NASA TECHNICAL NOTE

NASA TN D-2096

N64 10058

NASA TN D-2096



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1963

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SUMMARY

Ionization of the lower ionosphere by electrons from a type I aurora is discussed. The primary electrons produce ionization in the altitude range where in quiet conditions there is normally no ionization at night, but where the ionization during the day results from solar Lyman $\alpha$ and x-ray radiation. The bremsstrahlung resulting from the assumed flux of auroral electrons produces significant ionization at low altitudes (50 - 70 km) where normally cosmic rays are the only source of ionization. For certain values of the relevant parameters, predicted electron and ion densities, are given here for comparison with the charged particle profiles calculated for the case of no auroral flux.

CONTENTS

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(Manuscript Received July 8, 1963)

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## INTRODUCTION

Rocket measurements by McIlwain (Reference 1) have demonstrated that for certain types of auroral events a major portion of the luminosity can be accounted for by the action of electrons with energies less than 10 kev. This energy is, however, insufficient to allow the particles to penetrate the D region. The enhanced ionization of the lower ionosphere during an auroral event is in fact caused by the energy loss of electrons whose energy distribution falls between 10 and 200 kev. In addition to direct ionization, which occurs above 70 km, ion-pair production can also take place as a result of the indirect process of energy loss by radiation.

Meredith, Gottlieb, and Van Allen (Reference 2) first demonstrated that there was a photon flux in the energy range 10 to 100 kev resulting from bremsstrahlung production by auroral zone electrons. This radiation can penetrate well below 70 km and leads to enhanced ionization of the lower D region, which some investigators have called the C region. That enhancement will be the topic of this discussion. In addition to ionization by bremsstrahlung it will be necessary to include the effects of background cosmic rays which are the only source of ionization in this height range of the earth's atmosphere in the absence of solar flares.

The effect of auroral protons will be neglected. For this type of event protons have in general neither the flux nor the energy spectrum required to change the ion and electron densities appreciably. Loss processes considered important will be discussed and electron density profiles for various conditions will be derived.

## DIFFERENTIAL ENERGY SPECTRUM OF THE PARTICLES

In order to calculate the bremsstrahlung spectrum it is necessary to know the number and energy distribution of the auroral electrons at any atmospheric depth $x$. It will be assumed that the incident flux of particles is isotropic over a solid angle of $2\pi$ steradians and enters the atmosphere at a pitch

*Presented at the NATO Advanced Study Institute, Skeikampen, Norway, April 17-26, 1963.

angle $\theta$ with respect to a vertical magnetic field. McIlwain (Reference 1) has made a rocket measurement of the electron spectrum during a Type I aurora. His result can be approximated by a differential energy spectrum of the form

$$i_0 = \beta E^{-n} \tag{1}$$

where $E$ is the kinetic energy of the particles, $\beta = 1.6 \times 10^{12}$ particles/cm$^2$-sec-kev-ster, and $n = 5.2$.

As the electrons penetrate to greater depths, their interaction with the atmosphere causes a change in the form of the particle spectrum. This can be represented by an exponential attenuation of the incident spectrum such that at any level $x$ in the atmosphere the differential energy spectrum is given by

$$i(E,x) = 2\pi \int_{\theta=0}^{\pi/2} i_0(E) \exp\left(\frac{-x}{bE^m \cos\theta}\right) \sin\theta \, d\theta \tag{2}$$

where integration has been indicated over the polar angle and includes the pitch angle dependence. Following Maeda (Reference 3) $b = 3.15 \times 10^{-7}$ gm/cm$^2$ and $m = 2.2$. The values of $b$ and $m$ are valid for $5 < E < 300$ kev.

## PRODUCTION OF BREMSSTRAHLUNG PHOTONS BY AURORAL ELECTRONS

The cross section per atom for production of photons of energy $h\nu$ by an electron of energy $E$ is (Reference 4)

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

for energies much less than 510 kev. 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

$$dQ(h\nu)d\nu = k \int_{E=h\nu}^{\infty} \phi(E,h\nu)\; i(E,x)\; dE\; dx\; d\nu \tag{4}$$

where the electron omnidirectional differential energy spectrum $i(E,x)$ described previously must be employed, and $k$ is the number of atoms per gram. Note that only electrons of energy $E \geq h\nu$ contribute to the photon flux at energy $h\nu$. Thus the integration over $E$ is carried out from $h\nu$ to $\infty$.

The total production of bremsstrahlung is then the integral over atmospheric depth of Equation 4:

$$Q(h\nu)\, d\nu = k \int_{x=0}^{0.05} \int_{E=h\nu}^{\infty} \phi(E,h\nu)\; i(E,x)\; dx\; dE\; d\nu \tag{5}$$

The value $x = 0.05$ gm/cm$^2$ yields an attenuation of at least $e^{-1}$ for 200 kev electrons. This, combined with the relative sparsity $(E^{-n})$ of high energy particles allows us to set $x = 0.05$ gm/cm$^2$ as the upper limit for the integration over the source volume. Evaluating Equation 2 over x gives

$$\int_0^{0.05} i(E,x)\, dx = 2\pi \beta b E^{m-n} \quad . \tag{6}$$

Then

$$Q(h\nu)\, d\nu = K\beta \int_{E=h\nu}^{E=\infty} \frac{E^{m-n-1}}{\nu} \ln \frac{\left(\sqrt{E} + \sqrt{E-h\nu}\right)^2}{h\nu}\, dE\, d\nu \tag{7}$$

where

$$K\beta = 2\pi\beta b k \frac{8}{3} \alpha \rho_0^2 Z^2 mc^2$$

$$= 1.62 \times 10^{-6} \beta \quad .$$

Integrating by parts, we have

$$Q(h\nu)\, d\nu = K\beta \frac{d\nu}{\nu} \int_{E=h\nu}^{E=\infty} E^{m-n-1} \ln \frac{\left(\sqrt{E} + \sqrt{E-h\nu}\right)^2}{h\nu}\, dE \tag{8}$$

$$= K\beta \frac{d\nu}{\nu} \frac{16}{45} \frac{1}{(h\nu)^3} \quad .$$

The number of photons in the interval $h\nu_1$ to $h\nu_2$ is

$$Q(h\nu) = \frac{16}{45} K\beta \int_{h\nu_1}^{h\nu_2} \frac{d(h\nu)}{(h\nu)^4} = 0.19\beta \times 10^{-6} \times \left. \frac{1}{(h\nu)^3} \right|_{h\nu_2}^{h\nu_1} \quad . \tag{9}$$

Table 1 gives the number of photons/cm$^2$-sec-kev as a function of bremsstrahlung energy.

Anderson and Enemark (Reference 5) have derived an expression for the number of photons per unit energy produced by electrons having differential energy spectra of the form $BE^{-n}$ and $Ae^{-bE}$. Their calculation differs from that of the present authors in the use of the range-energy relationship $R = E/2000$ gm/cm$^2$ to describe the stopping of electrons and in the use of a single bremsstrahlung radiation length, $l_R$, for the production of X-rays. They obtained the result (for the case of a power law electron spectrum):

$$Q(h\nu_1, h\nu_2) = \frac{B}{2000\, l_R\, (n-1)(n-2)^2} \left[ \frac{1}{\left(h\nu_1\right)^{n-2}} - \frac{1}{\left(h\nu_2\right)^{n-2}} \right] \cdot \tag{10}$$

Table 1

Auroral Bremsstrahlung Production for Various Photon Energies.

| Mean Photon Energy (kev) | $\left(\frac{\text{photons}}{\text{cm}^2\text{-sec-kev}}\right)$ |
|---|---|
| 10 | 113 |
| 15 | 20 |
| 20 | 5.0 |
| 30 | 1.25 |
| 40 | .40 |
| 50 | .15 |
| 60 | .066 |
| 80 | .024 |

For $l_R = 100$ gm/cm² this reduces to

$$Q = 0.12 \, B \times 10^{-6} \left[ \frac{1}{(h\nu_1)^{3.2}} - \frac{1}{(h\nu_2)^{3.2}} \right] ,$$

where B is in electrons/cm²-sec-kev. To compare this to Equation 9 we must replace B by $2\pi B$, and we have (Reference 5)

$$Q = 0.75 \, \beta \times 10^{-6} \left[ \frac{1}{(h\nu_1)^{3.2}} - \frac{1}{(h\nu_2)^{3.2}} \right]$$

For the given input spectrum the present calculation thus predicts only about 1/3 as many photons.

## ATMOSPHERIC IONIZATION BY BREMSSTRAHLUNG

Having obtained the radiation flux incident at an atmospheric depth of 0.05 gm/cm², we must now consider the absorption of this flux as it penetrates into the lower mesosphere and stratosphere. For the energy range of interest, 10 to 100 kev, the mechanisms for photon absorption are (1) the photoelectric effect and (2) Compton scattering. In an energetic photoelectric interaction essentially all the photon's energy is transferred to the liberated electron. This electron can then produce secondary ionization at the rate of 1 ion pair per 32 electron volts of energy. The Compton effect, however, imparts a significant fraction of the incident energy to the scattered photon so that in a single interaction only a fraction of the energy is available to produce secondary ionization. Evans (Reference 6) has tabulated the product, $\sigma_a$, of the Compton scattering cross section $\sigma_T$ and the average fraction of energy transferred to the scattered electron for various energies. This will be employed to obtain the efficiency of ionization by the Compton absorption process.

The number of ion pairs/cm³-sec produced by bremsstrahlung at any altitude below $x = 0.05$ gm/cm² is expressed by

$$q = n(h) \left(\sigma_p + \sigma_a\right) \frac{h\nu}{.032} Q_\infty(h\nu) \, e^{-T} \tag{11}$$

Here $n(h)$ is the number density of molecules at a height $h$, $Q_\infty(h\nu)$ is the photon flux given in Table 1, and $\sigma_p$ is the cross section for photoelectric absorption as calculated by Gradstein (Reference 7). The total absorption of the bremsstrahlung photons is represented by $T$ which is expressed as

$$T = \left(\sigma_p + \sigma_a\right) \Delta n(h) H \quad , \tag{12}$$

where $\Delta n(h) H$ is the number of molecules between the height where the photon flux is unattenuated and any lower height $h$.

The foregoing expressions for $q$ and $T$ neglect the effect of the energy released from Compton interactions in the form of scattered photons. This energy is considered as neither locally absorbed nor neglected, but as transferred to the lower altitude region. An upper limit for the ionization produced in the lower altitude region has thus been computed. To assign a lower limit to the ionization vs. altitude, the calculation has been repeated with $\sigma_T$, the Compton scattering cross section, in place of $\sigma_a$ in Equations 11 and 12. This procedure regards all the energy of an electron involved in a Compton interaction as locally absorbed, with none transferred to lower altitudes. The results of this calculation were not significantly different from those involving $\sigma_a$, and will not be presented here.

Figure 1 illustrates the q's for different photon energies resulting from the use of Equation 11. It can be seen that most of the bremsstrahlung ion-pair production occurs for photons whose energy is less than 20 kev.

In order to calculate the total ionization below 100 km it is necessary to include the effect of cosmic rays and auroral electrons. Nicolet and Aikin (Reference 8) have shown that the effect of cosmic rays can be expressed as $q_{CR} = 10^{-17}\ n(h)$. Ionization energy loss by the primary auroral electrons is given by

$$q_\beta = \frac{p(h)}{0.032}\int_{E_{min.}}^{E_{max.}} K_e(E)\ i(E,h)\ dE \tag{13}$$

where $p(h)$ is the atmospheric density at height $h$ and $K_e(E)$ is the ionization energy loss formula for electrons. The energy loss expression corresponding to the exponential electron absorption which has been used is

$$K_e(E) = \frac{1}{3.5 \times 10^{-7}\ E^{1.2}}\ \frac{\text{kev}}{\text{gm/cm}^2} \tag{14}$$

for $E$ expressed in kev.

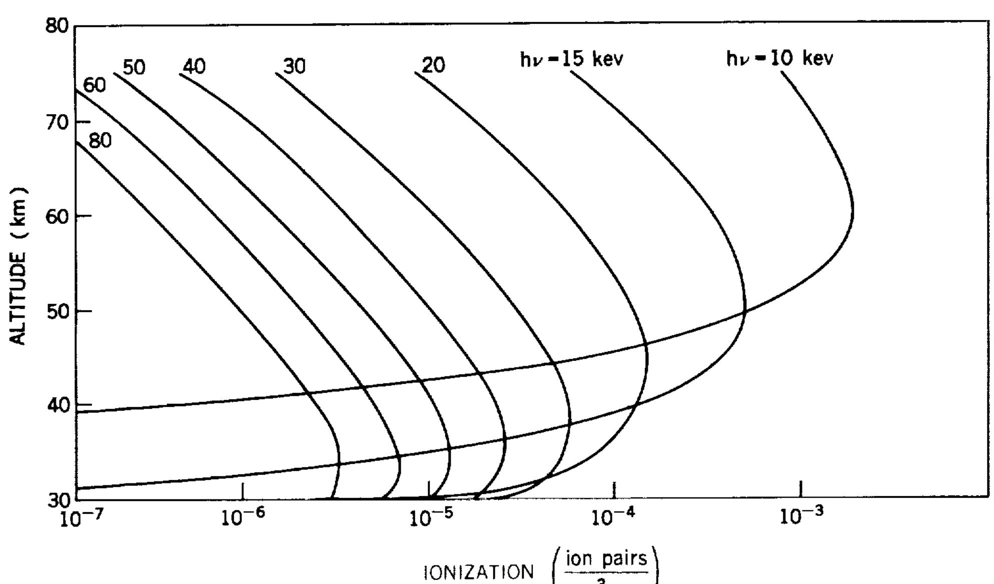


Figure 1—Ion-pair production functions due to bremsstrahlung, as functions of photon energy and altitude.

The integration involved in $q_\beta$ can be carried out analytically for incident spectra of the form

$$i_0(E) = \beta E^{-n} \text{ where } n = 4.2 \text{ or } 6.2$$

For the case $n = 5.2$, the values for $q_\beta$ were obtained by a graphical interpolation between the two analytic solutions where the two theoretical expressions had been normalized to incident spectra containing the same number of electrons at energies above 10 kev.

A comparison between the rates of ionization by cosmic rays, auroral electrons and bremsstrahlung is shown in Figure 2. Below 50 km bremsstrahlung plays practically no part in the ionization of the atmosphere for the number density and energy distribution of the particles considered in this work.

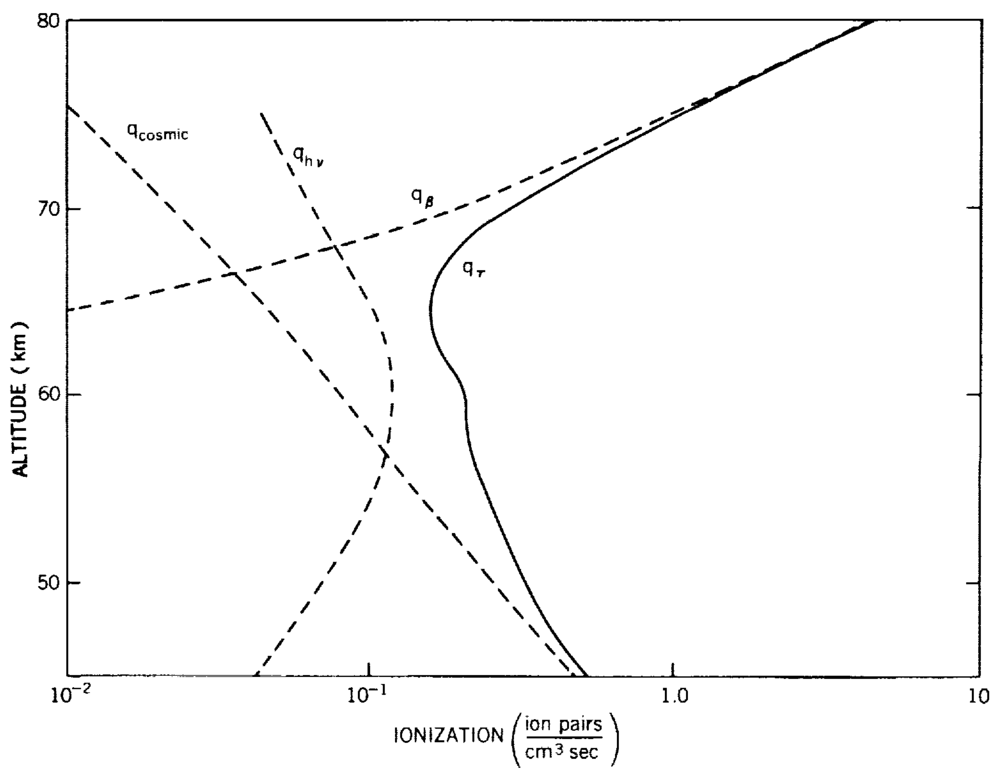


Figure 2—Ion-pair production functions for the various ionization mechanisms, as functions of altitude.

In order to calculate the electron density it is necessary to sum the q's described above and take into account loss processes, which will be discussed in the next section.

## DISCUSSION OF LOSS PROCESSES

Electron and ion densities in the ionosphere are the result of both ionization and recombination. It will be assumed that electrons are lost either by attachment to form negative ions or by dissociative recombination with positive ions. For loss by dissociative recombination, rate coefficients of $3 \times 10^{-8}$ cm$^3$/sec Aikin (References 8, 9) and $5 \times 10^{-7}$ cm$^3$/sec (Reference 10) have been chosen to exhibit the effect of this process on the distribution.

Processes have been included for the formation and loss of negative ions as discussed by Nicolet and Aikin (Reference 8). $0_2^-$ is considered to be the predominant negative ion. It is formed by the process of three-body attachment for which the rate is

$$a = 1.5 \times 10^{-30} \text{ cm}^6/\text{sec} \quad .$$

During the day, photodetachment is operative and

$$d = 0.44 \text{ sec}^{-1} \quad .$$

At night associative detachment of the form

$$0_2^- + 0 \longrightarrow 0_3 + e$$

is included. This process has been assigned a rate coefficient of $10^{-13}$ cm$^3$/sec. Associative detachment may be particularly important in auroral events, since there is considerable dissociation of molecular oxygen by auroral electrons as discussed by Maeda (Reference 3).

Ionic recombination of the form

$$XW^- + YZ^+ \longrightarrow XW + YZ$$

is operative and the rate coefficient $\alpha_1$ is taken to be $10^{-8}$ cm$^3$/sec. At low altitudes the Thompson three-body process must be included and

$$\alpha_T \approx 10^{-8} \text{ p}$$

where $k$ is in mm Hg.

For a production function $q$ the equations governing the distribution of ionization under equilibrium conditons are

$$\left.\begin{aligned}
N^+N_e &= \frac{q}{\alpha_D + \lambda\left(\alpha_1 + \alpha_T\right)} \\
N^+ &= (1 + \lambda)\, N_e = N^- + N_e \\
\lambda_{day} &= \frac{N^-}{N_e} = \frac{1.5 \times 10^{-30}\, n\left(0_2\right)^2}{0.44} \\
\lambda_{night} &= \frac{1.5 \times 10^{-30}\, n\left(0_2\right)^2}{10^{-13}\, n(0)}
\end{aligned}\right\} \qquad (15)$$

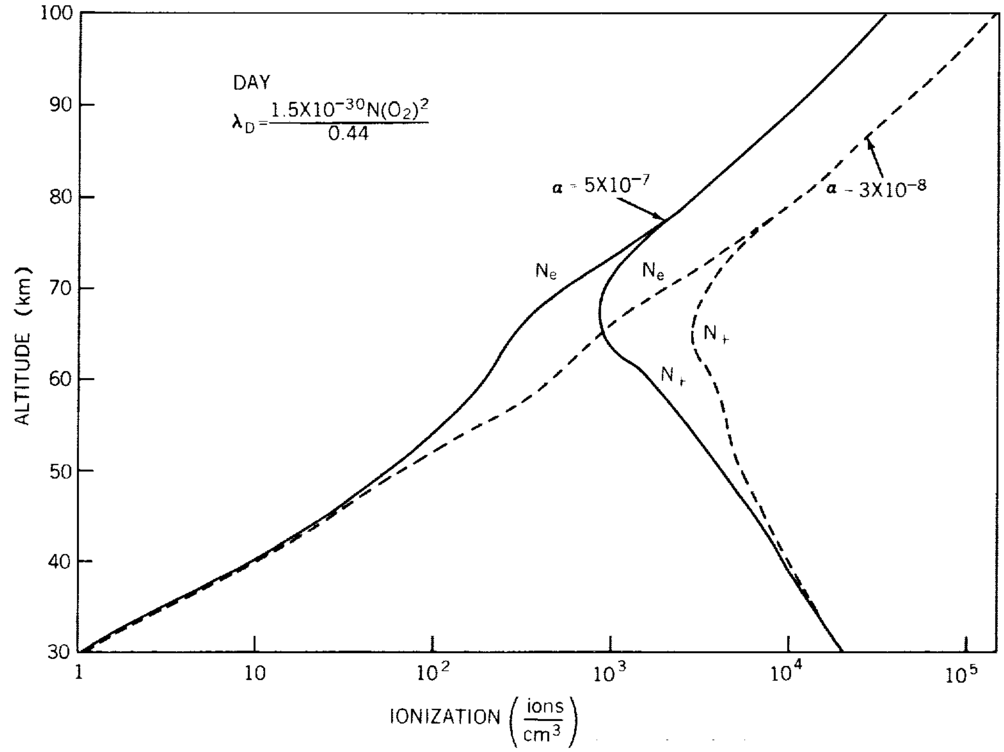


Figure 3—Daytime ionization of the mesosphere due to auroral electrons.

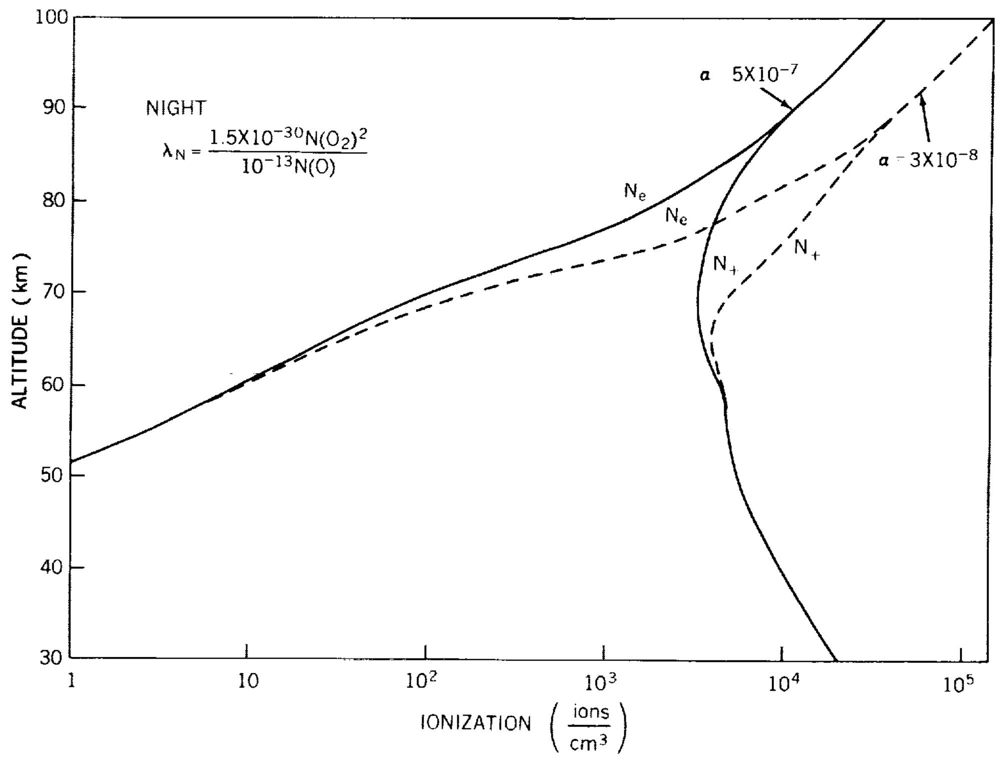


Figure 4—Nighttime ionization of the mesosphere due to auroral electrons.

Figures 3 and 4 give the electron and ion density distributions for an auroral event where the incident electron flux is that described previously. Both day and night conditions are described.

## CONCLUSIONS

It has been shown that bremsstrahlung resulting from auroral electrons can be an important source of ionization in the lower ionosphere. The effect of the bremsstrahlung is to extend the region of ionization of the primary electrons to altitudes where normally cosmic rays are the only source of ionization. When the energy spectrum of the particles can be represented as $1.6 \times 10^{12}\ E^{-5.2}$ particles/cm$^2$-sec-kev-ster, the ionization due to bremsstrahlung plays a significant role from 50 km to 70 km.

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NASA-Langley, 1963 G-464