cross section of less than $10^{-19}$cm$^2$ in air. Molecular oxygen is the limiting agent in this regard. In fact ultraviolet radiation having a wavelength shorter than the first ionization potential of $O_2$ at 1026.5A is precluded. At longer wavelengths the penetration of photons to sufficiently low altitudes can occur only in the atmospheric windows near 1216, 1187, 1167, 1157, 1143 and 1108A. For these wavelengths unit optical depth occurs near $10^{20}$ molecules cm$^{-2}$ of vertical column. When the number of molecules in a vertical column is sufficient to reduce a flux of photons to $1/e$ of its incident value, unit optical depth is attained.

At wavelengths longer than 1800A the penetration of radiation is also possible between the bands of the Schumann-Runge system of $O_2$.

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However, ionization by these wavelengths requires constituents for which the ionization potential (IP) is low, such as sodium (IP-2413A) and calcium (IP-2028A).

For wavelengths shorter than 12.4A (1 kev) the absorption cross section rapidly decreases below $10^{-19}$cm$^2$. It is found that the wavelength region most useful in the production of ionization between 70 and 85 km is 2 to 8A. The wavelength interval between 8 and 13A as well as near 35A does not penetrate to the *D* region since it is absorbed between 85 and 100 km resulting in the base of the *E* region. Radiations more energetic than 10 kev penetrate below 70 km as illustrated in figure 1. Here unit optical depth is plotted as a function of photon energy.

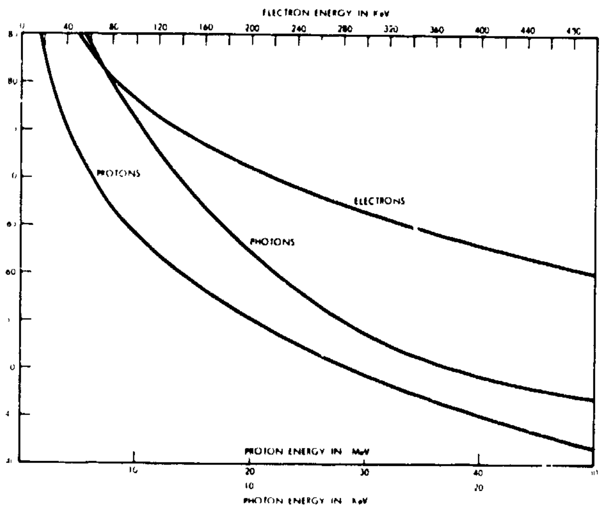


FIGURE 1.—Depth of penetration in the terrestrial atmosphere as a function of energy for photons, electrons and protons.

Nicolet and Aikin (1960) have compiled a table of the total absorption cross sections in $O_2$, $N_2$, A, and air for wavelengths between 10 and 0.1A. Both the photoelectric and Compton scattering cross sections for photons with energies greater than 10 kev, have been tabulated by Grodstein (1957). Above 1A, Compton scattering can be neglected and the absorption of a photon releases an electron whose energy depends on the ionization potential of the atom. If the electron is ejected from the *K* shell of the atom, the Auger effect must also be considered as a mechanism for producing additional electrons.

When an incident photon has an energy, $h\nu$, which exceeds the threshold of ionization for the *K* shell of $O_2$ and $N_2$ ($\sim$500 ev), the ejected photoelectrons will have a kinetic energy of $\frac{1}{2}mv^2 = h\nu - 500$. Since the average kinetic energy that is required of an electron to produce an ion pair is 35 ev, the efficiency of ionization, $\epsilon$, of a photon which interacts by the photoelectric effect can be computed.

The behavior of charged particles in the earth's atmosphere is complicated by the presence of the earth's magnetic field. This field determines the latitude dependence for the energy deposition point of charged particles and modifies the incident particle energy spectrum. However, in order to know what energies are required of various charged particles to contribute to the ionization of the *D* region, it is sufficient to consider the range in gm/cm$^2$ of air of the particles.

Experimental data on the range of protons in air has been given by Bethe and Ashkin (1953). For energies less than 500 Mev Maeda and Singer (1961) have employed the following empirical formula

$$R(\mathrm{gm/cm^2}) = E^{1.78}/420 \tag{1}$$

where E is the proton energy in Mev. This expression can be used to estimate the depth of penetration as a function of proton energy as illustrated in figure 1. It is seen that protons in the energy range 2 to 40 Mev dissipate most of their energy in the altitude region 85 to 45 km. Maeda and Singer (1961) have also given an approximate range for electrons of energy less than 0.2 Mev

$$R(\mathrm{gm/cm^2}) = E^{1.96}/0.75 \tag{2}$$

based on the data of Katz and Penfold (1953).

## III. THE PRODUCTION OF IONIZATION BY SOLAR PHOTONS

In the previous section a discussion was given of the absorption of photons in air and the subsequent production of ion pairs by the photoelectric and Compton processes. For the case of monochromatic solar radiation, the number of ion pairs produced cm$^{-3}$sec$^{-1}$ at an altitude $z$ is

$$q_z = n_j \epsilon_j' \sigma Q_\infty \exp(-\tau) \tag{3}$$

where $\sigma_j'$ is the effective ionization cross section in cm³ of the $j$ constituent, $n_j$ is the number density cm$^{-3}$ of that constituent, $Q_\infty$ is the number of photons/cm²/sec vertically incident on the earth's atmosphere and $\epsilon$ is the efficiency of ionization. The optical depth, $\tau$, is the sum of the products of the absorption cross section, $\sigma_{Ak}$, and the total number of absorbing molecules of species $k$ between the height $z$ and the sun. It is given by the expression

$$\tau = \sum_k n_k \sigma_{Ak} H_k \sec \chi \qquad (4)$$

where $\chi$ is the solar zenith angle, $n_k$ is the number of molecules of species $k$ at height $z$ and $H_k$ is the local scale height of molecule $k$. The quantity $n_k H_k \sec \chi$ represents the total number of absorbing molecules between the height, $z$ and the sun for a plane earth. However, for solar zenith angles greater than 85° it is necessary to take into account the curvature of the earth. This has been considered in various calculations for the sunrise effect in the ionosphere. Chapman (1931) has derived a function which can be used in place of sec $\chi$ in equation 4 provided that the scale height is constant. The peak altitude for the production of ion pairs can be obtained by differentiating (3). For an overhead sun this occurs for the condition

$$\tau = 1 + \beta \qquad (5)$$

where $\beta = dH/dz$ is the gradient of the scale height $H_k$. Since $\beta$ is small at the height levels of interest, the altitude of the electron production peak is approximately the altitude of unit optical depth which is shown in figure 1.

Both satellite and rocket observations have been made of solar X-rays in the 2 to 8A region. Measurements employing rocket-borne Geiger counters sensitive to the total intensity in this wavelength range, have been conducted for several years by the U.S. Naval Research Laboratory, (Friedman (1962)). The results have demonstrated that the flux varies considerably depending on the degree of solar disturbance. Utilizing this data Nicolet and Aikin (1960) divided the 2 to 8A range into 3 wavelength bands centered at 2, 4, and 6A. Their results are given in table 1 for various solar conditions ranging from solar sunspot minimum to class 3 solar flares. Measurements of the spectral distribution in the 4 to 8A range have been carried out on rockets by Pounds and Sanford (1962) and on the Ariel I satellite by Pounds, et al (1963). The results of these measurements are in agreement with table 1.

TABLE 1.—*Variations in the X-Ray Intensities According to Various Solar Conditions*

Energies in erg cm$^{-2}$ sec$^{-1}$

| Condition of the Sun | 2A | 4A | 6A |
|---|---|---|---|
| Completely Quiet | $10^{-8}$ | $10^{-7}$ | $10^{-6}$ |
| Solar Minimum | | | |
| Quiet | $10^{-7}$ | $10^{-6}$ | $10^{-5}$ |
| Lightly Disturbed | $10^{-6}$ | $10^{-5}$ | $10^{-4}$ |
| Solar Maximum | | | |
| Disturbed | $10^{-5}$ | $10^{-4}$ | $10^{-3}$ |
| Special Events | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ |
| Flares | | | |
| Class 3 Flares | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ |

The cause of sudden ionospheric Disturbances was at one time attributed to enhancement of hydrogen Lyman alpha radiation (1216A). However, a rocket experiment by Chubb et al (1957), during the course of a flare, established that although the intensity of 2 to 8A X-rays was enhanced, no appreciable change occurred in the Lyman alpha flux. Satellite observations have shown that the 2 to 8A flux enhancement is quite different from one event to another. Furthermore the enhancement of the X-ray flux may last much longer than the optical portion of the flare and take hours to decay to its preflare value. Also increases in the short wavelength range below 2A have been observed coincident with radio noise bursts at the commencement of a strong flare by various workers including Peterson and Winckler (1959). Nicolet and Aikin (1960) have shown that the radiation below 2A will be important only if its ionizing effect is greater than the effect of cosmic rays, which are the normal source of ionization below 70 km.

Since the X-ray flux emitted by the sun at sunspot minimum is insufficient to cause any appreciable ionization, another mechanism must be found to explain the formation of the $D$ region during quiet sun conditions. The hypothesis that the $D$ region might be formed by the ionization of nitric oxide by Lyman alpha radiation was postulated by Nicolet (1945). It was shown in section II that Lyman alpha is absorbed in the *D* region. Watanabe (1954) has measured the ionization cross section of nitric oxide at 1216A and found it to be $2\times10^{-18}cm^2$. It then remains to establish the presence of a sufficient quantity of nitric oxide in the mesosphere.

Nitric oxide is a minor constituent of the mesosphere. The most important processes determining the nitric oxide distribution involve atomic nitrogen, which is produced by dissociative recombination of $N_2^+$ and $NO^+$ (see section VI). When the concentration of atomic nitrogen is sufficiently great, the density of NO will be determined by the reactions of N with $O_2$ and NO namely

$$N+O_2 \rightarrow NO+O \quad (6)$$

$$N+NO \rightarrow N_2+O \quad (7)$$

The ratio of the rate coefficients of these reactions has been measured by Clyne and Thrush (1961) and found to be $0.28 \exp(-3450/T)$, where T is the gas temperature in °K. The density of nitric oxide is then

$$n(NO)=0.28n(O_2)\exp(-3450/T) \quad (8)$$

Barth (private communication) has detected nitric oxide bands in the dayglow spectrum. Nitric oxide concentrations at least as large as those given by (8) can be deduced from the intensity of the dayglow. It has been demonstrated by Nicolet and Aikin (1960) that even concentrations of the order of $10^{-10}$ of the total number density are sufficient to account for *D* region ionization in the absence of X-rays. Inn (1961 a and b) has suggested that the photoionization of vibrationally excited $O_2$ by Lyman alpha may contribute significantly to the ion density of the *D* region.

## IV. THE COSMIC RAY PRODUCTION FUNCTION

Galactic cosmic radiation is also an important factor in the formation of the *D* region. The ionizing effect of cosmic rays was first considered by Nicolet (1958). If $q_0(\phi)$ is the ionization rate for $n_0=2.6\times10^{19}$ molecules $cm^{-3}$ at geomagnetic latitude $\phi$, then the ionization rate for a number density n is

$$q(\phi)=q_0(\phi)n/n_0 \ cm^{-3}\ sec^{-1} \quad (9)$$

Van Allen (1952) has shown that $q_0(\phi)$ is reduced by a factor of 10 at the geomagnetic equator compared to a latitude of 70° namely between 30 and 300 ion pairs $cm^{-3}\ atm^{-1}\ sec^{-1}$. The time variation of cosmic rays has been summarized by Webber (1962). The important factor to bear in mind is that $q_0(\phi,z)$ is 50 percent larger at sunspot minimum compared to sunspot maximum. Figure 2 shows the results of a calculation of the ion pair

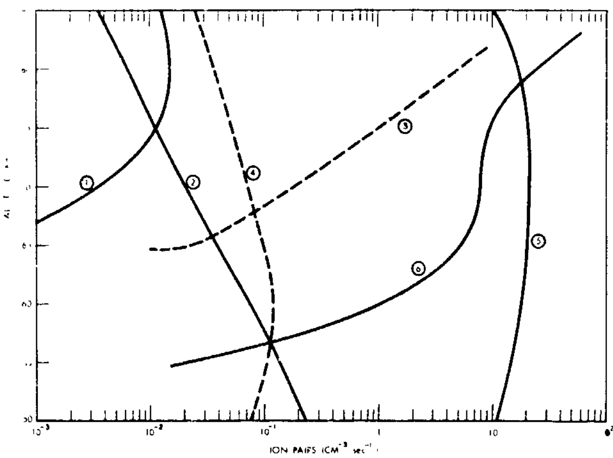


FIGURE 2.—Ion-pair production functions for different sources of ionization.
(1) Solar Lyman alpha ionizing nitric oxide.
(2) Galactic cosmic rays.
(3) Electrons precipitated in the auroral zone.
(4) Bremsstrahlung due to electrons precipitated in the auroral zone.
(5) Polar cap protons.
(6) Enhanced x-ray emission during a solar flare.

production function $q(\phi,z)$ for a $q_0(\phi)$ equal to 269 ion pairs $cm^{-3}\ atm^{-1}\ sec^{-1}$.

## V. IONIZATION BY LOW ENERGY ELECTRONS AND PROTONS

The number of ion-pairs, $q_\beta$, $cm^{-3}\ sec^{-1}$ produced at a height, $z$, by charged particles with an energy distribution between $E_{min}$ and $E_{max}$ may be expressed as

$$q_\beta=\frac{\rho(z)}{0.032}\int_{E_{min}}^{E_{max}} K_e(E)i(E,z)dE \quad (10)$$

where $\rho(z)$ is the atmospheric density in gm $cm^{-3}$ at altitude $z$. The formula for energy loss by ionization, $K_e(E)$, has been approximated by Maeda and Singer (1961) to be

$$K_e(\mathrm{E}) = \frac{-dE}{dR} = 0.38E^{-0.96} \qquad (11)$$

for electrons and

$$K_p(\mathrm{E}) = \frac{-dE}{dR} = 236E^{-0.78} \qquad (12)$$

for protons, where $R$ is the range in gm/cm² and $E$ is expressed in Mev. The number of charged particles of energy, $E$, arriving at a height $z$ is $i(E,z)$ cm$^{-2}$ sec$^{-1}$ kev$^{-1}$. It can be found if the incident spectrum of the particles is known. Since the particles enter the atmosphere at various angles with respect to the earth's magnetic field and have a spatial distribution, it is necessary to calculate $i(E,z)$ by integrating over both the pitch and solid angles.

Maeda (1963) has shown that

$$i(E,\ z) = \int_0^{\theta}\int_0^{\pi/2} j(E)\ \exp\left[-\frac{x}{\lambda(E)\cos\alpha}\right]\sin\alpha d\alpha d\theta \qquad (13)$$

where $\theta$ is the solid angle, $\alpha$ is the pitch angle, $x$ is the atmospheric depth at height $z$, and $\lambda(E) = (3.15)10^{-7}E^{2.2}$ is the attenuation mean free path. For the case of an auroral absorption event a possible representation of the differential energy spectrum is $j(E) = (1.6)10^{12}E^{-5.2}$ particles cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ kev$^{-1}$. This type of spectrum and flux of particles has been observed by McIlwain (1960). However, there were no accompanying measurements of electron density in the $D$ region. The production function $q_B$ for this type of input spectrum is illustrated in figure 2.

Aikin and Maier (1963) have calculated the ionizing effect of bremsstrahlung produced by the electron differential energy spectrum described above. The cross section per atom for production of photons of energy h$\nu$ by an electron of energy $E$ is

$$\phi(E,\ h\nu)d\nu = (8/3)\alpha\ \rho_0^2Z^2mc^2\frac{1}{\nu E}\ \ln\frac{\{\sqrt{E}+\sqrt{E-h\nu}\}^2}{h\nu}d\nu \qquad (14)$$

for energies less than 510 kev (Heitler, 1954). Here $\alpha$ represents the fine structure constant, $\rho_0$ the classical radius of the electron and $Z$ the charge of the nucleus. The differential energy spectrum of photons $dQ(h\nu)$ emitted at an atmospheric depth $x$ in a thickness $dx$ is

$$dQ(h\nu)d\nu = K\int_{E-h\nu}^{\infty}\phi(E_{h\nu},h\nu)i(E,x)dE\ dxd\nu \qquad (15)$$

where $K$ is the number of atoms per gram. Note that only electrons of energy $E \geq h\nu$ contribute to the photon flux at energy $h\nu$. The resulting ion-pair production function is also illustrated in figure 2.

Although most auroral absorption events are caused by electrons, accompanying proton fluxes have also been observed. Large solar flares are sources of large fluxes of protons and heavier particles, which produce polar cap absorption events. These events have been discussed by Bailey (1957, 1959) and Webber (1962). Calculations of the type discussed above for electrons can be carried out to estimate the ionizing effect of solar flare protons incident on the atmosphere. Reid (1961) has performed such a calculation for a power law differential energy spectrum of the form $j(E) = K\,E^{-4}$. However, Webber (1962) finds a better fit to the experimental data if use is made of an exponential spectrum of the form

$$i(P) = Ke^{-P/P_0} \qquad (16)$$

where $P$ is the rigidity of the particles. $P_0$ may range from 50 to 200 Mv, depending on the geomagnetic latitude at which the ionization is observed. For instance observations of the absorption of cosmic noise for latitudes greater than 70° require a rather steep particle spectrum or a $P_0 < 100$ Mv. For geomagnetic latitudes of 65° or less a $P_0 > 150$ Mv is required. This requirement can also be met by introducing a geomagnetic cutoff into a power law spectrum. Curve 5 of figure 2 is taken from Webber (1962) and illustrates the electron production function for an integral intensity of solar protons of 0.05 particles/cm² ster sec for energies greater than 100 Mev. A rigidity spectrum is assumed and $P_0$ is taken to be 50 Mv. More recently Webber and Freier (1963) have shown that $\alpha$ particles should be included in the calculation of the production function for polar cap events.

## VI. LOSS PROCESSES

The distribution of ions and electrons in the $D$ region depends on the interactions of these particles with one another as in the case of recombination and on interactions with constituents of the neutral atmosphere. In the latter instance, negative ions may be formed through the process of electron attachment, also charge transfer and ion-atom interchange reactions modify the distribution of various species of ions. At the present time the problem is complicated by a lack of experimental data. Although some measurements of positive ion density have been reported, the technique is presently in the development stage. No data are available on the species of positive and negative ions found in the mesosphere. The problem is further complicated by the difficulty of duplicating lower ionospheric conditions in laboratory experiments for the determination of reaction cross sections. There are a large number of possible reactions, but only those which are currently in use will be discussed here.

Dissociative recombination involves an electron and ion through the reaction

$$XY^{+}+e \rightarrow XY^{*} \rightarrow X'+Y' \qquad (17)$$

where * and ′ denote excited states of the molecule and atoms respectively. The three ions of importance in the $D$ region are $O_2^+$, $N_2^+$, and $NO^+$. The rates of dissociative recombination of $O_2^+$ and $N_2^+$ have been measured by Kasner, et al (1961), who employed a mass spectrometer for the identification of ions. Values of $\alpha_D(O_2^+) = (1.7 \pm 1)10^{-7}$ cm$^3$ sec$^{-1}$ and $\alpha_D(N_2^+) = (3 \pm 1)10^{-7}$ cm$^3$ sec$^{-1}$ were reported for a nitrogen partial pressure $\lesssim 1$ mmHg at 300°K. Although the rate coefficient for dissociative recombination is temperature dependent, see Bates and Dalgarno (1962), the temperature employed in the laboratory measurements is close enough to the mesospheric temperature of about 200°K that this dependence can be ignored.

The measurements of the dissociative recombination coefficient $\alpha_D(NO^+)$ are not so well developed as those for $O_2^+$ and $N_2^+$. Guntan and Inn (1961) have reported a value of $(1.3)10^{-6}$ cm$^3$sec$^{-1}$ and Doering and Mahan (1962) a value of $(3^{+17}_{-2})10^{-7}$cm$^3$sec$^{-1}$. Since both these measurements were conducted at partial pressures of NO > 0.1 *mmHg*, where the formation of complex ions is possible and no mass spectrometer measurements were made of the ions, there is some doubt as to whether these measurements really refer to $\alpha_D(NO^+)$. Ionospheric experiments tend to support a slower rate of recombination and indicate that $\alpha_D(NO^+)$ should be less than either $\alpha_D(O_2^+)$ or $\alpha_D(N_2^+)$. Nicolet and Aikin (1960) employed the value of (3) $10^{-9}$ cm$^3$ sec$^{-1}$ for $\alpha_D(NO^+)$ but revised estimates of the nitric oxide densities and measurements of electron densities together with solar radiations would tend to support a rate in the neighborhood of $1-5$ $10^{-8}$ cm$^3$ sec$^{-1}$, (Aikin, et al, (1963)).

Gali, et al (1963) have investigated the ion-molecule reactions

$$N_2^{+}+O_2 \rightarrow NO^{+}+NO(\gamma) \qquad (18)$$

and

$$O_2^{+}+N_2 \rightarrow NO^{+}+NO(\gamma_2) \qquad (19)$$

where the rate coefficients $\gamma_1$ and $\gamma_2$ were assigned an upper limit of $(2.1)10^{-13}$cm$^3$/sec for both these reactions. The ratio of the neutral particle to electron density in the $D$ region is such that these would be important reactions for rate coefficients as low as $10^{-18}$ cm$^2$/sec. The net result of these processes is to make NO$^+$ the dominant species of positive ion in the $D$ region. Therefore, an in situ ion mass spectrometer measurement cannot be used to establish the validity of the Lyman alpha hypothesis for the formation of the quiet sun $D$ layer. The reaction

$$N_2^{+}+O_2 \rightarrow O_2^{+}+N_2(\gamma^3) \qquad (20)$$

is also energetically possible and may have a rate coefficient as high as $10^{-16}$ cm$^3$ sec$^{-1}$.

Electrons can attach themselves to oxygen molecules through the three-body process

$$e+O_2+O_2 \rightarrow O_2^{-}+O_2 \qquad (21)$$

to form negative ions of $O_2$. Chanin, et al (1962) have measured the rate of this reaction. At $D$ region temperatures a value of $a(O_2) = 1.5 \times 10^{-30}$cm$^6$ sec$^{-1}$ is found. Burch, et al (1958) have studied the rate of photodetachment of electrons from $O_2$ as a function of wavelength of the radiation. They estimate that for the solar spectrum a photodetachment coefficient of

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

is applicable for $O_2^-$. Branscomb, et al (1958) have made a similar study for atomic oxygen from which they deduce a radiative attachment coefficient, $a(O)$, of electrons to atomic oxygen of $(1.3)10^{-15}$ cm$^3$ sec$^{-1}$ and a photodetachment rate, $d(O)$, of 1.4 sec$^{-1}$.

The problem of the removal of negative ions in the absence of photodetachment is unclear at the present time. Phelps and Pack (1961) have measured the rate of collisional detachment of $O_2^-$ in the presence of $O_2$ and find a rate coefficient, $\eta$, of (4) $10^{-20}$ cm$^3$ sec$^{-1}$. It was also found that $N_2$ was ineffective as a detaching agent.

Associative detachment of the form

$$O_2^- + O \rightarrow O^3 + e \qquad (22)$$

has also been proposed as a possible mechanism for the removal of negative ions. Possible values of the rate coefficient, $\rho$, of this reaction range from $10^{-14}$ cm$^3$ sec$^{-1}$ to $10^{-10}$ cm$^3$ sec$^{-1}$. A similar process involving $O^-$ may take place.

The remaining process to be considered is mutual neutralization of a positive and negative ion. This process is of the form

$$XY^+ + WZ^- \rightarrow XY + WZ \qquad (23)$$

The rate coefficient, $\alpha_i$, has been measured in the laboratory for the mutual neutralization of $NO^+$ and $NO_2^-$ by Mahan and Person (1964). A value of (2.1) $10^{-7}$ cm$^3$ sec$^{-1}$ was obtained. At altitudes below 45 km the Thompson three-body process must be considered. This reaction is of the form

$$XY^+ + WZ^- + M \rightarrow XY + WZ + M \qquad (24)$$

and has a rate coefficient of

$$\alpha_T = 8\times10^{-3} p/T^{5/2} \text{cm}^3\text{sec}^{-1}$$

here $p$ is the pressure in *mmHg* and $T$ the temperature in °$K$.

The continuity equations governing the altitude distribution of each species of ion and electrons in the $D$ region can be written so that the processes discussed above are included together with the appropriate ion-pair production function. Such a set of simultaneous differential equations can be solved with the aid of a computer, however, usually the approximation is made that $dN/d^3 = 9$, i.e., that quasi-equilibrium exists throughout the $D$ region.

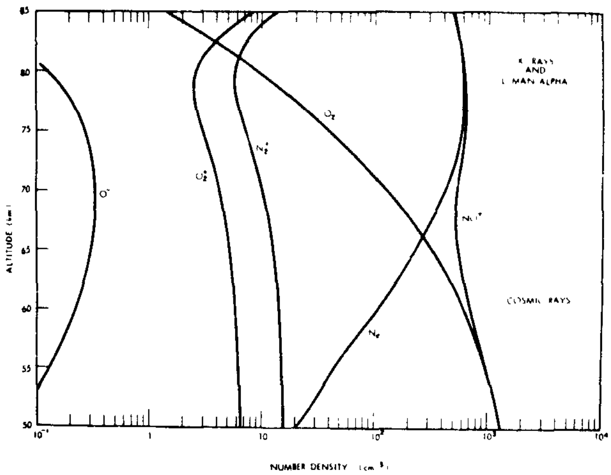


FIGURE 3.—Ion and electron density distributions for the rate coefficients listed in table II.

The results of an exact solution of such a set of equations are illustrated in figure 3 for a geographic latitude of 38°. Here the relative importance of Lyman alpha, cosmic rays, and x-radiation in the formation of the $D$ region under conditions of a completely quiet sun is shown for a solar zenith angle of 55°. The effect of reactions (18) through (20) in changing $N_2^+$ and $O_2^+$ into $NO^+$ when the rate coefficients are $10^{-18}$ cm$^3$ sec$^{-1}$ is clearly demonstrated. This will enhance the electron density, since the dissociative recombination coefficient of $NO^+$ has been taken to be almost an order of magnitude below that of $O_2^+$ and $N_2^+$. Table 2 summarizes the numerical factors employed in the calculation.

TABLE 2.—*Rate Coefficients Employed in the Calculations for Figure 3*

| *Symbol* | *Rate* |
|---|---|
| $\alpha DO_2$ | $1.7\times10^{-7}$cm$^3$/sec |
| $\alpha DN_2$ | $2.8\times10^{-7}$cm$^3$/sec |
| $\alpha DNO$ | $3\times10^{-8}$cm$^3$/sec |
| $\gamma_1$ | $10^{-18}$cm$^3$/sec |
| $\gamma_2$ | $10^{-18}$cm$^3$/sec |
| $\gamma_3$ | $10^{-18}$cm$^3$/sec |
| $a(O_2)$ | $1.5\times10^{-30}$cm$^6$/sec |
| $d(O_2)$ | 0.44 sec$^{-1}$ |
| $a(O)$ | $1.3\times10^{-15}$cm$^3$/sec |
| $d(O)$ | 1.4 sec$^{-1}$ |
| $\eta$ | $4\times10^{-20}$cm$^3$/sec |
| $\rho$ | $10^{-13}$cm$^3$/sec |
| $\alpha_i$ | $10^{-7}$cm$^3$/sec |

The nitric oxide density is $10^{-10}$n(M).

## VII. THE NOCTURNAL *D* REGION AND THE SUNRISE EFFECT

In the absence of ionization sources other than cosmic rays, the *D* region electron density decays to low values at night. Thus, it is extremely difficult to obtain electron density measurements during this period. However, observations are possible in the auroral zone with the aid of cosmic noise absorption techniques. This has led to a comparison of the sunlit and dark *D* regions under the action of the same flux of ionizing particles. In this way the different processes affecting the negative ion distribution can be examined. Let us first discuss the behavior of the undisturbed *D* region at sunrise.

A good deal of information concerning the electron density distribution has been determined from the phase and amplitude of 16 kc/sec waves reflected from the ionosphere at near vertical incidence. Bracewell (1952) has noted that the amplitude of such a wave begins to decrease at a time when the sun's rays grazing the earth illuminate an area 60 km above the ground. There is no corresponding decrease in phase at this time. Rather a decrease in phase path begins just before ground sunrise with the major portion of the drop occurring after ground sunrise, the total change in height amounting to 15 km. These results were interpreted by Bracewell and Bain (1952) as being due to a double-layered *D* region.

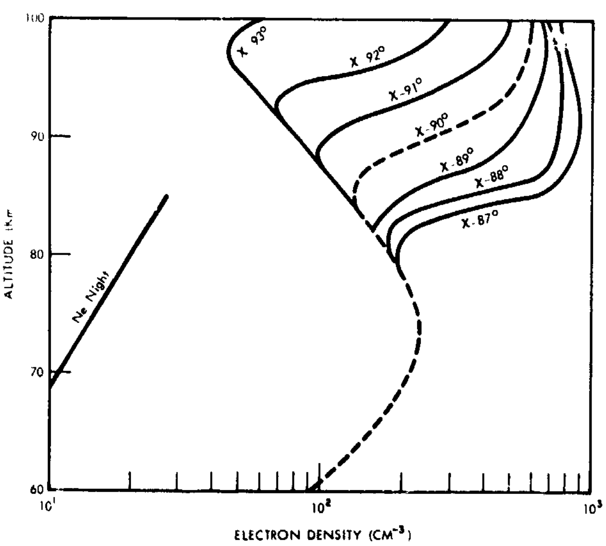


FIGURE 4.—The electron density distribution at sunrise for different solar zenith angles and the nocturnal electron density distribution.

The origin of the double layer lies in the ability of solar radiation in the visible wavelength region to penetrate to the lower *D* region and photodetach electrons from $O_2^-$ ions, which are produced as the result of cosmic ray ionization. This layer centered around 73 km will thus appear before Lyman alpha and X-rays have had a chance to penetrate into the *D* region. As the solar zenith angle decreases these radiations produce a second *D* region above the cosmic ray layer thus forming a two-layered *D* region. Eventually the two layers merge to form the normal daytime *D* region. The theoretical variation of the electron density distribution at sunrise is illustrated in figure 4 which is taken from Aikin (1962).

As noted previously most *D* region calculations are performed using the equilibrium solutions of the continuity equations for electrons and the various species of ions. This has led to the definition of the negative ion to electron ratio $\lambda$. During the day, $\lambda$ can be approximated as the ratio of the rate of attachment to photodetachment which for $O_2^-$ is

$$\lambda_{O_2^-} = (3.4)10^{-30}[n(O_2)]^2 \qquad (25)$$

and for $O^-$

$$\lambda_{O^-} = 10^{-15}n(O) \qquad (26)$$

Even in the upper *D* region where atomic oxygen reaches the peak of its concentration, $\lambda_{O^-}$ is less than $10^{-2}$. On the other hand $\lambda_{O_2^-}$ is equal to 1 near 70 km so that $O_2^-$ is the primary negative ion in the *D* region as shown in figure 3.

The diurnal variation of cosmic noise absorption during auroral and polar cap events has recently been used to derive information on the rate coefficients affecting the ratio $\lambda$. For a constant flux of ionizing particles it has been demonstrated (see e.g., Bailey (1957)), Hultquist (1963), Webber (1962), that the ratio of day to night absorption $A_D/A_N = 1+\lambda_N/1+\lambda_D$ where $\lambda_N$ is the night average value of $\lambda$ at the height where the absorption occurs and $\lambda_D$ is the day average for the same altitude range. This expression is valid only for the case where the absorption occurs in a relative narrow altitude range of about 5 km. The more general case has been considered by Reid (1961).

Because the fluxes of auroral particles are highly variable, a statistical analysis must be employed to find the ratio $A_D/A_N$ for auroral absorption events. Holt and Landmark (1963) deduce a value of 2, while Hultquist (1962) deduced yearly averages between 0.89 and 1.38 with a 4 year average of 1.16.

Polar cap absorption events yield higher values of $A_D/A_N$ than auroral absorption observations. Webber (1962) has summarized riometer data from a large number of polar stations and finds that for geomagnetic latitudes greater than 70° $A_D/A_N \cong 6.5 \pm 1$ and for 65° or less $A_D/A_N \cong 5 \pm 1$. The difference in the two cases being accounted for in the rigidity and therefore atmospheric penetration of the protons. Since the protons penetrate to greater atmospheric depths than auroral electrons, the cosmic noise absorption during polar cap events occurs at altitudes where $\lambda$ is more of a determining factor for the absorption. Various authors have shown that collisional detachment values must exceed the laboratory estimates by 3 orders of magnitude to explain the observations. Whitten and Poppoff (1962) have suggested that associative detachment may replace collisional detachment as the negative ion removal process during darkness.

The variation of polar cap absorption events during twilight periods has given rise to speculation that a negative ion other than $O_2^-$ is found in the *D* region. It has been observed that nighttime values of absorption are reached despite the fact that the sun did not set at heights greater than 50 km (see for example Reid and Collins (1959), and Eriksen, et al (1960)). These observations led Reid and Leinbach (1962) and Eriksen et al (1960) to suggest that the dominant negative ion during twilight was not $O_2^-$ but rather an ion with a much larger electron affinity requiring ultraviolet light for photodetachment.

Clearly the explanation of the diurnal variation of auroral and polar cap absorption depends on a more exact knowledge of the particle spectrum and species of negative ion as well as the inclusion of solar radiations in the calculations of cosmic noise absorption. There is, however, laboratory evidence for the existence of a negative ion with a high value of electron affinity. Curran (1962) has demonstrated that the electron affinity of $NO_2^-$ is greater than 3.82 ev. For photodetachment to occur by solar radiation whose wavelength range is in the near ultraviolet an electron affinity of about 4 ev is required. Thus $NO_2^-$ is a possible candidate. However, since the $NO_2$ concentration is predicted to be only a fraction of the nitric oxide concentration and Curran (1962) has found that direct attachment of electrons to $No_2$ is unimportant, charge exchange processes involving $O^-$ and $O_2^-$ must be operative in order to form an appreciable amount of $NO_2^-$. Curran (1962) has given a rate coefficient of $10^{-9}$ to $10^{-10}$cm³/sec for the formation of $NO_2^-$ by

$$O^- + NO_2 - NO_2^- + O \tag{27}$$

Inasmuch as $O^-$ is thought to be a negative ion of minor importance, the reactions

$$O_2^- + O \rightarrow O^- + O_2 \tag{28}$$

and

$$O_2^- + NO_2 \rightarrow NO_2^- + O_2 \tag{29}$$

should also be considered.

The theory of formation of the D region is by no means complete. While the sources of ionization and their efficiency of ion pair production have been reasonably well established, the chemistry of a nitrogen-oxygen system under the influence of different radiations is not well understood. A great deal more investigation is required in order to establish the role of the various reactions discussed here. In situ measurements are becoming increasingly more important not only because of the promise of measuring difficult parameters such as negative ions, but also because the necessary simultaneous determination of several parameters can be effected. Such phenomena as auroral absorption events and ionization by X-ray enhancements during the course of solar flares cannot be adequately explained without recourse to such experiments.

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*This is an excellent review of rocket and satellite measurements of the solar spectrum.

†A more detailed discussion of loss processes is given in this article.

# SOME RESULTS OF ROCKET EXPERIMENTS IN THE QUIET *D* REGION*

A. C. AIKIN, J. A. KANE AND J. TROIM†

Two electron density profiles have been obtained for the quiet day mid-latitude *D* region by means of ground to rocket radio propagation experiments. These profiles are interpreted between 85 and 70 km in terms of solar Lyman alpha ionization of nitric oxide. The role of 2 to 10 Ångstrom X-rays is shown to be unimportant to the formation of the *D* region for the quiet solar conditions piesent during the two rocket flights. The electron collision freouency in the *D* region is shown to be subject to significant variations which are correlated to pressure varia- of the stratosphere.

## INTRODUCTION

A theory of the formation of the *D* region was proposed by Nicolet and Aikin in 1960. The sources of *D* region ionizations under conditions of a quiet sun were explained by solar Lyman alpha ionizing nitric oxide in the altitude region between 85 and 70 km, while ionization below 70 km was attributed to cosmic rays. In the present paper, the results of two rocket experiments are presented together with an interpretation of these results which is consistent with that theory.

Measurements of the atmospheric attenuation of Lyman alpha flux as a function of altitude are used to determine the electron collision frequency profile for each flight. It is shown that the collision frequency is subject to significant variations which are correlated with meteorological processes occurring at the 30 km level of the stratosphere. With a knowledge of the collision frequency, electron density profiles are deduced from the results of radio propagation experiments. Based on satellite data the contribution of 2 to 8 Ångstrom solar X-rays to the ionization of the *D* region is estimated. Finally a discussion of the different nitric oxide data available since 1910 is given in terms of the effect on the *D* region recombination coefficient.

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The experimental method is based upon the Nike-Apache sounding rocket. The results from two such rocket flights at Wallops Island, Virginia, latitude 38°, are reported here. The first, labeled 14.107, was fired at 1430 hours EST on March 8, 1963, and the second, 14.108, was fired at 1530 hours EST on April 9, 1963. The solar zenith angles were 53° and 55° respectively.

## LYMAN ALPHA FLUX

On both flights Lyman alpha flux was measured by means of a lithium fluoride window ionization chamber filled with carbon disulfide gas. For $Q_\infty$, the Lyman alpha flux incident upon the earth's atmosphere, a value of $(3\pm1)\times10^{11}$ photons $cm^{-2}$ $sec^{-1}$ was obtained. This value is consistent with the results of Friedman *et al.*, (1963) who have shown that the Lyman alpha flux is not strongly dependent upon solar activity.

## PRESSURE AND ELECTRON COLLISION FREQUENCY DETERMINATION

The Lyman alpha flux $Q(z)$ that penetrates the atmosphere to an altitude $z$ is given by

$$Q(z)=Q(\infty)e^{-\sigma\int_z^\infty N(z)dz} \tag{1}$$

where, assuming $O_2$ to be the dominant source of absorption, $\sigma$ is the absorption cross section of an $O_2$ molecule and $N(z)$ is the $O_2$ number density.

Since the partial pressure of $O_2$ at an altitude $z$ is defined as

$$PO_2(z)=\int_z^\infty N(z)Mg\,dz \qquad (2)$$

equation (1) can be rewritten as

$$Q(z)=Q(\infty)e^{-\frac{\sigma PO_2(z)}{Mg}} \qquad (3)$$

where $M$ is the mass of an $O_2$ molecule and $g$ is the gravitational acceleration. A measurement of the ratio $Q(\infty)/Q(z)$ yields therefore the partial pressure of $O_2$ from which, assuming a constant ratio between oxygen and nitrogen partial pressures, the total pressure is derived.

The derived pressures can be used to obtain the collision frequency of electrons with neutral molecules. Phelps (1960) from laboratory measurements has shown that $\nu$, the electron collision frequency in air for monoenergetic electrons, is proportional to the electron energy. From this and the gas law it follows that for monoenergetic electrons of energy $kT$, the collision frequency is proportional to the atmospheric pressure. The relationship is

$$[\nu]_{AIR}=9\times10^7 p(mmHg)\text{sec}^{-1} \qquad (4)$$

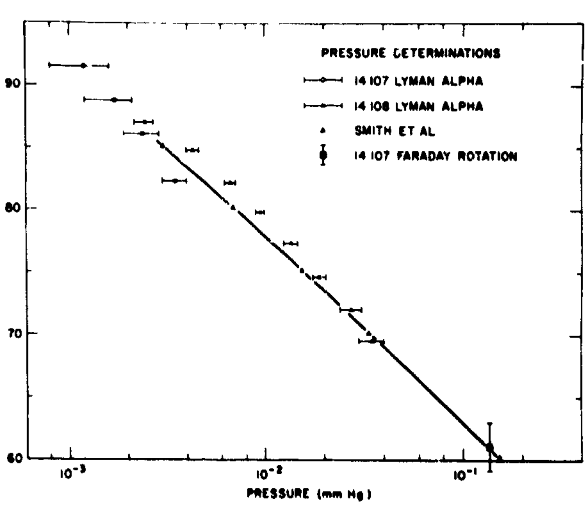


FIGURE 1.—Atmospheric pressure versus altitude at Wallops Island measured at 14:30 hours (14.107) and 19:00 hours (Smith et al.,), March 8, 1963, and at 15:30 hours, April 9, 1963 (14.108).

The results of the pressure determinations on flights 14.107 and 14.108 are shown on Figure 1. The resolution in the pressure measurements, indicated by the horizontal bars, is determined by the precision to which the Lyman alpha ion chamber aspect angle is known. Included in this figure is the pressure profile determined by Smith *et al.*, (1964) who performed a rocket-borne grenade experiment at Wallops Island five hours after flight 14.107. It is believed that the indicated pressure differences in these three measurements are real and indicate the presence of meteorological effects in the mesosphere.

## METEOROLOGY

From Equation (4) of the previous section it can be expected that the $D$ region collision frequency profile will be subject to the diurnal, seasonal and latitudinal variation of mesospheric pressure that the work of Stroud and Nordberg (1961) and others has revealed.

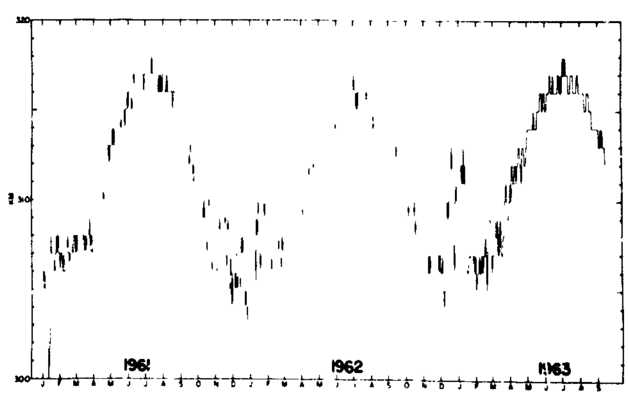


FIGURE 2.—Seasonal variation of the altitude of the 10 millibar pressure level at Wallops Island.

In Figure 2 is shown for Wallops Island a plot of the altitude of the 10 millibar pressure level for a three year period. In addition to the very apparent seasonal variation comparable short term variations are present, particularly during winter. The Meteorologische Abhandlunge Vol. XL, 1963, from which these data are taken shows that a sudden warming event occurred in the stratosphere over Canada on April 4. By April 9 the effects of this event could be noticed at Wallops Island where the altitude of the 10 millibar level increased from 30.80 km on March 8 to

31.16 km on April 9 while the temperature of this level increased from −47°C to −36°C. These stratospheric changes lend support to our April 9 collision frequency profile since the mesosphere is linked to the stratosphere through the pressure relation

$$p(z) = p_0 e^{-\int_{z_0}^{z} dz/H(z)} \qquad (5)$$

where the scale height H(z) is proportional to the temperature T(z). Although no measurements of T(z) exist for 14.108 a reasonable model can be constructed which leads to mesospheric pressures of the required magnitude.

Convincing evidence for the existence of an ionosphere-stratosphere interaction has been given by Bossolosco and Elena (1963) who have shown that a strong correlation exists between the temperature at the 10 millibar level and mid-latitude winter radio wave absorption at frequencies around 2 Mc/s. Their results show a temperature increase of 20° at the 10 millibar level correlated with a factor 2 increase in absorption. Our results would seem to indicate that this effect, the so called winter absorption anomaly, is due simply to an increase in mesospheric pressure. However, since radio wave absorption involves the electron density as well as collision frequency, and since both the electron production and loss mechanisms are pressure dependent, such a conclusion must be withheld until quantitative calculations have been made.

## ELECTRON DENSITY PROFILES

The electron density profiles reported here were obtained by means of radio propagation techniques employing ground to rocket transmissions. In flight 14.107 linearly polarized signals were transmitted from the ground at frequencies of 3.0 and 4.9 Mc/s. The mechanical spin of the rocket of about 3 cycles per second was used to rotate the rocket-borne receiving antennas through the polarization patterns of the arriving waves. The telemetered signal strengths exhibited a fading pattern, the frequency of which was the sum of the rocket spin frequency and the ionospheric Faraday rotation frequency. A comparison of the period of this fading pattern with the mechanical spin period, independently measured by means of a solar aspect sensor, yielded the Faraday rotation of the plane of polarization.

Under the condition of quasi-longitudinal propagation, the plane of linear polarization, defined by the angle $\psi$, rotates with rocket altitude $z$

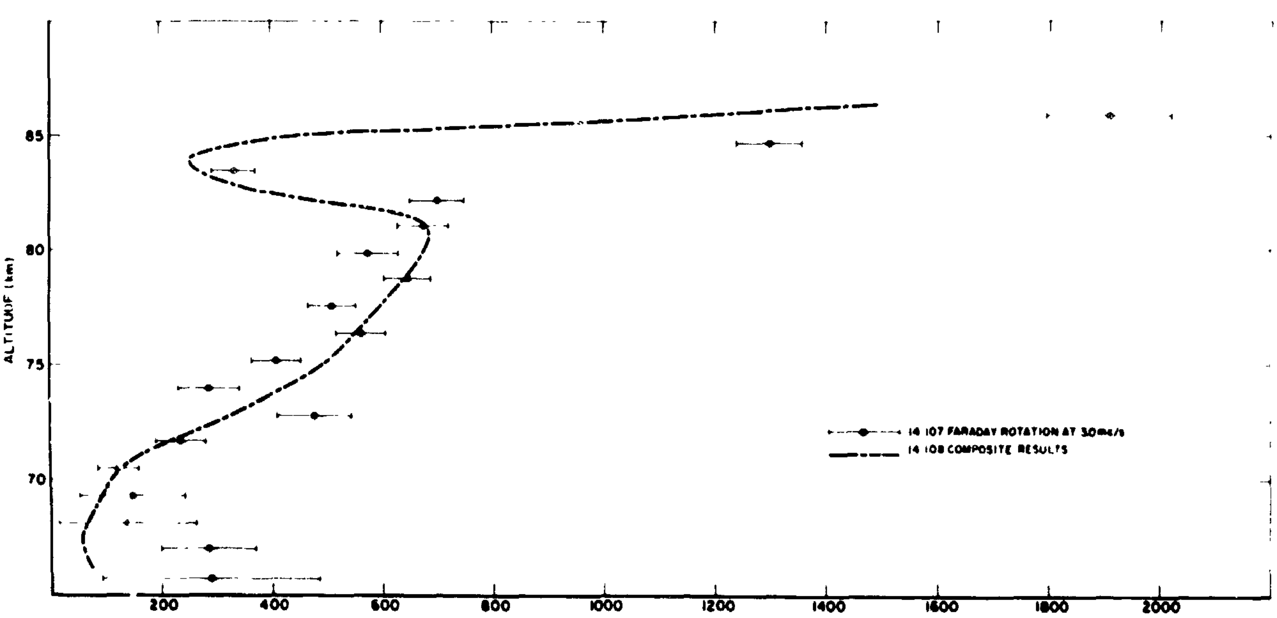


**FIGURE 3.**—Electron density versus altitude for March 8, 1963 (14.107). Dashed curve is a composite of the results shown in Figure 4.

according to an expression of the form

$$\frac{d\psi}{dz}=N_e(z)F(\omega,\ \omega_H,\ \nu(z)) \qquad (6)$$

where $N_e(z)$ is the electron density and $F$ is a function of the exploring frequency $\omega$, the gyrofrequency $\omega_H$ and the collision frequency $\nu$. The explicit form of $F$ involves the Dingle integrals of the generalized Appleton-Hartree formula (Sen and Wyler, 1960). Before $F(z)$ can be evaluated it is necessary to have a collision frequency model, the determination of which was described in section 2. The Faraday rotation experiment by itself allows the collision frequency to be determined at a single altitude. This follows from the fact that the function $F(\omega,\ \omega_H,\ \nu(z))$ changes sign at a unique value of $\nu/\omega$. By noting the altitude at which the reversal in the sense of the Faraday rotation occurred on flight 14.107 a value of $\nu=13.8\times10^6\text{sec}^{-1}$ was deduced for an altitude of $61\pm2$ km. As seen in Figure 1 this value is consistent with the March 8 pressure profile obtained from the grenade experiment of Smith *et* al., (1964).

The electron density results of the 14.107 Faraday rotation experiment at 3.0 Mc/s are shown in Figure 3. Each point is the average electron density in an altitude interval of approximately one kilometer. The horizontal bar indicates the probable uncertainty in the determination of this average value. This uncertainty is due to random echoes from above the $D$ region distorting the Faraday pattern. This effect was more severe on the 4.9 Mc/s Faraday experiment which yielded electron densities in agreement with those shown in Figure 3, but with uncertainties two to three times as large.

In flight 14.108 linearly polarized signals were transmitted at frequencies of 1.8 and 4.9 Mc/s. A 3.0 Mc/s signal was also transmitted from ground to rocket on flight 14.108, but in this case the transmitted pattern was alternately switched between opposite circularly polarized modes, which in the ionosphere were differentially absorbed. Denoting the received signal strength of the two polarization modes as $E_0$ and $E_X$, the altitude variation of the logarithmic ratio $ln(E_0/E_X)$ can be expressed as

$$\frac{d}{dz}\ln(E_0/E_X)=N_e(z)G(\omega,\ \omega_H,\ \nu(z)) \qquad (7)$$

where again $N_e(z)$ is the electron density and $G(z)$ is an altitude dependent function involving the Dingle integrals and requiring a collision frequency model for explicit evaluation.

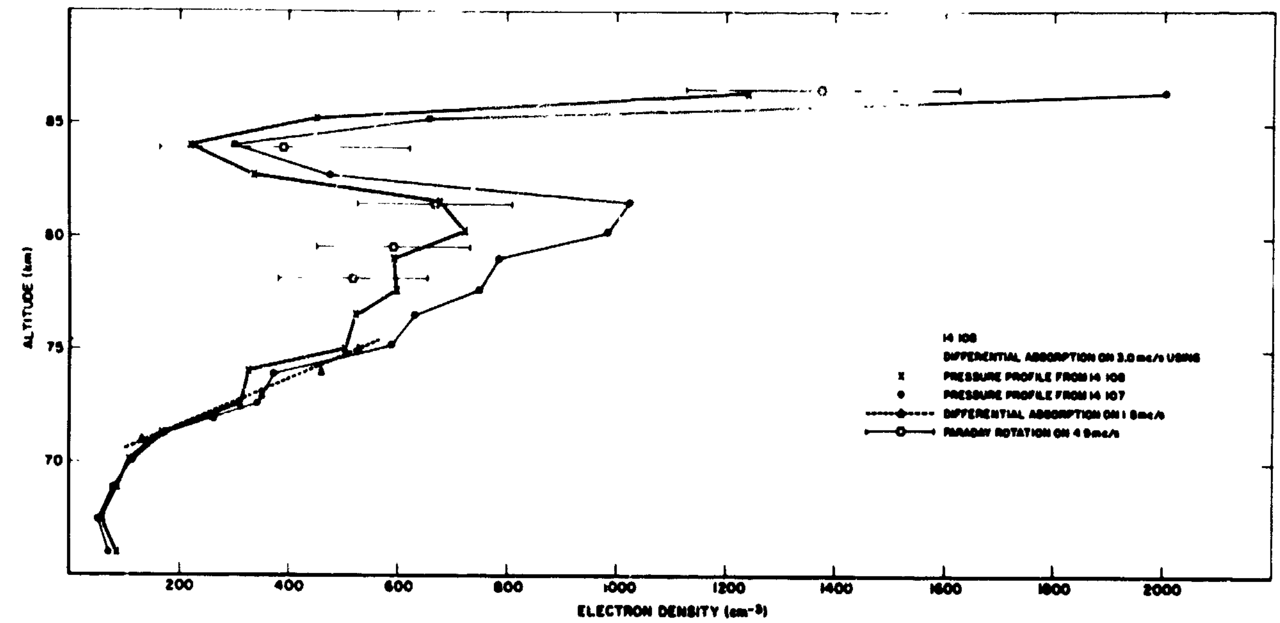


**FIGURE 4.**—Electron density versus altitude for April 9, 1963 (14.108) showing the effect of the choice of collision frequency model used to interpret radio absorption data.

In addition to a direct comparison of circularly polarized $E_0$ and $E_X$ signal strengths, it is possible to obtain differential absorption data also from the Faraday pattern of a linearly polarized signal. This follows from the fact that the maximums in the Faraday pattern represent the sum, while the nulls represent the difference of the $E_0$ and $E_X$ signal strengths. This technique was the basis of the 1.8 Mc/s experiment.

The results of the three propagation experiments on flight 14.108 are shown in Figure 4. The electron densities deduced from the 4.9 and 1.8 Mc/s propagation experiments are relatively insensitive to the choice of collision frequency profile. This is not true however for the 3.0 Mc/s differential absorption experiment. In Figure 4 are shown two electron density profiles deduced from the 3.0 Mc/s differential absorption measurement, the open circle points were computed using the Figure 1 pressure values of Smith, while the values shown as crosses were computed using a 50 percent higher pressure profile. It is seen that consistency between the results of the 14.108 Faraday experiment on 4.9 Mc/s and the 14.108 differential absorption experiment on 3.0 Mc/s requires collision frequency values which between 75 and 80 km are approximately 50 percent higher than those observed one month previously. This requirement is satisfied by the Lyman alpha data shown in Figure 1. For comparison with the 14.107 electron densities the results from 14.108 are plotted as the dashed line in the previous Figure 3. The similarity of the two profiles is apparent, particularly with respect to the minimum at the mesopause (83 km). Possible causes of the minimum at the mesopause include a temperature dependent nitric oxide distribution, and the attachment of electrons to dust. This latter hypothesis has some support from the work of Witt *et al.*, (1962) who reported the detection of dust in the vicinity of the mesopause, and the work of Frocco and Smullin (1963) who reported scattering of a laser beam in this altitude region.

In order to interpret the electron density profiles presented here it is necessary to have a knowledge of the ion pair production function for each of the ionizing radiations affecting the $D$ region. This is the subject of the following sections.

## COSMIC RAY IONIZATION

The contribution of cosmic rays to the ionization content of the normal $D$ region has been considered by Nicolet and Aikin (1960). They showed an ion production rate which was important below 70 km and which involved a variation of a factor 10 between the geomagnetic latitudes of 0° and 70°. For a geomagnetic latitude of 50°, based on the work of Webber (1962), a slightly revised ionization rate of $180 \pm 30$ ion pairs/sec/atmosphere can be assumed for the altitude region between 60 and 85 km for the 1963 portion of the solar cycle. Combining this value with a model atmosphere yields the altitude dependence of the cosmic ray ionization rates shown as the lower portion of the curves labelled $q_{O_2}$ and $q_{N_2}$ in Figure 5.

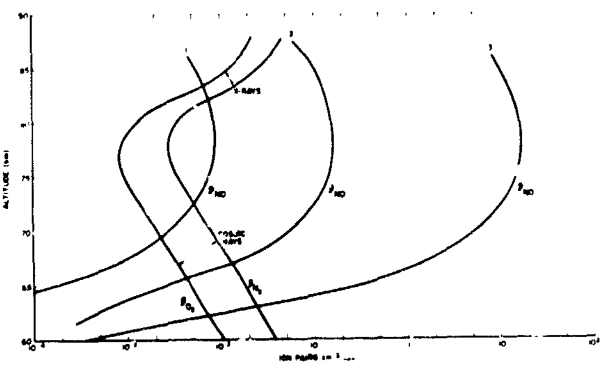

FIGURE 5.—Calculated ionization production function versus altitude. Curves labeled 1, 2, and 3 show the effect of Lyman alpha flux on three different nitric oxide distributions.

## X-RAY IONIZATION

The major atmospheric constituents of the $D$ region can be ionized by solar X-rays in the 2 to 8Å wavelength region. The importance of this process will depend, however, upon the degree of solar activity. Instrumentation failure prevented a direct measurement of 2–8Å X-rays during our flights. Thus it is necessary to rely on estimates of the flux. The basis of these estimates are the 2800 Mc flux as measured at Ottawa, the McMath-Hulbert calcium plage data, and the Zurich provisional sunspot number. White (1964) has compared direct measurements of X-ray flux from the OSO–1 satellite with these indices and derived an empirical relation for estimating the X-ray intensity. From these data White estimates that the 2 to 8Å flux was the same to within 50 percent during both our rocket flights and had an integral value of $1.9\times10^{-4}$ ergs/cm²sec.

From Ariel I satellite, Pounds *et al.*, (1961)

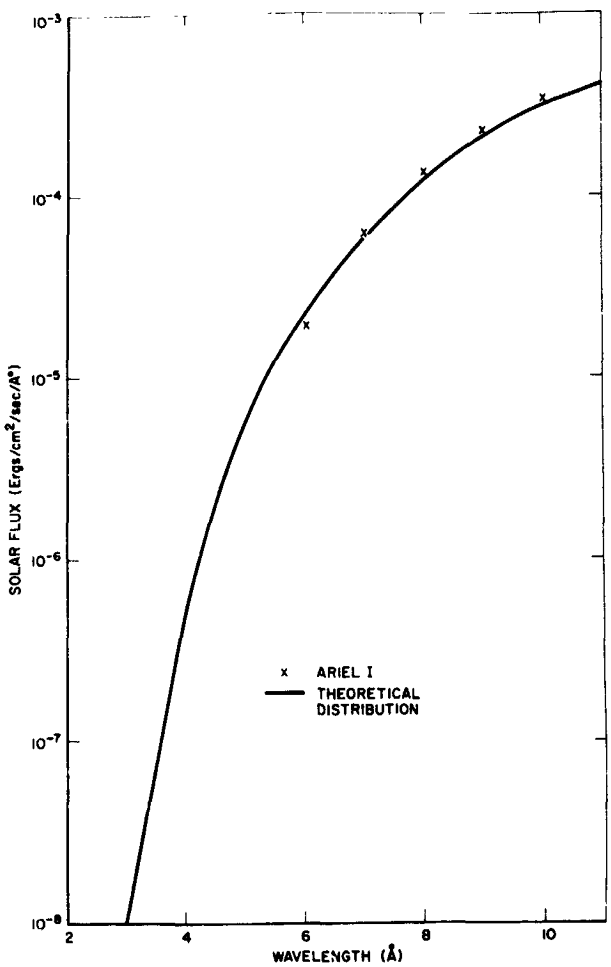


FIGURE 6.—Quiet sun spectrum in the 2 to 10 Ångstrom wavelength interval. Solid curve is the spectral distribution $J(\nu)d\nu=Ae^{-h\nu/kT}d\nu$, with T equal to $2.8\times10^6$ °K.

have obtained solar spectra between 6 and 11Å. The crosses in Figure 6 show a typical non-flare spectrum in which the integrated intensity below 8Å was $1.3\times10^{-4}$ergs/cm²/sec. According to White (1963) both the Ariel I and OSO-1 non-flare data can be fitted to a frequency spectrum of the form $J(\nu)d\nu\propto e^{-h\nu/kT}d\nu$ with $T$ equal to $2.8\times10^6$ °$K$. This is shown as the solid curve of Figure 6.

Using the ionization cross sections given by Nicolet and Aikin (1960) together with a model atmosphere derived from the Smith pressure profile and the spectral distribution of Figure 6 (normalized to an integral value of $1.9\times10^{-4}$ergs/cm²/sec), the ion pair production function due to X-rays can be calculated as a function of altitude. The results are shown as the upper portion of the curves labelled $q_{O_2}$ and $q_{N_2}$ in Figure 5. Before the relative importance of ion pair production by X-rays can be evalutated, it is necessary to have some knowledge of the concentration of nitric oxide, which is the trace constituent ionized by the Lyman alpha flux.

## NITRIC OXIDE

For sufficiently large concentrations of atomic nitrogen estimates of the nitric oxide distribution can be based upon the processes

$$N+O_2\rightarrow NO+O \quad (8)$$

and

$$N+NO\rightarrow N_2+O \quad (9)$$

which have rate coefficients $b_1$ and $b_2$ respectively. The density of NO in the $D$ region is then determined by

$$n(NO)=(b_1/b_2)n(O_2) \quad (10)$$

Nicolet and Aikin (1960) adopted $5\times10^{-10}$ as the ratio $b_1/b_2$. The ion-pair production function resulting from such a distribution is shown as curve 1 of Figure 5. A laboratory measurement of $b_1/b_2$ by Clyne and Thrush (1961) yielded a value of $9\times10^{-9}$. The ion-pair production function for this nitric oxide distribution is labeled curve 2 in Figure 5. Barth (1964) has made a direct measurement of the nitric oxide concentration in the upper atmosphere and has obtained a value of $6.2\times10^7$cm$^{-3}$ between 75 and

TABLE 1

| Curve # | $b_1/b_2$ | $n(NO)$(cm$^{-3}$) | $\alpha$(cm³/sec) |
|---|---|---|---|
| 1 | $5\times10^{-10}$ | $4\times10^4$ | $2\times10^{-8}$ |
| 2 | $9\times10^{-9}$ | $6\times10^5$ | $3\times10^{-7}$ |
| 3 | $9\times10^{-7}$ | $6\times10^7$ | $3\times10^{-5}$ |

85 km. If this density is used in Equation (10) for an altitude of 80 km, then a $b./b_2$ ratio of $9\times10^{-7}$ is obtained. The resulting production function is shown as curve 3 in Figure 5. Table 1 summarizes the nitric oxide information for an altitude of 80 km. Also tabulated for this altitude are three derived values of the recombination coefficient $\alpha$. This parameter is the topic of the following section.

## RECOMBINATION COEFFICIENT

The electron densities of Figure 3 are elated to the ion production functions of Figure 5 by the equation

$$N_e^2 = \Sigma_i q_i/\alpha_i \qquad (11)$$

where $\alpha_i$ is the effective recombination coefficient of the $i^{th}$ species of positive ion. Biondi (1964) has indicated that $O_2^+$ and $N_2^+$ recombine dissociatively with a rate coefficient of $2\times10^{-7}$cm$^3$ sec$^{-1}$, while $NO^+$ has a recombination coefficient of less than $5\times10^{-7}$cm$^3$sec$^{-1}$. The values of recombination coefficient derived from curves 1 and 2 of Figure 5 and given in Table 1 are consistent with dissociative recombination of $NO^+$ as the electron loss process of the D region. Curve 3 requires the introduction of loss processes not previously considered in *D* region theory since $10^{-6}$cm$^3$sec$^{-1}$ is the upper limit assigned to dissociative recombination by both laboratory measurements and theoretical determinations.

By using in Equation (11) the recombination coefficients given by Biondi together with the ion production functions shown in Figure 5, it is seen that the ionization due to X-rays can dominate the quiet *D* region only above 83 km and even than only for the case of a nitric oxide distribution corresponding to curve 1 of Figure 5.

## CONCLUSION

Electron density and collision frequency profiles have been obtained for the quiet day mid-latitude *D* region. The electron collision frequency is subject to significant variations of a meteorological nature. The electron density profiles agree with the theory that for a reasonably quiet sun solar X-rays are unimportant, and Lyman alpha ionization of nitric oxide is the major contributor to the ionization content of the *D* region. Although existing theory can explain these measured profiles, the recent nitric oxide measurements of Barth (1964) would, if accepted, require a reevaluation of the electron-ion less processes.

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