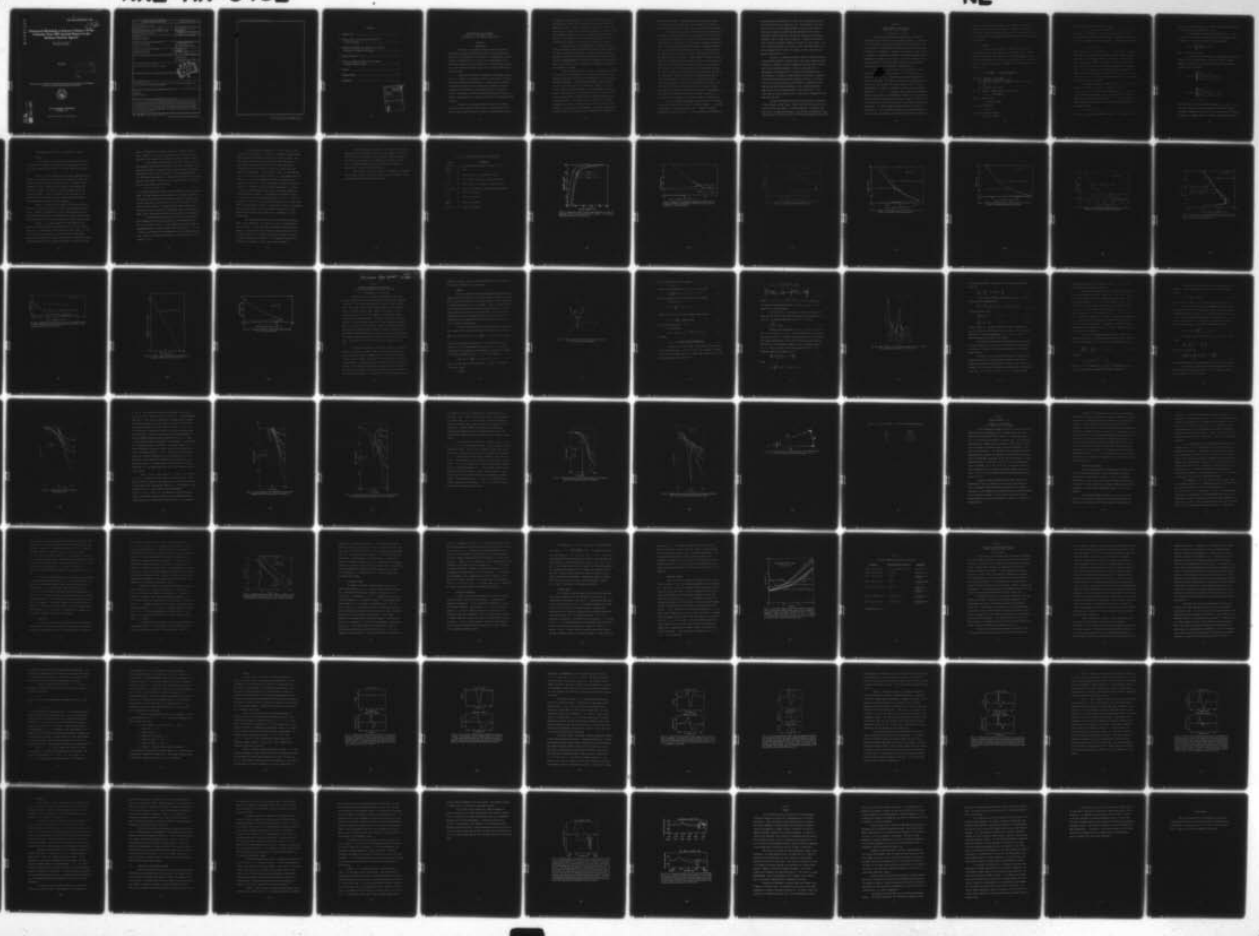
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# Numerical Modeling of Aurora Volume I of the Calendar Year 1975 Annual Report to the Defense Nuclear Agency

*Plasma Dynamics Branch*
*Plasma Physics Division*

April 1977

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This research was sponsored by the Defense Nuclear Agency under subtask L25-AAXHX633, work unit 15, work unit title Numerical Auroral Models.

NAVAL RESEARCH LABORATORY
Washington, D.C.

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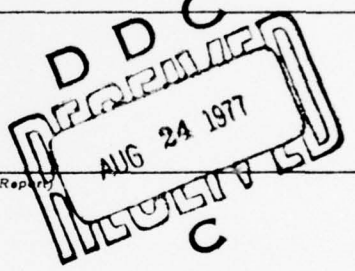
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Work on aurora models by the Plasma Dynamics Branch of NRL for the year 1975 is reported. Correlations between auroral phenomena and high altitude nuclear explosion effects are discussed. An improved proton deposition code is described which includes cross sections for $O_2$, O and $N_2$ interactions with protons. The accuracy of the NRL electron deposition code for large angle scattering has been confirmed by a study of electron backscatter. An analysis of NO densities observed in auroral arcs is also presented. The report concludes with a presentation of recent improvements in the NRL auroral electrodynamic models.

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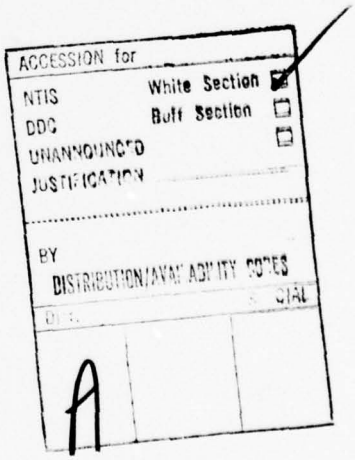
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NUMERICAL MODELING OF AURORA
Volume I of the Calendar Year 1975
Annual Report to the Defense Nuclear Agency

# Section 1

# INTRODUCTION

At the core of the modern defensive systems are lines of communication serving as intelligence links for the initiation and direction of countermeasures. Confidence in a communication system's immunity to disruption is a function of one's understanding of the large scale changes that can be induced in the communications environment by both natural and other means, such as a high altitude nuclear explosion (HANE).

A HANE causes ionospheric disturbances from prompt gamma-ray, x-ray, UV, optical, or IR emissions, from late time motion of ionized debris and emissions from that debris. A complex series of physical and chemical reactions can be initiated with consequent enhanced ionization and perturbation of the ambient electric and magnetic fields. The program of the NRL Plasma Dynamics Branch is designed to produce reliable models for predicting ionospheric disturbances produced by HANEs.

Confidence in a numerical model derives from the model's ability to produce results consistent with a suitably complete and accurate observational data base. However, the observational data for

the response of the ionosphere to nuclear events is insufficient and the augmentation of the data is precluded by treaty restrictions on atmospheric testing. Under these circumstances, what is needed is a natural source of large scale ionospheric disturbances for which sufficient observations have been made. In addition there must be some parallels in the physics of the natural event and that of a HANE. The disturbances responsible for the aurora meet these requirements.

HANEs and auroras are characterized by energetic charged particles streaming along geomagnetic field lines and interacting with the ambient atmospheric constituents. Particle energies, degrees of ionization and heating rates differ between the two events, but ample theoretical correlations exist to make one's capability for modeling the aurora a good measure of one's capability for modeling the response of the ionosphere to a HANE.

Auroral models also help to provide a link between the modeling of the late time development of scintillation sources from HANE induced disturbances and scintillation observations (e.g. the Wideband Satellite Experiment). HANE phenomenology models provide as output the basic or initial state of the ionospheric plasma (i.e. electric fields, currents and plasma densities) in the immediate aftermath of a nuclear event and this in turn serves as the input for programs which follow the development of irregularities in those regions where the plasma is unstable. The auroral models are analogous to the HANE phenomenology models in that their output is the basic state of the ionosphere, but for an auroral disturbance. The auroral precipitation patterns which serve as input for auroral models can be supplied by

satellite observations. The plasma densities, currents and electric fields which the model computes are also observable by satellite and ground based radar and thus a check on the auroral model is available.

An auroral model in which confidence has been established can, in conjunction with observations on the ionospheric basic state, serve as a check on the programs used to model both HANE and aurora-induced irregularities. Observation of the ionospheric parameters necessary as input for the programs which model the formation of irregular regions are, for practical reasons, limited in coverage. Much scintillation data will be taken in regions for which no observations of the basic ionospheric state have been made. Auroral models, in which the output quantities are computed self-consistently, can be used to determine the missing data points, thereby extending the scope of the scintillation observations. A more important consequence of this derives from the fact that the model can provide the basic state parameters over much of the auroral oval. Smaller scale computer programs then are used to follow the development of irregularities in regions where plasma instabilities prevail. These are the same codes that are used in the HANE program. The output of these codes serves as input to signal propagation codes which predict scintillation effects. Comparisons of the computed and observed scintillations provides a measure of the reliability of the programs used to model ionospheric irregularities.

NRL has continued to progress along three lines of investigation which form the core of the auroral modeling programs: (1) particle interactions, (2) chemical reactions, and (3) changes in ambient ionospheric currents and fields. The proton deposition code PRODEP has

been improved by the addition of $O_2$ and O to the original code which had provided only for the presence of $N_2$. The influence of the geomagnetic field in proton energy degradation has also been included. Other work on particle interactions has included a study of backscattered electrons which has confirmed the accuracy of the electron deposition code for large angle scattering. A summary of the year's work on particle interaction appears in section 2 of this volume. The work on particle deposition in sections 2 and 3 was done early in CY 75 and was stopped in FY 76 under the guidance of DNA. Note that this annual report covers CY 75.

Section 4, on auroral chemistry, contains a critical analysis of NO densities observed in auroral arcs. This study demonstrates the importance of having an accurate knowledge of even the minor constituents in the disturbed atmosphere. Finally we conclude with a presentation of improvements in the auroral electrodynamic models. The importance of anomalous plasma processes on structure of electric fields and current systems has been studied in detail, as the structure of the fields and currents are important to ionospheric plasma stability and scintillation phenomena. Also, we present improved model results for the midnight region of the auroral oval. It is these types of results which will be of great use in interpreting Wideband Satellite Data.

The work performed at NRL during the past year is summarized in the remainder of this volume. Much of this work has been previously reported in NRL Memo Reports, at several symposia, in technical journals, and at DNA sponsored meetings. The principal contributors in each technical area are listed as authors of the section describing that work.

Section 2

# IMPROVED MODEL TO STUDY PROTON DEPOSITION IN THE ATMOSPHERE

J. E. Rogerson and J. Davis

The deposition of energetic particles into the earth's atmosphere causes an abundance of interesting phenomena. In addition to the spectacular visual display produced by auroral emissions, the auroras provide a unique means for studying the complex of mechanisms occurring in the atmosphere. Knowledge of the causes of these effects is important in assessing the influence the disturbed atmosphere has on communication systems and their design. Also, since enhanced ionization is generated in the polar region, changes in the atmosphere's characteristics can be investigated during PCA events.

Many studies of the auroral electron deposition[1-8] and proton deposition[9-14] has been reported. In an earlier report, a simplified model based on a continuous-slowing-down approximation (CSDA) was described. This model contained only one atmospheric constituent, $N_2$, and neglected the earth's magnetic field. In this revised model, the number of atmospheric constituents is extended by including $N_2$, $O_2$, and O. By assuming a dipole model of the geomagnetic field, an expression for the differential element of arc length traversed by a charged particle spiraling around a magnetic field line[16-17] is incorporated into the CSDA to produce a more realistic proton energy degradation. The charge exchange formalism as given by Allison[18] is generalized to a three component atmosphere and a charge-equilibrated flux of protons and hydrogen atoms is generated from which atmospheric

excitation and ionization processes can be calculated. Secondary electron effects are treated as before[15]. Finally, total ionization results are presented and compared with results of the previous model[15] and with similar calculations by Eather and Burrows[9], who used a different technique.

## 2.1 THE MODEL

A charged particle moving in a magnetic field follows a spiral path about the field lines due to the Lorentz force. The arc length of this spiral path depends on the particle's charge, velocity, mass, and pitch angle with respect to the given field line. An equation for the differential element of arc length of the spiral path can be given as [16,17]

$$ds = \left\{ \frac{(1-3x/4)}{(1-x)} \cdot \frac{x^3}{x^3-\sin^2\alpha_e \sqrt{4-3x}} \right\}^{\frac{1}{2}} dr \ , \qquad (2.1)$$

where ds = increment of arc length,
dr = increment of geocentric distance,
$r_e$ = equatorial radius of the magnetic field line (L shell),
$x = r/r_e$,
$\alpha_e$ = equatorial pitch angle.

Eq. (2.1) assumes a dipole magnetic field given by

$$B(r,\lambda) = M\sqrt{1+3\sin^2\lambda} \ / \ r^3 \ , \qquad (2.2)$$

where M = dipole moment

$\lambda$ = magnetic latitude.

$\lambda$ and r are related by

$$r = r_e \cos^2\lambda \ . \qquad (2.3)$$

The first adiabatic invariant

$$\sin^2\alpha/B = \text{constant} \qquad (2.4)$$

is also included, where $\alpha$ is the pitch angle.

Eq. (2.1) contains a singularity at x = 1, or r = $r_e$. This singularity corresponds to a point in the equatorial plane. For auroral studies, high latitude regions are of primary interest, and it is therefore reasonable to avoid this point. A singularity also occurs for

$$x^3 - \sin^2 \alpha_e \sqrt{4-3x} = 0,$$

which corresponds to a mirror point ($\alpha = \pi/2$). This second singularity corresponds to an initially downward-moving particle being reflected upward due to the converging magnetic field lines. Such a particle does not penetrate as deeply as it might if it had a smaller pitch angle; hence, it does not produce as much ionization as it otherwise might. Also, the treatment of "mirroring" particles introduces further complexities into the calculation. For this reason, and because the aim is to study the maximum perturbations created in the atmosphere, this singularity is also avoided.

By assuming a spherical earth of radius a, Eq. (2.1) can be taken as a function of altitude z by setting r = a+z; then x = (a+z) / $r_e$. For a given altitude difference, $z_1 - z_2$, Eq. (2.1) can be numerically integrated from $z_1$ to $z_2$ to give the arc length traveled by the particle in going from $z_1$ to $z_2$. Then, by using the CSDA as described in Reference 15, the proton energy degradation is computed as follows:

$$\Delta E = N_t (z_1) L_p (E,z_1) \Delta S , \qquad (2.5)$$

where $N_t(z_1)$ is the total atmospheric density at $z_1$, $L_p(E,z_1)$ is the

total proton loss function at $z_1$ for energy E, and $\Delta E$, and $\Delta S$ is the arc length traversed in going from $z_1$ to $z_2$.

The individual loss function for protons in $N_2$, $O_2$, and O are adapted from analytic expressions given by Green and Peterson[19]. At altitude z, the total loss function is computed from

$$L_p(E,z) = \sum_{i=1}^{3} \frac{N_i(z)}{N_t(z)} L_{pi}(E,z), \tag{2.6}$$

where i is the species index.

At a given altitude and energy, a generalized charge equilibrated flux is calculated based on Allison's[18] charge exchange formalism. The generalized equilibrated fraction of protons and hydrogen atoms are given by

$$F_1(E,z) = \frac{\sum_i N^i(z)\, \sigma_{01}{}^i(E)}{\sum_i N^i(z)\, [\sigma_{01}{}^i(E) + \sigma_{10}{}^i(E)]}, \tag{2.7}$$

$$F_o(E,z) = \frac{\sum_i N^i(z)\, \sigma_{10}{}^i(E)}{\sum_i N^i(z)\, [\sigma_{01}{}^i(E) + \sigma_{10}{}^i(E)]}$$

$$= 1 - F_1(E,z),$$

where the index i runs over the three species $N_2$, $O_2$, and O. $\sigma_{10}$ is the cross section for charge exchange of a proton with a neutral (creating a hydrogen atom), and $\sigma_{01}$ is the cross section for electron stripping of a hydrogen atom by a neutral (creating a proton again).

For a given process $\alpha$ involving proton impact on species i, a volume production rate at altitude z for a given proton flux $\phi$ (E) is

$$P^{i}_{p\alpha}(z) = N^{i}(z) \int F_1(E,z)\, \sigma^{i}_{p\alpha}(E)\, \phi(E)\, dE, \tag{2.8}$$

and similarly for hydrogen atom impact processes with $F_1(E,z)$ replaced by $F_o(E,z)$.

To describe the creation of secondary electrons of kinetic energy T by direct ionization processes, an energy-differential cross section of the form

$$S(E,T) = d\sigma(E)/dT$$

$$= \frac{\sigma_{ion}(E)}{\Gamma \tan^{-1}\left(\frac{T_{max}}{\Gamma}\right)} \left[1 + T^2/\Gamma^2\right]^{-1} \tag{2.9}$$

as given by Edgar, Miles, and Green[14] is used. For E in keV, and $T_{max}$ in eV,

$$T_{max} = 2.18\ E. \tag{2.10}$$

This is equivalent to a form given by Banks, Chappell, and Nagy[3] for secondary electron production from electron impact ionization. By using the $\Gamma$ values given in Reference 3 and the value of 22 eV given by Reference 14 for proton impact ionization of $N_2$, $\Gamma$ values for proton impact ionization of $O_2$ and O can be obtained by scaling. The same S(E,T) was used for both proton and hydrogen atom impact on the same target gas because of insufficient data. Secondary electrons created by the charge exchange cycle are treated exactly as in Reference 14; i.e.,

$$S_{01}(E,T) = \sigma_{cycle}(E)\, \alpha e^{-\alpha T} (1-e^{-\alpha T_{max}})^{-1}, \qquad (2.11)$$

where $\sigma$ cycle - $\sigma_{10}\,\sigma_{01}/(\sigma_{10} + \sigma_{01})$, and $1/\alpha$ is taken to be 5 eV for each species. Excitation and ionization by secondary and higher order electrons are treated by the method described by Dalgarno[7] and used by Julienne[8].

## 2.2 CROSS SECTIONS

The principal sources for H and $H^+$ impact cross section data are the review articles by McNeal and Birely[20,21]. The charge exchange cross section for $O_2$ is taken from Stebbings, et al.[22] for lower energies and by doubling the O charge exchange cross section as given by Allison[18] for the higher energies. The electron stripping reaction of H by $O_2$ is obtained from doubling the O cross-section data given by Allison[18] for the same process. The charge exchange cross section for O was taken from Neynaber, et al.[23] for energies below one kev and from McNeal and Birely[21] for higher energies. Many of these cross sections do not extend below two to four keV in energy and were extrapolated to lower energies.

The input cross-section data points for proton, hydrogen atom, and electron impact processes are fitted to the points on a chosen energy grid E by a cubic spline representation as a function of ln E. In this way, only a few experimental points are needed for a good representation, and analytic fits to cross sections are not required. The cross sections are extrapolated to high energies by using the appropriate asymptotic forms.

The electron cross sections are summarized in Table 2.1

## 2.3 RESULTS

In this section, some results of the revised proton deposition model are presented and compared with the previous model[15] and with similar calculations by Eather and Burrows (hereafter denoted by EB).

Figure 2.1 shows a comparison of the energy degradation of an incident 100 kev proton in the two NRL proton deposition models for a pure $N_2$ atmosphere; in these calculations, the 1965 Jacchia[24] model atmosphere is used. Results for pitch angles of zero degrees and for about 45 degrees are shown when the earth's magnetic field is taken into account. It can be clearly seen that the effect of the magnetic field is to greatly increase energy degradation and thus reduce the penetration depth into the atmosphere.

Figure 2.2 shows the total number of $N_2^+$ ions produced as a function of altitude for these same 100 keV proton deposition calculations. At higher altitudes there is very little difference, but at lower altitudes, fewer ions are created when the earth's magnetic field is included because of the reduced penetration into the denser regions.

Figures 2.3-2.6 show comparisons of some results of the revised NRL model with similar calculations by EB. In these computations, the 1961 Chamberlin[25] model atmosphere is used, and $N_2$, $O_2$, and O are included as constituents. In the EB results, monoenergetic protons with isotropic pitch angle distributions are considered, whereas monoenergetic protons with a single pitch angle are treated in the NRL

results. Depositions in the polar regions are considered in both cases. Figures 2.3-2.6 present comparisons of the total ionization produced per unit volume versus altitude at several incident energies.

It can be seen in these Figures that the EB results at the lower energies can be matched very well at the lower altitudes by varying the pitch angle. At higher altitudes, there is some disagreement, especially for the 1000 keV calculation. The large differences for a 1000 keV proton are suggestive of a significant difference in the models used by EB and by NRL. Further study of References 9 and 25 indicated that the cross section for the process

$$H^+ + X \rightarrow H^+ + X^+ + e, \qquad (2.12)$$

i.e., direct ionization by protons, was not included in the EB calculations. At lower energies, charge exchange is the dominant process for ionization by protons, and the equilibrium fraction of hydrogen atoms is much larger than for protons; hence, this is a reasonable approximation at lower energies. At higher energies charge exchange cross sections are greatly reduced, the equilibrium fraction of protons is large, and the contribution from direct ionization is very significant.

To check whether this was indeed the case, the depositions were recomputed with the cross sections for the processes given by Eq. (2.12) set equal to zero. By then redefining the total number of charged particles at a given altitude as the sum of the $N_2^+$, $O_2^+$, and $O^+$ ions plus the number of protons generated from the charge exchange cycle, a new set of results was obtained. These results are shown in Figures 2.7-2.10.

It is seen that for energies of 100 keV or less, the agreement with EB is still good. In Figure 2.7, adding the charge exchange protons greatly overestimates the peak of the curve by about 50 per cent, whereas agreement is very good without this contribution. As noted in the previous section, however, the cross sections were extrapolated to very low energies, and this is probably the major source of the discrepancy. (The results in Figure 2.7 for total ions only are the same as the results in Figure 2.3. This follows from the fact that at 3 keV, the equilibrium fraction of hydrogen atoms is approximately unity; i.e., direct ionization by protons is effectively turned off.) Agreement is good for either calculation at 30 keV and 100 keV, as might be expected since this is the energy regime where charge exchange is dominant. The notably better agreement occurs at 1000 keV, as may be seen by comparing Figures 2.6 and 2.10. While the agreement in Figure 2.10 is not totally satisfactory, it is much better than that represented by Figure 2.6 and appears to verify the assumption that the proton direct ionization process is omitted by EB. The remaining discrepancies are probably due to differences in cross-section data.

The results presented thus far have involved only monoenergetic proton depositions. The program also treats a distribution of proton energies. An input flux with the energy distribution shown in Figure 2.11 was inserted into the program, and the results for total ionization produced as a function of altitude are shown in Figure 2.12. In this calculation, the Chamberlin 1961 atmosphere was again used, although it is possible to use any given model atmosphere.

Results given in this report have dealt only with ionization produced by proton depositions. However, it is possible to calculate the creation of other excited states or emission lines by putting in the relevant cross sections. For example, the calculation of the $N_2$ + 3914 angstrom emission line can be calculated by using the McNeal-Birely[20] data for this cross section.

The deposition model can be applied to deposition of energetic ions in debris particles such as that associated with STARFISH. In the coming year work will be done in this regard.

TABLE 2.1 - ELECTRON IMPACT CROSS SECTIONS FOR $N_2$

| STATE | REFERENCES |
|---|---|
| Ionization | Rapp and Englander-Golder[26]; Schram, et al.[27] |
| $A^3\sum_u^+$ | Borst[28] |
| $B^3\Pi_g$ | Chung and Lin[30]; Stanton and St. John[29] |
| $C^3\Pi_g$ | Finn, Aarts, and Doering[31]; Aarts and de Heer[32] |
| $W^3\Delta_u$ | Chung and Lin[30]; normalized to Chutjin, et al.[33] |
| Vibrational | Schulz[35]; normalized to Spence, Mauer, and Schulz[36] |
| $a^1\Pi_g$ | Green and Stolarski[34] |
| $b^1\Pi_u$ | Green and Stolarski[34] |
| $b^1\sum_u^+$ | Green and Stolarski[34] |
| Rydbergs | Green and Stolarski[34] |

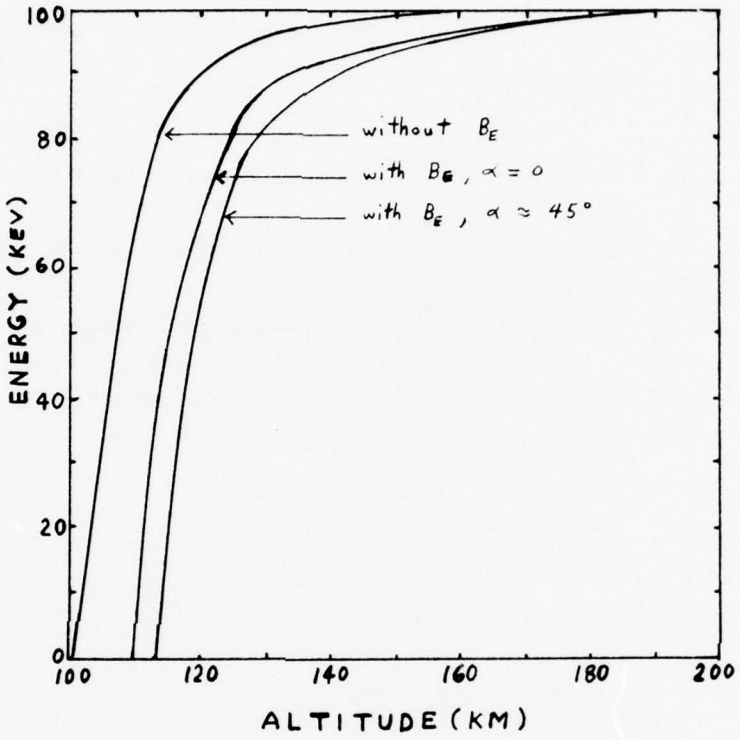



Fig. 2.1 — Comparison of 100 keV proton energy degradation in a pure $N_2$ atmosphere with and without the geomagnetic field $B_E$. $\alpha$ is the proton pitch angle with respect to the field lines.

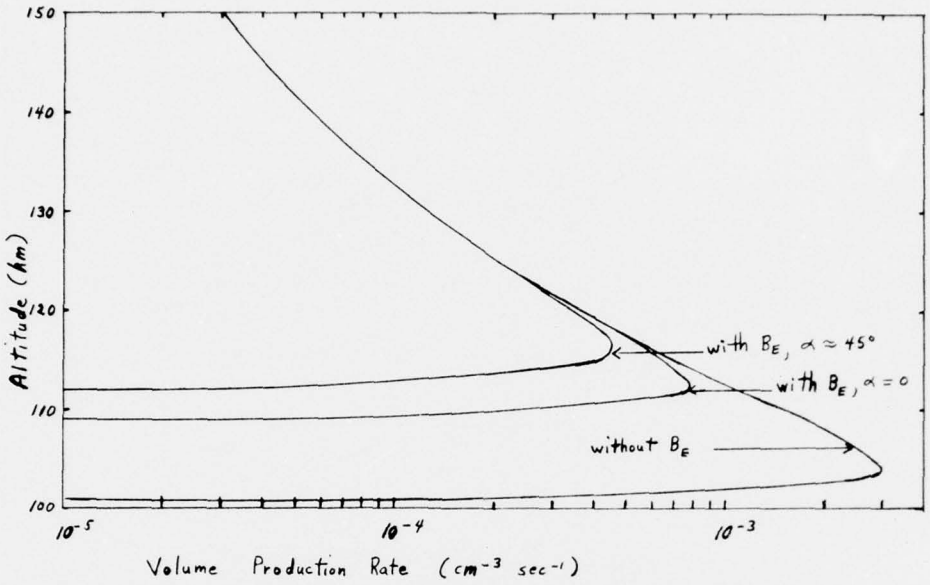



Fig. 2.2 — Number of ions produced vs altitude with and without the geomagnetic field $B_E$ by deposition of a 100 keV proton in a pure $N_2$ atmosphere. $\alpha$ is the pitch angle.

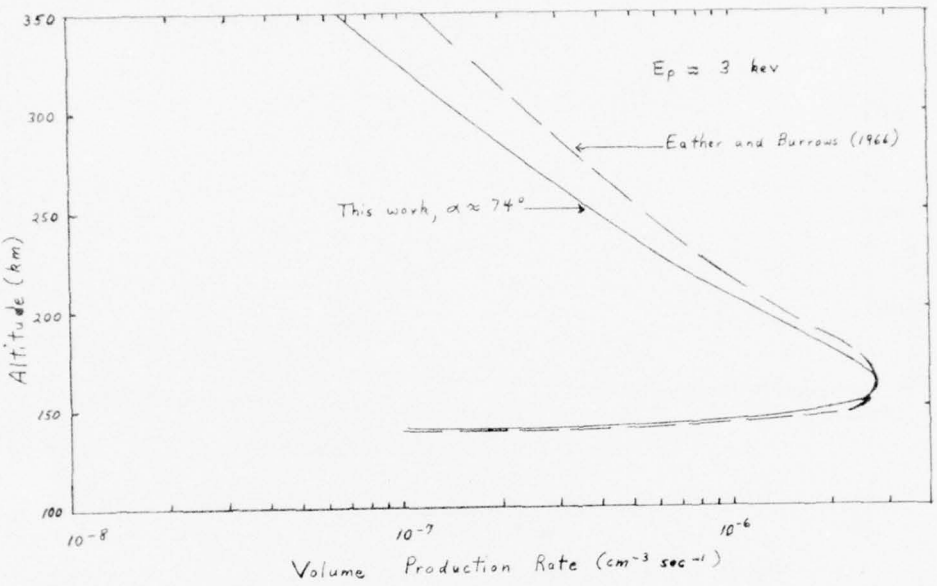



Fig. 2.3 — Number of ions produced by a 3 keV proton as a function of altitude in a Chamberlin 1961 model atmosphere

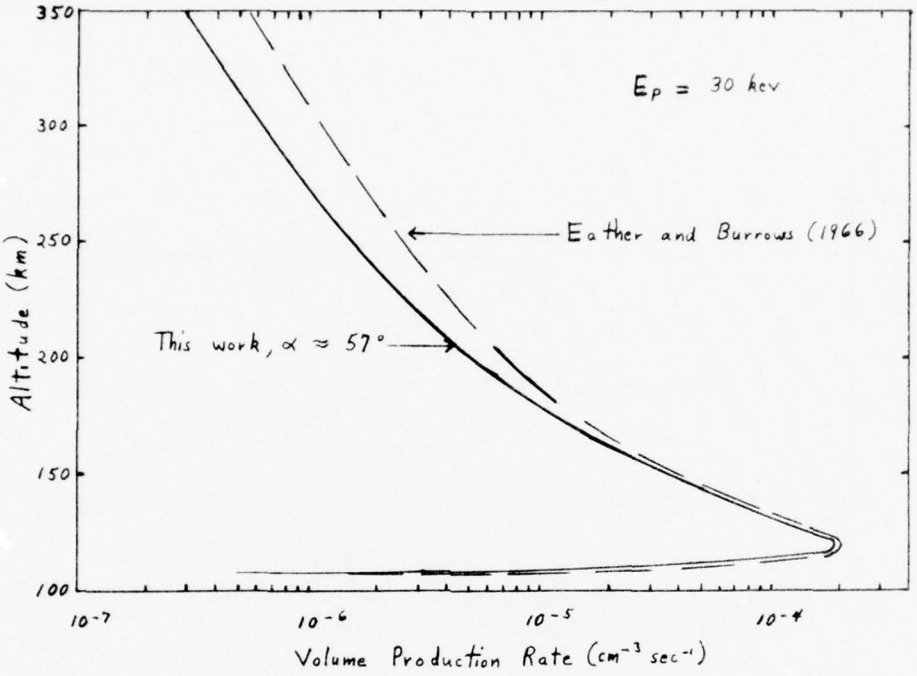



Fig. 2.4 — Number of ions produced by a 30 keV proton as a function of altitude in a Chamberlin 1961 model atmosphere

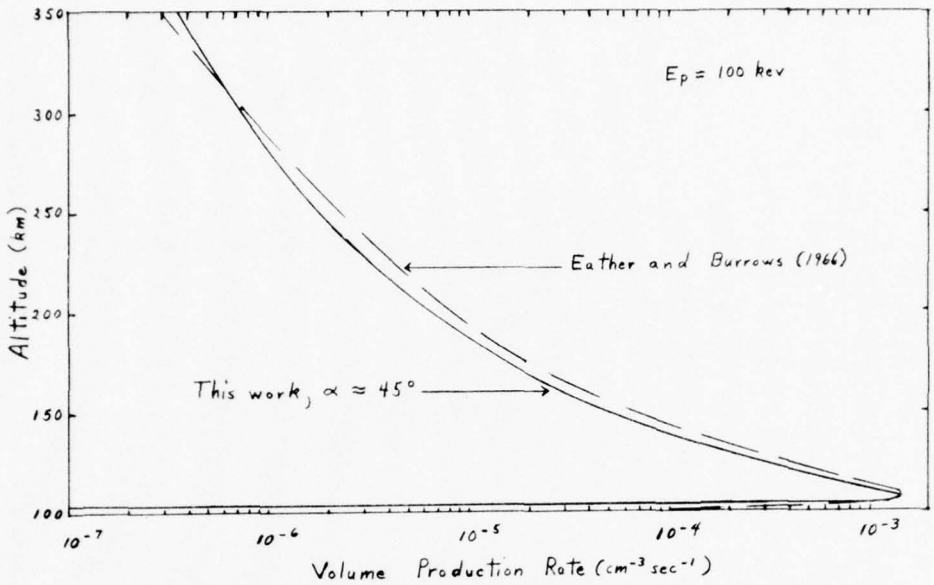



Fig. 2.5 — Number of ions produced by a 100 keV proton as a function of altitude in a Chamberlin 1961 model atmosphere

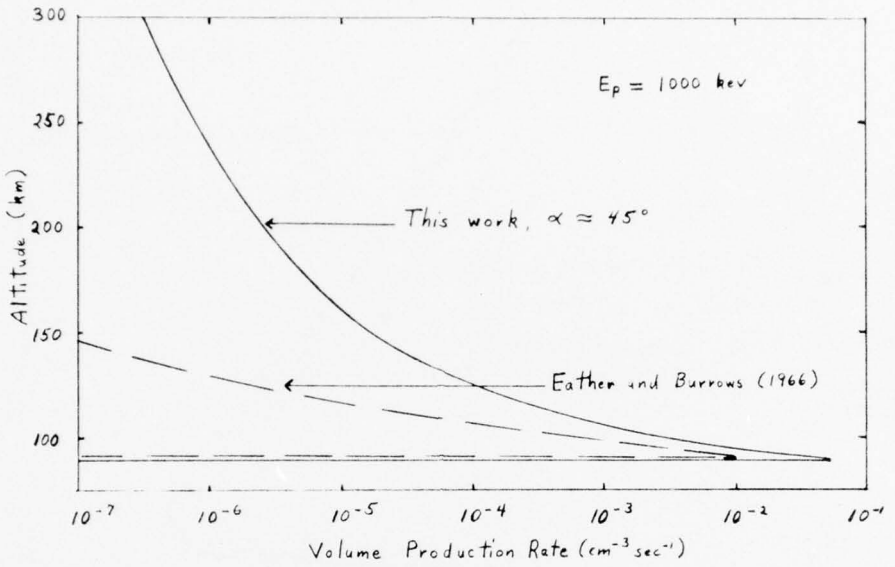



Fig. 2.6 — Number of ions produced by a 1000 keV proton as a function of altitude in a Chamberline 1961 model atmosphere

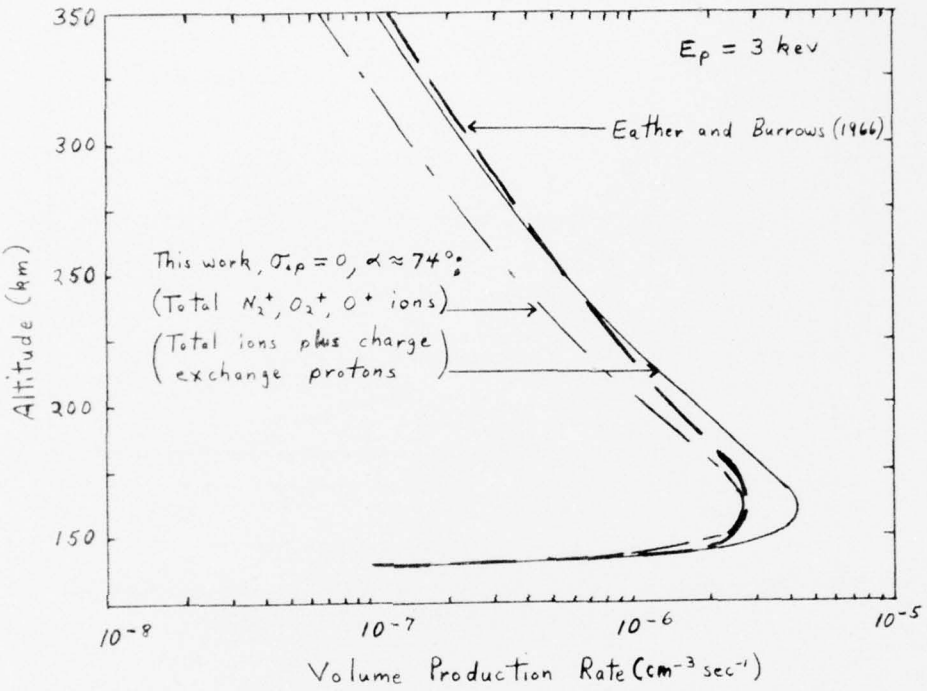



Fig. 2.7 — Recalculation of the ionization produced by a 3 keV proton in a 1961 Chamberlin model atmosphere when the cross section $\sigma_{ip}$ for direct ionization by protons is set equal to zero

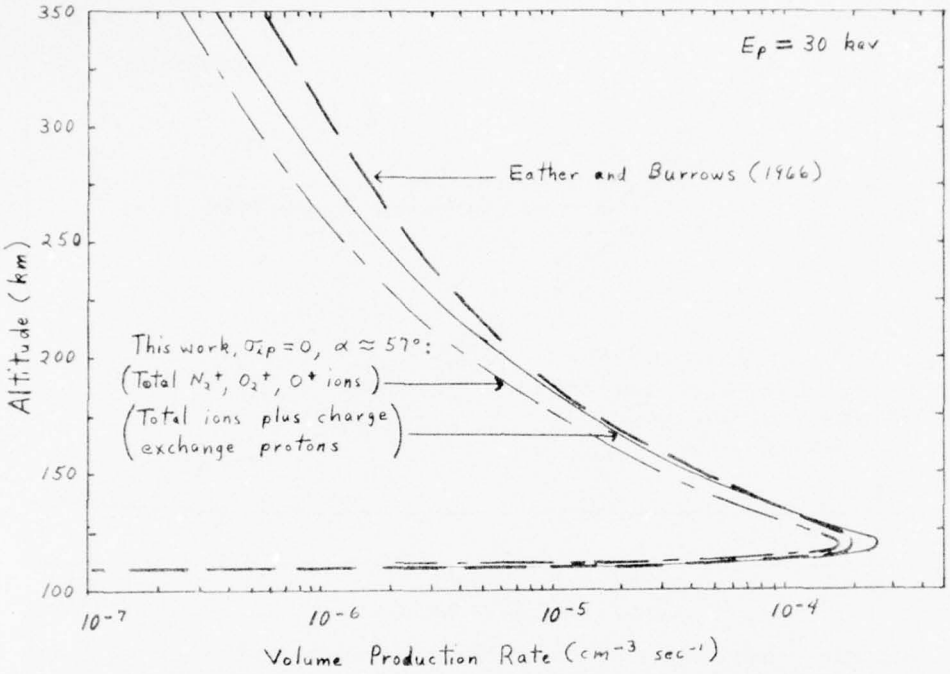



Fig. 2.8 — Recalculation of the ionization produced by a 30 keV proton in a 1961 Chamberlin model atmosphere when the cross section $\sigma_{ip}$ for direct ionization by protons is set equal to zero

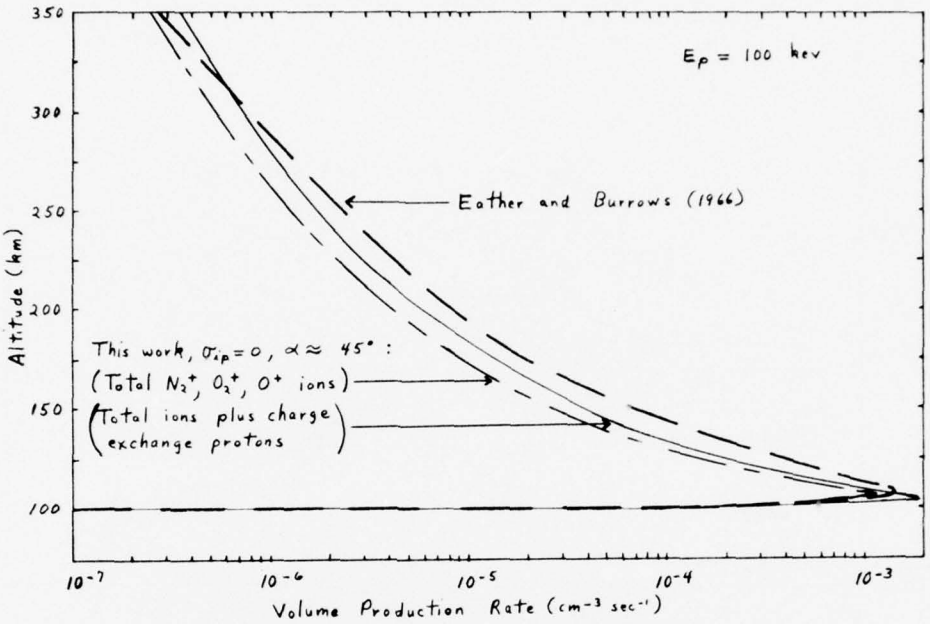



Fig. 2.9 — Recalculation of the ionization produced by a 100 keV proton in a 1961 Chamberlin model atmosphere when the cross section $\sigma_{ip}$ for direct ionization by protons is set equal to zero

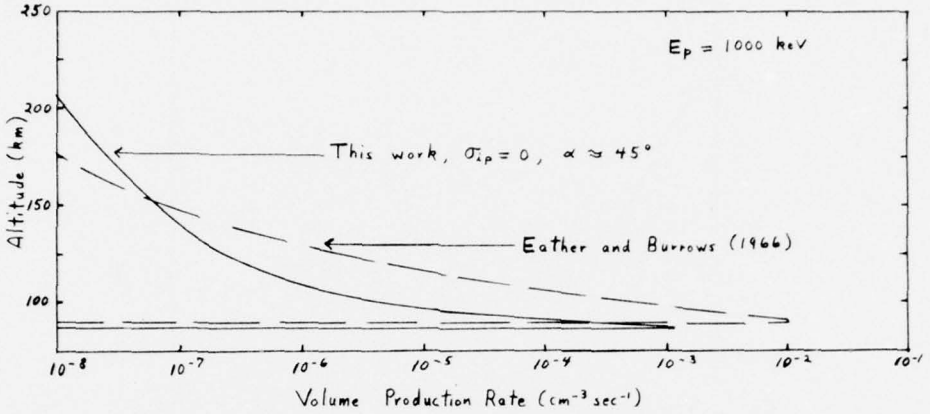



Fig. 2.10 — Recalculation of the ionization produced by a 1000 keV proton in a 1961 Chamberlin model atmosphere when the cross section $\sigma_{ip}$ for direct ionization by protons is set equal to zero

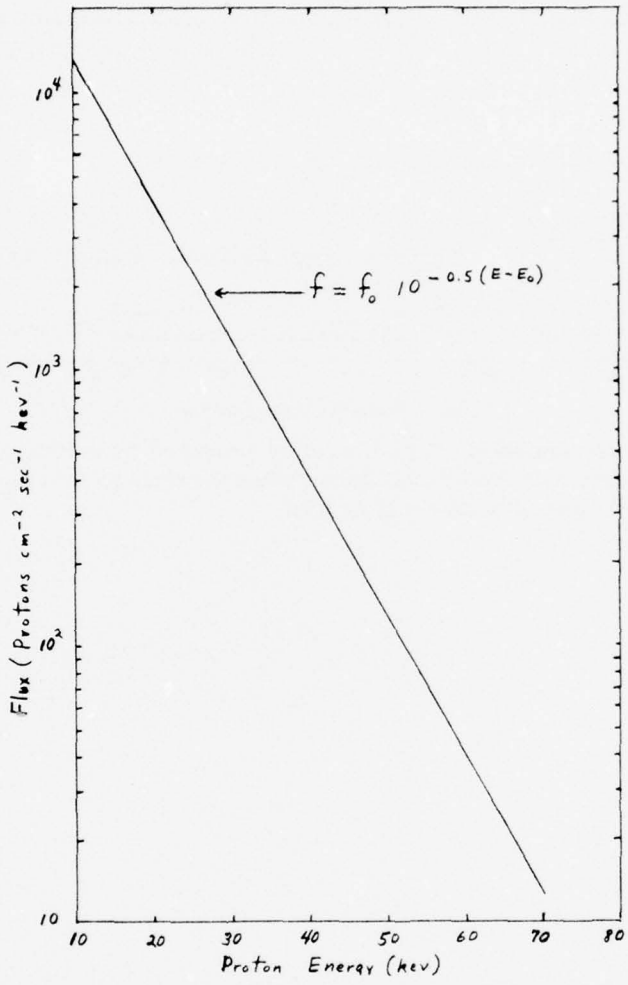



Fig. 2.11 — Proton energy distribution used in calculating the ionization vs altitude curve shown in Fig. 2.12

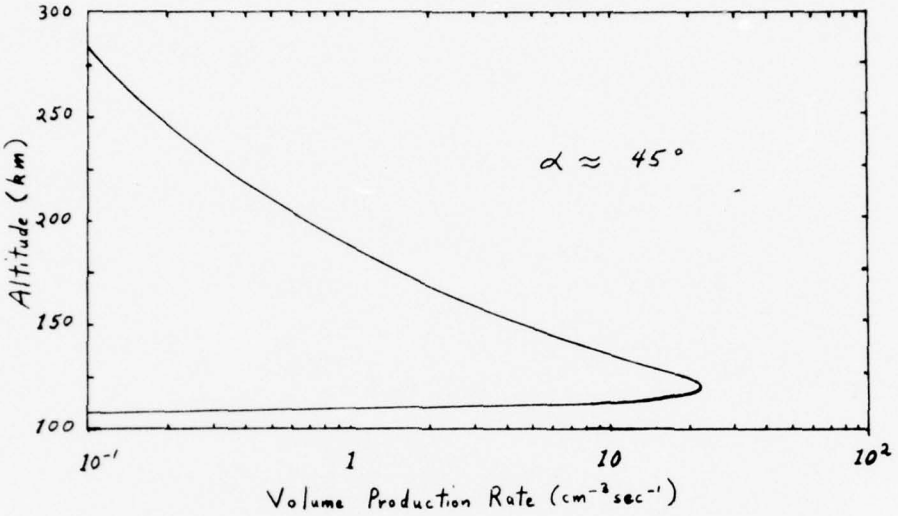



Fig. 2.12 — Ionization vs altitude in a Chamberlin 1961 atmosphere by proton flux of Fig. 2.11

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Section 3

# TRANSPORT TECHNIQUES FOR DESCRIBING THE ELASTIC SCATTERING OF ENERGETIC ELECTRONS

D. J. Strickland and I. B. Bernstein

In the past year, a code has been developed at the Naval Research Laboratory which solves an equation of transfer for energetic electrons.[43] The code is being applied to auroral studies and determines, for a given incident auroral electron spectrum, the electron flux as a function of pitch angle, energy, and altitude. The backscattered flux near 180° is very sensitive to the detailed angular dependence of the cross sections. In spite of the fact that the cross sections for large scattering angles are orders of magnitude smaller than for angles close to zero degrees, changes in the cross sections at large scattering angles produce noticeable changes in backscatter. To investigate such angular behavior in detail, we have applied the program to a simpler problem, that of purely elastic scattering by one constituent. The accuracy of the results is easier to determine for this case.

We begin by discussing the equation of transfer or Boltzmann equation for elastic scattering. This is followed by introducing a cutoff angle for a single scattering in order to study the importance of large angle scattering. Next, the Fokker-Planck equation for elastic scattering is introduced since it is derivable from the equation of transfer. Both numerical and analytic solutions have been obtained for the equation of transfer, and analytic solutions have been obtained for the Fokker-Planck equation. A subsection is devoted to discussing these

methods of solution. Finally, selected results for the two equations are presented followed by our conclusions.

## 3.1 METHODS

We wish to describe electron distribution functions which may possess strong anisotropies. The Boltzmann equation provides a starting point for such an exercise but in its most general form is not practical for most applications due to its complexity. There are several simplified versions of this equation which have had extensive use over the years, especialiy in the area of plasma physics. Of these we shall consider two here, the Boltzmann equation for infinitely massive scatterers and the counterpart Fokker-Planck equation, both for the case of elastic scattering alone.

We begin with the Boltzmann equation governing the distribution function f for elastic scattering by infinitely heavy scatterers:

$$\frac{\partial f}{\partial t} + \underline{v}\cdot\nabla_r f - \frac{e}{m}\left(\underline{E} + \frac{1}{c}\,\underline{v}\times\underline{B}\right)\cdot\nabla_v f = n\int d\Omega\,\sigma\,(v,\Theta)v\left[f(f(\underline{r},\underline{v}'t)-f(\underline{r},\underline{v},t)\right] \tag{3.1}$$

where n is the density of scatterers, $\sigma$ is the differential cross section, and $\Theta$ is the scattering angle (see Fig. 3.1). Consider a steady state in the absence of electromagnetic fields where f depends on the space coordinate z alone. Eq. (3.1) then reduces to

$$\mu\,\frac{\partial}{\partial z}\,vf(z,v) = n\int d\Omega\,\sigma(v,\Theta)v\left[f(z,\underline{v}') - f(z,v)\right] \tag{3.2}$$

where $\mu$ is the cosine of the pitch angle ($\mu = \underline{v}\cdot\hat{e}_z/v$). Define the total cross section

$$\sigma_o = \int d\Omega\,\sigma \tag{3.3}$$

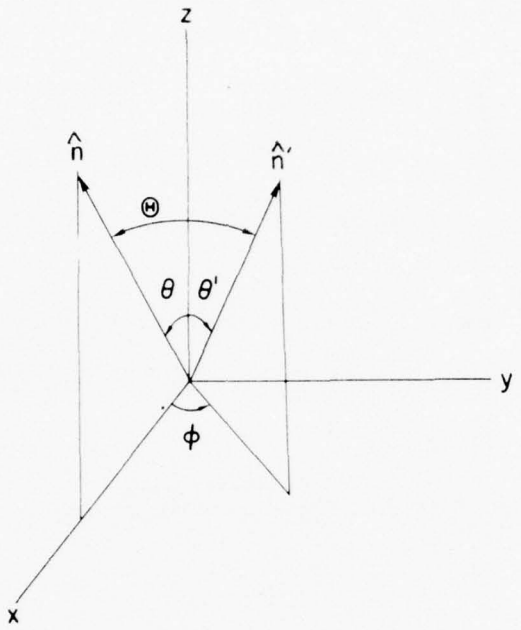



Fig. 3.1 — Geometry for the scattering of a particle from direction $\hat{n}'$ to $\hat{n}$ referenced to fixed direction z

and the differential scattering depth

$$d\tau = n\sigma_o dz \ . \tag{3.4}$$

Assuming azimuthal symmetry in f, Eq. (3.2) then yields

$$\mu \frac{\partial f}{\partial \tau} = \int d\mu' \ R(\mu, \mu') \ [f(\tau,\mu') - f(\tau,\mu)] \tag{3.5}$$

which is conventionally termed the equation of transfer.

The kernel R is

$$R(\mu,\mu') = \int_o^{2\pi} d\phi \ \sigma(v,\Theta)/\sigma_o \ . \tag{3.6}$$

Consider the case of the screened Coulomb cross section

$$\sigma(v,\Theta) = \frac{z^2e^4}{v^2p^2} \ \frac{1}{(1-\cos\Theta + 2\eta)^2} \tag{3.7}$$

with screening parameter $\eta$ .[44,45]

On introducing

$$\cos\Theta = \underline{v}\cdot\underline{v}'/v^2 = \mu\mu' + \sqrt{1-\mu^2}\sqrt{1-\mu'^2}\cos\varphi \tag{3.8}$$

R becomes

$$R(\mu,\mu') = \frac{2\eta(1+\eta)(1+2\eta-\mu\mu')}{[(\mu-\mu')^2 + 4\eta(1-\mu\mu') + 4\eta^2]^{3/2}} \tag{3.9}$$

Consider next a cutoff angle $\Theta_c$ such that for larger values of the scattering angle $\Theta$,$\sigma$ is set to zero. The parameter $\Theta_c$ enables us to examine the dependence of f on large angle scattering. In terms of this modified cross section, R is

$$R(\Theta_c,\mu,\mu') = \frac{2\eta(1 + 2\eta-\mu_c)}{\pi(1 - \mu_c)} \quad \frac{1}{a^2-b^2} \quad \cdot$$

$$\left[\frac{-b\sin\varphi_{max}}{a + b\cos\varphi_{max}} + \frac{2a}{\sqrt{a^2-b^2}} \tan^{-1}\left(\frac{\sqrt{a^2-b^2}}{a + b} \tan\frac{\varphi_{max}}{2}\right)\right] \tag{3.10}$$

where $a = 1 + 2\eta - \mu\mu'$, $b = \sqrt{1-\mu^2}\sqrt{1-\mu'^2}$, $\mu_c = \cos\Theta_c$, and $\varphi_{max}$ is the maximum allowed azimuthal angle for given $\Theta_c$, $\mu$ and $\mu'$. (See Appendix A for further details).

To solve Eq. (3.5), the range in $\mu$ has been divided into N zones, and the flux has been given a piece-wise linear dependence over the grid. The matrix representation of Eq. (3.5) is then

$$\mu_i \frac{\partial f_i}{\partial\tau} = \Sigma A_{ij} f_j \quad . \tag{3.11}$$

Examples of the dependence of R on $\Theta_c$, $\mu$ and $\mu'$ are given in Fig. 3.2 for a value of $\eta$ of $10^{-4}$. Such a value would be appropriate for electrons in the 100 kilovolt range scattering off a light nucleus. The sharply-peaked behavior of R at small scattering angles suggests that one make a Fokker-Planck expansion of the collision integral in Eq. (3.2) (see, e.g. Bethe et al.[45] and Rosenbluth et al.[46]). The resulting equation [see Appendix B] is

$$\mu \frac{\partial f}{\partial\tau} = \frac{Q}{2\sigma_o} \frac{\partial}{\partial\mu} \left[(1 - \mu^2) \frac{\partial f}{\partial\mu}\right] \tag{3.12}$$

where

$$Q = 2\pi\int_o^\pi d\Theta \sin\Theta (1 - \cos\Theta)\sigma(v,\Theta) \tag{3.13}$$

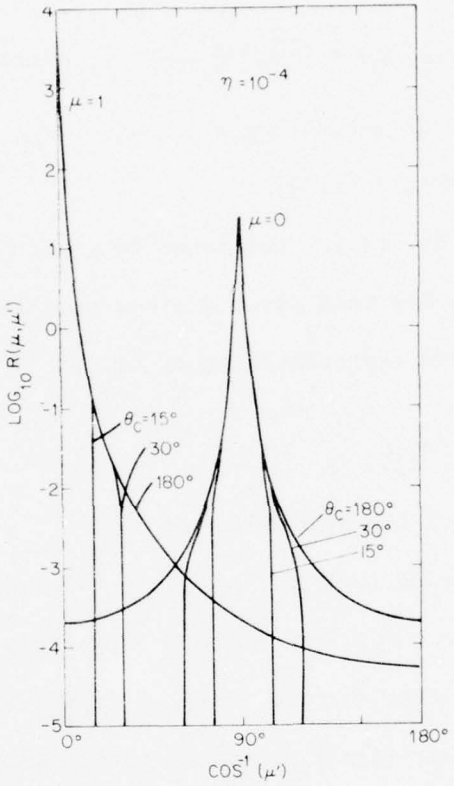



Fig. 3.2 — Plots of $R(\Theta_c, \mu, \mu')$ vs incident pitch angle for $\eta = 10^{-4}$ and for the two resultant pitch angles $\cos^{-1} \mu = 0$ and $90^\circ$

is the momentum transfer cross section. For the screened coulomb potential

$$\frac{Q}{2\sigma_o} = \eta \left[ (1+\eta) \ln \frac{(1+\eta)}{\eta} - 1 \right]. \tag{3.14}$$

In our finite difference approximation to Eq. (3.12), the right hand side is represented by

$$\frac{Q}{2\sigma_o} \Delta\mu^2 \left[ (1-\mu^2_{i-\frac{1}{2}})(F_{i-1}-f_i) - (1-\mu^2_{1+\frac{1}{2}})(f_i-f_{i+1}) \right] \tag{3.15}$$

at interior points, and by

$$\frac{-Q}{\sigma_o \Delta\mu} (f_1-f_2) \qquad (\mu = 1) \tag{3.16}$$

$$\frac{Q}{\sigma_o \Delta\mu} (f_{N-1} - f_N) \qquad (\mu = 1) \tag{3.17}$$

where the domain in $\mu$ has been divided into N equal intervals and $\mu_{i-\frac{1}{2}}$ is the value of $\mu$ half-way between $\mu_{i-1}$ and $\mu_i$. We have further multiplied the terms corresponding to $\mu = \pm 1$ by $(1 - \Delta\mu/4)$ for reasons explained at the end of this section.

Both numerical and analytic methods have been used to solve the matrix equations. Specifically, both methods have been applied to the equation of transfer, and the analytic technique to the Fokker-Planck equation.

Physically, for a well posed problem one must stipulate the distribution function for those particles incident on the system; collisions then determine the properties of those particles that are emerging. For the case here considered this corresponds to stipulating $f(o,\mu)$ for $1 \geq \mu > 0$ and $f(\tau_o,\mu)$ for $0 > \mu \geq -1$. In the work here

presented the choice for all cases was $f(\tau_o,\mu) = 0$, $0 > \mu \geq -1$, corresponding to an absorbing boundary.

The solutions obtained by numerical integration are based on an iteration scheme as follows: First, for $0 < \mu_i \leq 1$, $f_i(\tau)$ is set to zero and using a second order predictor-corrector scheme, Eq. (3.11) is integrated forward to $\tau = \tau_o$ (the lower boundary) for $0 < \mu_i \leq 1$ and in the process the results are stored on a pre-specified grid in $\tau$. Eq. (3.11) is then integrated backwards to $\tau = 0$ for $0 < \mu \geq -1$ using the values of $f_i(\tau)$ just computed for $0 < \mu_i < 1$, and just as with the forward integrations, the results are stored on the same grid in $\tau$. Forward and reverse integrations proceed until the values of $f_i(\tau)$ do not change appreciably. In practice, a technique is used which projects the iterated values of $f_i$ to their converged values in only three or four iterations.

We have used a standard eigenvalue method to obtain the analytic solutions of the difference differential equations. Assuming $f_i$ can be represented by $\psi_i e^{-\lambda\tau}$ we solve the characteristic equation

$$\sum_j \left( \frac{A_{ij}}{\mu_i} - \lambda \delta_{ij} \right) \psi_j = 0 \qquad (i = 1,N) \tag{3.18}$$

leading to

$$f_i(\tau) = \sum_\ell C_\ell \psi_{i\ell} e^{-\lambda_\ell \tau} \qquad (\ell = 1,N) \tag{3.19}$$

where $\lambda_\ell$ is the $\ell^{th}$ eigenvalue, $\psi_{i\ell}$ is the $\ell^{th}$ eigenfunction at $\mu_i$, and $C_\ell$ is a coefficient determined by boundary conditions.

By inspection, one can verify that the following is also a solution to either the equation of transfer or the Fokker-Planck equation:

$$f_i = \alpha + \beta \left( \mu_i - \frac{Q}{\sigma_o} \tau \right) \tag{3.20}$$

where $\alpha$ and $\beta$ are constants (for further details see Bethe et al.).

It turns out that two of the eigensolutions to the discretized equations serve to represent this solution, namely those with eigenvalue which go to zero as $N \to \infty$. In order to minimize errors for $\tau_o \gg 1$ associated with approximating the exact solution (Eq. 3.20) by a sum of exponentials, it is convenient to suppress the two eigensolutions corresponding to the smallest eigenvalues and write

$$f_i = \alpha + \beta \left( \mu - \frac{Q\tau}{\sigma_o} \right) + \sum_{\ell = 1}^{N-2} C_\ell \psi_{i\ell} e^{-\lambda_\ell \tau} \tag{3.21}$$

If one seeks eigensolutions $\phi_\ell(\mu) e^{-\lambda_\ell \tau}$ to Eq. (3.12), they satisfy

$$\lambda_\ell \mu \phi_\ell = \frac{d}{d\mu} \left[ (1 - \mu^2) \frac{d}{d\mu} \phi_\ell \right] \tag{3.22}$$

from which it follows that

$$\lambda_\ell \int_{-1}^{+1} d\mu \, \mu \phi_\ell = \int_{-1}^{+1} d\mu \, \frac{d}{d\mu} \left[ (1 - \mu^2) \frac{d\phi_\ell}{d\mu} \right] = 0. \tag{3.23}$$

Hence, eigensolutions of the differential equation carry no current.[45]

To enhance the correspondence between eigensolutions to the Fokker-Planck matrix equation and Eq. (3.12), the former are made to satisfy condition (3.23) in the form

$$y_1 + 2 \sum_{i=2}^{N-1} y_i + y_N = 0 \qquad (3.24)$$

where $y_i$ within the sum is given by our finite difference approximation to the right hand side of Eq. (3.22) (see Eq. (3.15)). Equation (3.24) then specifies $y_1$ and $y_N$ and leads to the replacement of Eqs. (3.16) and (3.17) by

$$\text{RHS} = -\frac{Q}{\sigma\Delta\mu}\left(1 - \frac{\Delta\mu}{4}\right)(\phi_1 - \phi_2) \quad (\mu = 1) \qquad (3.25)$$

$$= \frac{Q}{\sigma\Delta\mu}\left(1 - \frac{\Delta\mu}{\mu}\right)\left(\phi_{N-1} - \phi_N\right) \quad (\mu = -1) \qquad (3.26)$$

## 3.2 RESULTS

In this section, we present solutions of the equation of transfer and of the Fokker-Planck equation for a variety of conditions. Values of $10^{-3}$ and $10^{-4}$ for the screening parameter are considered, which would apply to kilovolt electrons scattering off light nuclei. A wide range of total scattering depths $\tau_o$ is assumed, from values of 5 to 1000. Values of the cutoff angle $\Theta_c$ of $15^\circ$, $30^\circ$ and $110^\circ$ have been used in the equation of transfer. Finally, incident fluxes with both isotropic and Gaussian dependences have been assumed.

Figs. 3.3 and 3.4 demonstrate the sensitivity of the back-scattered flux to $\sigma(\Theta,\eta)$ at large pitch angles. The solutions were obtained with the equation of transfer. The screening parameter is $10^{-4}$ for results in Figs. 3.3 and $10^{-3}$ for those in Fig. 3.4, thus providing for much stronger forward scattering for the first set of results. The total scattering depth $\tau_o$ is 100 for both systems. In each figure, results are given at $\tau = 0$ and 50 for $\Theta_c$ values of $180^\circ$,

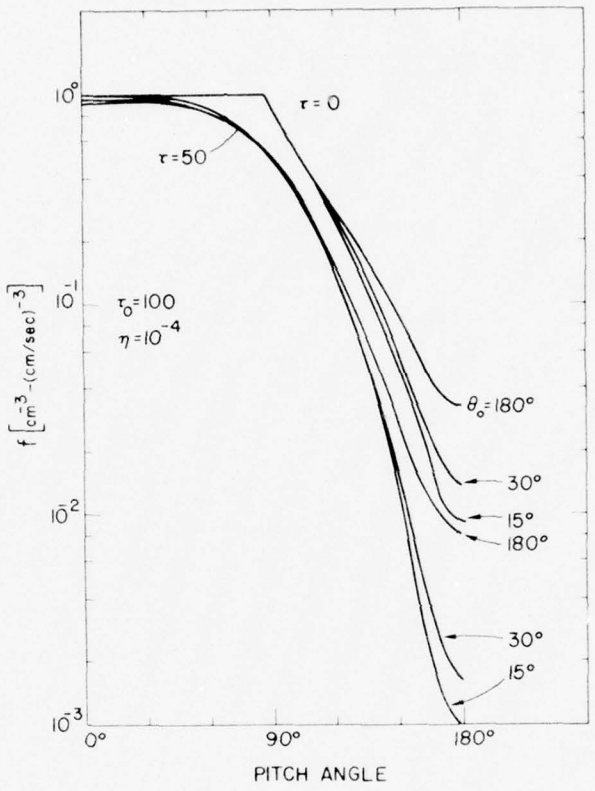



Fig. 3.3 — Solutions to the equation of transfer at the upper boundary and halfway through the medium for cutoff angles $\Theta_c$ of 180°, 30°, and 15° and for $\eta = 10^{-4}$

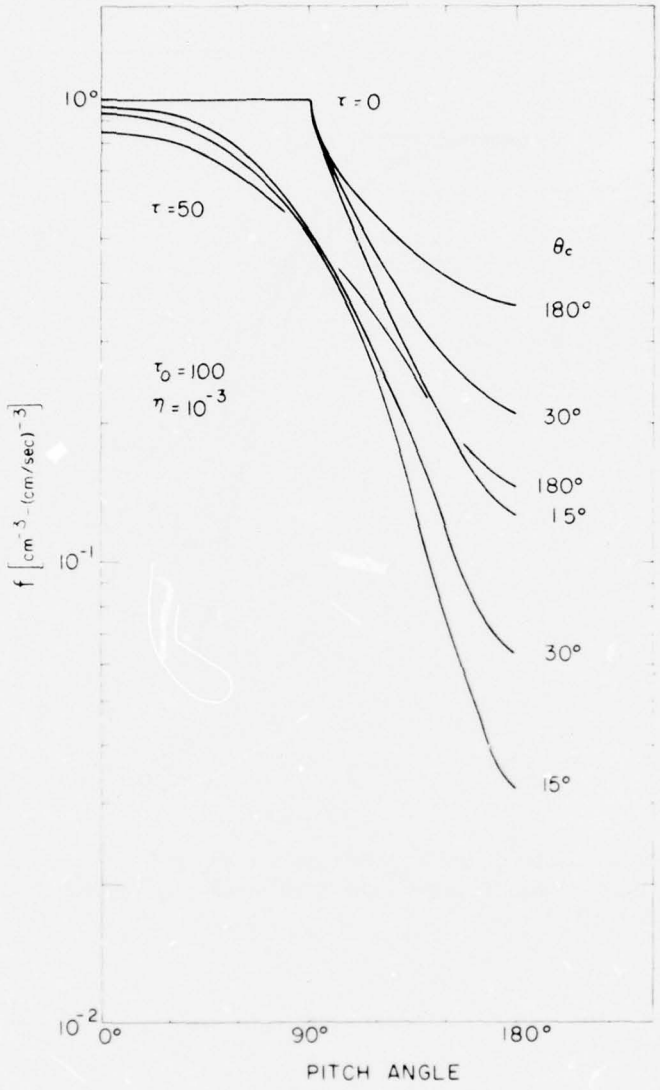



Fig. 3.4 — Solutions similar to those in Fig. 3.3, but with $\eta = 10^{-3}$

$30^{\circ}$ and $15^{\circ}$. We remind the reader that scattering is restricted to values less than or equal to the chosen value of $\Theta_c$. The backscattered flux near $180^{\circ}$ does decrease significantly as large angle scattering is restricted in spite of the fact that the values of the cross sections being affected are extremely small (see Fig. 3.2 for $\eta = 10^{-4}$). The results can be explained in terms of the effective turning point for the particle. Once the particle does turn, its probability of directly escaping through the upper boundary goes as exp $(-\tau)$ where $\tau$ is the depth from this turning point to the boundary. A small change in $\tau$ arising from varying $\Theta_c$ produces a much larger change in the escape probability, which then reflects itself in the backscattered flux. The results in Figs. 3.3 and 3.4 lead to an important point -- namely that a detailed knowledge of the scattering cross section is essential to accurately predict backscatter for systems with $\tau_o$ not much greater than 1. The Fokker-Planck solutions exhibit a similar sensitivity to $\Theta_c$ through changes that occur in the momentum transfer cross section.

Figs. 3.5 and 3.6 give fluxes at $\tau = 0$ for $\eta = 10^{-3}$ and for $5 \leq \tau_o \leq 1000$. Since all results refer to the same value of $\eta$, the ratio of the total number of scatterers for any two situations is simply the ratio of the corresponding values of $\tau_o$. The incident flux is isotropic in Fig. 3.5 and assumes a Gaussian dependence $[\exp (-1-\mu)^2/.25)]$ in Fig. 3.6. For each case, solutions have been obtained to both the integral equation and its counterpart Fokker-Planck equation and are presented in these figures. As $\tau_o$ increases,

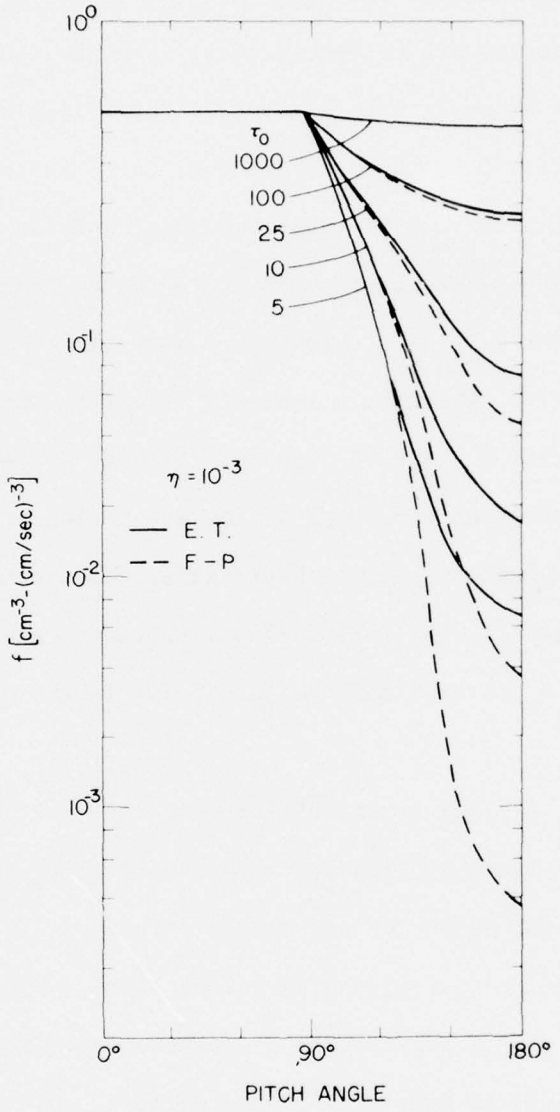



Fig. 3.5 — Transfer solutions and Fokker-Planck solutions for an isotropic incident flux and a range of total depth $\tau_o$

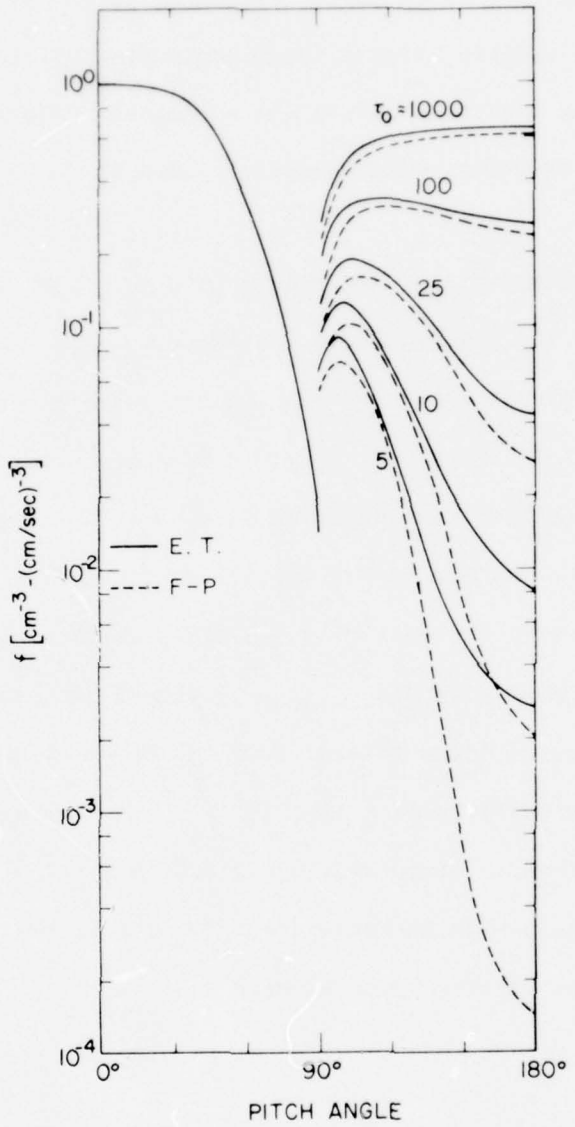



Fig. 3.6 — Solutions similar to those in Fig. 3.5 except with an incident flux having the Gaussian dependence exp $(-(1-\mu)^2)/.25$

the albedo or ratio of total backscatter to total incident flux approaches unity. Results for both equations are in good agreement for systems with $\tau_o \geq 100$. For such cases, enough scatterers are present for multiple small angle scattering to be effective. With decreasing $\tau_o$, however, single large angle scattering becomes relatively more important and is not adequately described by the Fokker-Planck equation, which underestimates the true amount of backscatter.

The variation of the flux with $\tau$ is shown in Fig. 3.7 for $\eta = 10^{-3}$, $\tau_o = 10$, and isotropic incidence. Again, solutions to both equations are given. Since we are considering a rather thin system, the incident flux experiences very little attenuation. The solution at $\tau = 10$ illustrates the lower boundary condition: zero flux from below. A second example of the variation of the flux with $\tau$ is shown in Fig. 3.8. Here, the system is ten times thicker and the incident flux has a Gaussian dependence on $\mu$. Fokker-Planck solutions are not included because of the number of curves already presented. Their behavior can be fairly well estimated from considering the previous figures. The imposed minimum at $\tau = 0$ due to the incident profile rapidly disappears with increasing $\tau$. For $\tau \geq 5$, the flux becomes a monotonically decreasing function with $\mu$.

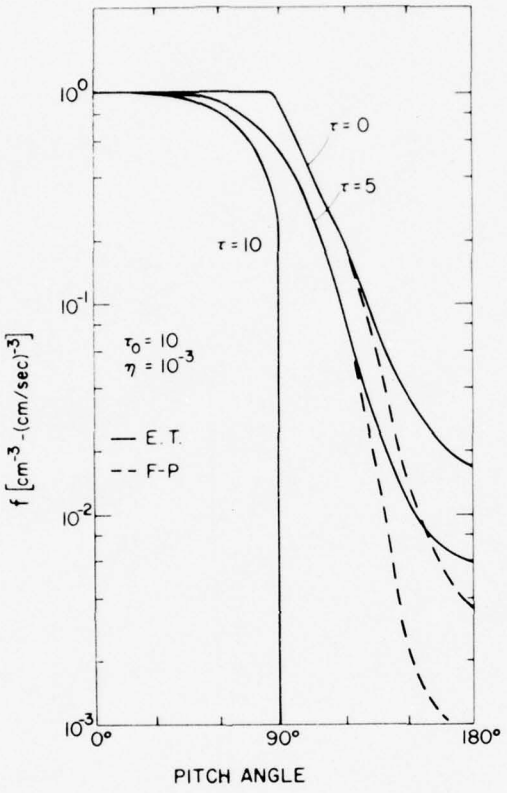



Fig. 3.7 — Transfer solutions and Fokker-Planck solutions for an isotropic incident flux showing their variation with depth $\tau$

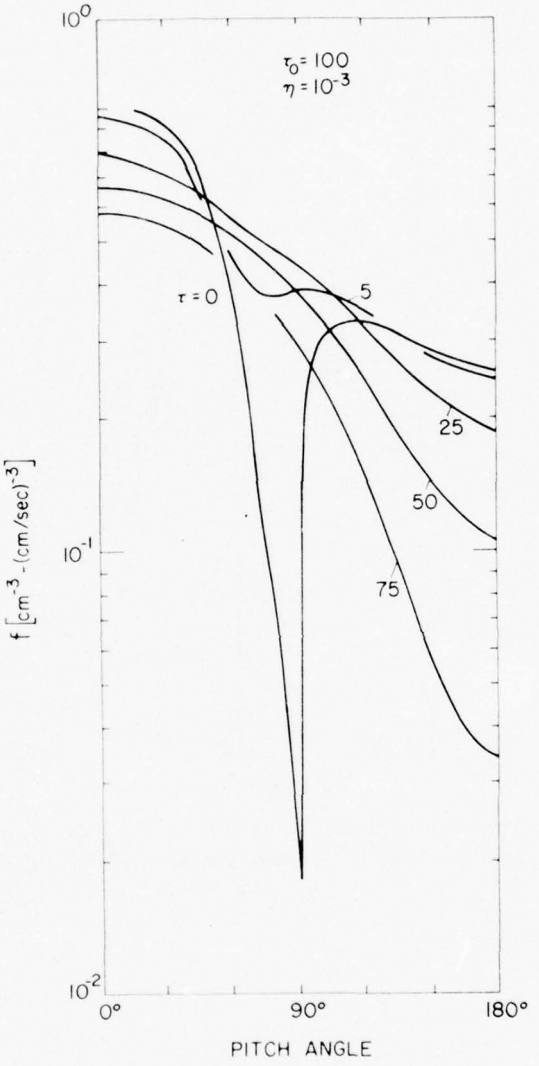



Fig. 3.8 — Transfer solutions for an incident flux with Gaussian dependence given in Fig. 3.6 showing their variation with depth $\tau$

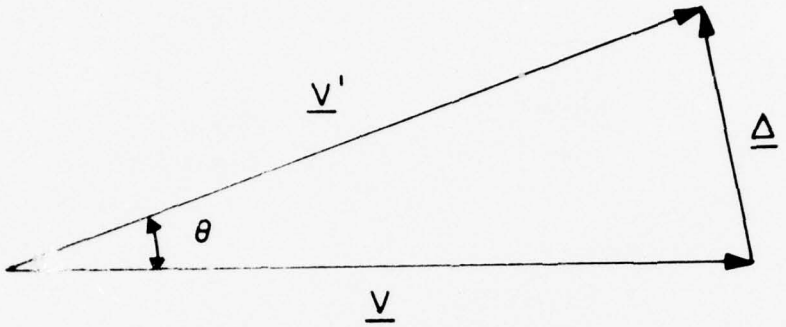



Fig. 3.9 — Relationship between incident velocity $\underline{v}$ and resultant velocity $\underline{v}' = \underline{v} + \Delta$. The case treated is for elastic scattering, i.e. $v' = v$.

Table 3.1. $(Q/2\sigma_o)$ from Eq. (3.14) versus Screening Parameter $\eta$.

| $\eta$ | $Q/2\sigma_o$ |
|---|---|
| $10^{-2}$ | $3.6 \times 10^{-2}$ |
| $10^{-3}$ | $5.9 \times 10^{-3}$ |
| $10^{-4}$ | $8.2 \times 10^{-4}$ |

Section 4

# AURORAL CHEMISTRY -- NO

E. Hyman, D. J. Strickland,
P. S. Julienne and D. F. Strobel

A most intriguing aeronomical problem in recent years is the anomalously large enhancements of NO concentration that have been inferred from measured $[NO^+]/[O_2^+]$ ratios[47-49]; [Swider and Narcisi, 1970; 1974] and directly measured[50] in auroral arcs. (The analysis of Jones and Rees[51] suggests that a measurement of the $[NO^+]/[O_2^+]$ ratio is not necessarily an accurate means to infer the NO density at the time of the measurement.) The available evidence suggests that these enhancements are spatially and temporally restricted to auroral arcs. There is considerable variability in the peak NO densities; for example, Swider and Narcisi[49] infer $[NO] \sim 6 \times 10^8$ cm$^{-3}$ at 110 km whereas Zipf et al.[50] measured $3.8 \times 10^{10}$ cm$^{-3}$ at 120 km. It should be noted that other measurements on the latter rocket flight suggest [NO] was only $1\text{-}5 \times 10^{10}$ cm$^{-3}$ at 110 km as compared with the mass spectrometer result of $2 \times 10^{11}$ cm$^{-3}$.[51]

Attempts to deduce NO concentrations from studies of the deactivation of $N_2(A^3\Sigma_u^+)$ molecules[52] and from NO $\gamma$ band emission[53] are not conclusive since the production mechanisms are not properly understood. In the former case the experimental cross sections adopted in the study were too high.[54] In the latter case it has not been demonstrated that auroral $\gamma$ band emission is indicative of ambient NO concentrations.

The Zipf et al. measurements are thus the most perplexing observations to explain and appear to violate the principle of energy conservation if precipitating auroral primaries are the major energy source.[51] Previous theoretical studies of auroral events have addressed a broad range of auroral processes but have not specifically tackled the formidable problem of auroral NO.[51] In this paper we confine our attention to auroral NO and investigate the applicability and limitations of conventional midlatitude ionospheric chemistry and certain speculative chemical schemes to address the question of how much NO can be produced during an auroral event and how chemically this production can be maximized. We conclude that while localized enhancements of $[NO]$ to $\sim 10^{10}$ $cm^{-3}$ are possible in a narrow altitude range, special and improbable circumstances are required; for example, vibrationally hot $O_2$.

## 4.1 CONVENTIONAL CHEMISTRY

First we discuss auroral NO production on the basis of conventional midlatitude chemistry, where odd nitrogen is formed by dissociation and ionization of $N_2$ with 9.8 and 15.6 eV required, respectively. In the case of $N_2^+$ production subsequent ion-molecule reactions are needed to break the $N_2$ bond, but these reactions are very exothermic. In either event considerable energy ($\geq$ 10eV) must be expended.

In the altitude range of interest, 100-120 km, $N_2$ is the dominant constituent and consequently the precipitating energetic electrons will dissipate most of their energy by dissociating and

ionizing $N_2$. There are three principal channels that must be considered and are illustrated in Figure 4.1. A direct ionization channel results in the production of $N_2^+$ which either reacts with O to form $NO^+$ and $N(^2D)$[55] or with $O_2$ to recycle $N_2$. For typical fluxes and auroral composition, 16% of the particle flux energy is expended to produce odd nitrogen by this channel. If $[NO] \sim [O]$ then $N_2^+$ would preferentially react with NO to give $NO^+ + N_2$ and cut off odd nitrogen production.

$N_2$ also dissociates in the manner described by Oran et al.[55] to produce $N(^2D) + N(^4S)$. Approximately 26% of the total energy is consumed in this channel. In addition 11% of the particle energy is used to dissociatively ionize $N_2$ and form $N^+$ and N. The electronic state of the N atom is not known but presumed, without serious consequences, to be in the ground $^4S$ state. The $N^+$ will react with $O_2$ to produce either $NO^+$ or $N(^2D)$. According to studies by Rusch et al.[56] and Strobel et al.[57], recent odd nitrogen data requires that $NO^+$ dissociatively recombine to form principally $N(^2D)$. Thus, the principal source of $N(^4S)$ is the pure dissociation channel.

The remaining ~ 50% of the energy is used to ionize O and $O_2$, to produce radiation, etc. Subsequent reactions of $O_2^+$ and $O^+$ do not produce odd nitrogen, except the minor reaction path $O^+ + N_2 \rightarrow NO^+ + N(^4S)$. In the region 100-120 km $O^+$ reacts preferentially with $O_2$ unless either $O^+$ is translationally hot and/or $N_2$ is vibrationally excited. The measured $O^+$ concentrations preclude the rapid removal of $O^+$ by a fast reaction path and imply that $O^+$ has less than 0.4 eV of translational energy and that the $v \geq 2$ vibrational

levels of $N_2$ have a Boltzmann distribution at the kinetic temperature.

In summary, the precipitating energetic electrons expend ~ 50% of their energy in the production of odd nitrogen. It takes about 10 eV to dissociate $N_2$ and about 20 eV to produce a pair of odd nitrogens, which is more efficient than the 35 eV required to produce an ion pair. Thus, while odd nitrogen is efficiently produced, substantial energy (10eV) is required to initiate its production. The chemistry outlined in Fig. 4.1 results in the production of 1.9 $N(^2D)$ atoms for each $N(^4S)$ atom. The molecular processes involved in N atom production are not sensitive to the environmental conditions in the auroral zone in a manner that would alter the $N(^2D)$ to $N(^4S)$ production ratio.

For $N(^2D)$ and $N(^4S)$ there are two major reaction paths: a fast reaction with NO and a slower reaction with $O_2$. In the case of $N(^2D)$ the reaction paths are comparable when $[NO]/[O_2] \sim 0.1$. Thus, until NO is built up to large concentrations $N(^2D)$ mostly reacts with $O_2$ to produce more NO. For $N(^4S)$ it is well known that its reaction with $O_2$ involves a substantial activation energy (~ 6 k cal) and at room temperature is very slow ~ $10^{-16}$ $cm^3$ $sec^{-1}$. The reaction paths of $N(^4S)$ are comparable when $[NO]/[O_2] \sim 4 \times 10^{-6}$; i.e., for NO concentrations below ambient values. Large buildups of NO are precluded in a short period of time under normal circumstances as much of the NO produced by $N(^2D) + O_2$ will be destroyed by $N(^4S) + NO$. It is obvious that to maximize the auroral NO production rate the appropriate chemistry must favor conversion of $N(^4S)$ into NO rather than $N_2$. Accordingly the reaction $N(^4S) + O_2$ must proceed at a rapid rate. The small steric

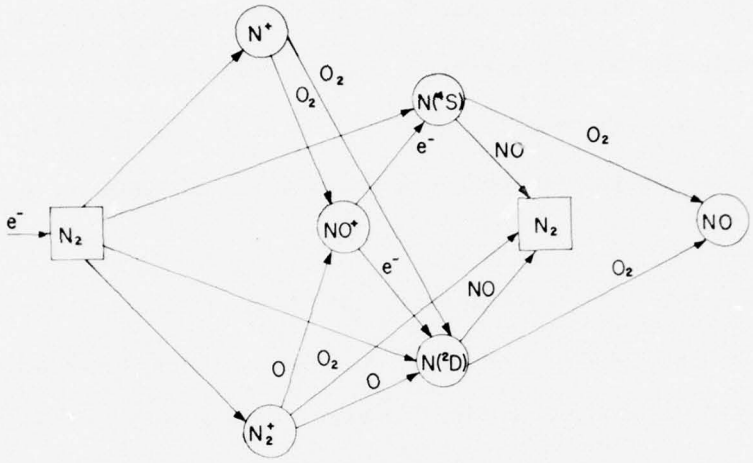



Fig. 4.1 — Principal odd nitrogen reactions leading to the formation of auroral NO

factor for this reaction eliminates the possibility of hot $N(^4S)$ atoms reacting with $O_2$ before being thermalized by collisions with the more abundant $N_2$ molecules. Electronic excitation of $O_2$ to $^1\Delta_g$ state does not help since the reaction $N(^4S) + O_2(^1\Delta_g) \rightarrow NO + O$ is slow [$< 3\times10^{-15}$ $cm^3$ $sec^{-1}$, Clark and Wayne[58]]. An examination of the reaction trajectory suggests that $O_2$ vibrational energy should be available to surmount the energy barrier. For sufficiently hot $O_2(v)$ $N(^4S)$ could react at a rate approaching $2\times10^{-12}$ $cm^3$ $sec^{-1}$ and $[NO]/[O_2] \sim 0.05$ would be the condition for equal probability of reaction with $O_2$ and NO.

Even with vibrationally hot $O_2$ in an auroral arc, the buildup of NO would terminate when $[NO]/[O_2] \geq 0.1$, since any additional $N(^4S)$ and $N(^2D)$ atom production would destroy rather than increase the NO concentration. At 120 km we estimate that NO could not exceed $5\times10^9$ $cm^{-3}$ in contradiction to the mass spectrometer measurements of Zipf et al.[50] This upper limit [NO] estimate would have to be lowered if large amounts of $O_2$ were dissociated as the spectrometer results of Zipf et al. suggest. It should be emphasized that given sufficient time ($\gg 10^4$ seconds for a typical auroral arc) the NO concentration will build up to $0.1[O_2]$ if the $N(^2D)$ production rate exceeds that of $N(^4S)$ and if transport effects are not included.

## 4.2 THE MODEL

To make these estimates quantitative we have constructed an idealized model to describe the buildup of NO during auroral events. The model is described in detail in a technical report available from

the authors.[59] Production rates of ions, excited states, $N(^4S)$, $N(^2D)$, optical emission, etc., are generated by an energetic electron deposition code described in a technical report by Strickland et al.[60] The severity of the auroral NO problem allows us to neglect transport processes. Our model results may yield larger NO densities than measured as a consequence of this assumption. For initial values of odd nitrogen densities, the model of Strobel[61] was adopted; the results are insensitive to this choice. The time dependent continuity equations are integrated for all important constituents whose chemical time constant exceeds one second. Chemical equilibrium is assumed for constituents with chemical time constants less than one second. The important rate constants are tabulated in Table 4.1.

The model was applied to describe the remarkable auroral arc probed by Zipf et al. The energy deposition rate, illustrated in Fig. 4.2, was chosen to reproduce the measured 3914 Å intensity as a function of altitude. Under the most favorable conditions, $T_v(O_2) \geq$ 2 eV, the NO buildup as a function of time and altitude is illustrated in Fig. 4.2. According to Donahue[51] this auroral arc existed previous to the measurement for $\sim 4 \times 10^3$ seconds. Our model predicts a maximum $[NO] \sim 5 \times 10^9$ cm$^{-3}$ with the enhancement localized in the 95-115 km region. To reach the NO cutoff density $\sim 0.1[O_2]$ requires buildup times $\gg 1\text{-}^4$ seconds.

The sensitivity of the model to various input parameters is illustrated in Fig. 4.3. The NO buildup is most sensitive to the $O_2$ vibrational temperature and the $N(^2D)$ branching ratio for $NO^+ + e$.

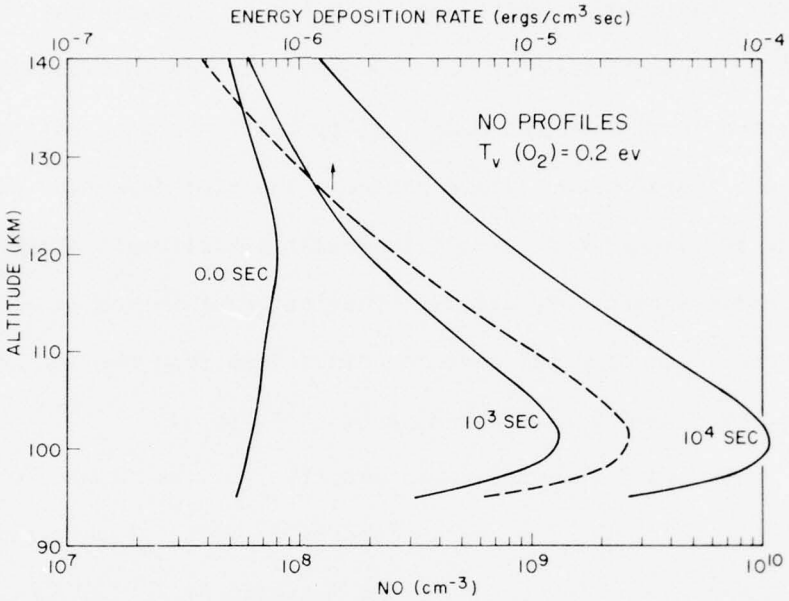



Fig. 4.2 — Altitude profiles of the [NO] buildup as a function of time for vibrationally hot $O_2$, $T_v(O_2)$ = 0.2 eV. The energy deposition rate is also illustrated and produces 26 kR of 3914 Å radiation at 100 km.

With 50% $N(^4S)$ production from $NO^+ + e$, the NO buildup is severely limited by the large chemical loss from the reaction $N(^4S) + NO$. However, such a large $N(^4S)$ production is not consistent with midlatitude data.[56,57] Our results are not sensitive to the selection of initial NO densities. The sensitivity of the NO buildup to a decreased O content of the model atmosphere is due to a reduction of odd nitrogen production, as more $N_2^+$ reacts with $O_2$ rather than with O. This reduction in NO production exceeds an opposite tendency due to reduced $N(^2D)$ quenching by O. An increase in the O content produces less pronounced [NO] changes.

## 4.3 CRITIQUE OF MODEL

The model can describe a rapid buildup of NO if the $O_2$ vibrational temperature, $T_v(O_2)$, is large, but the sources and sinks of $O_2$ vibrational energy must be compatible with high $T_v(O_2)$ in auroral arcs. Measurements at 1600-3300° K indicate that O atoms are efficient quenchers of $O_2$ vibrational energy.[62] Extrapolating their results down to 300° K, we obtain a quenching rate of $\sim 10^{-12}$ $cm^3$ $sec^{-1}$ for $O_2(v=1)$. Two possible sources of $O_2$ vibrational excitation are the precipitating electrons and collisions of $O_2$ with translationally hot ions. In the former case less than 5% of the energy deposition is channeled into $O_2$ vibrational energy. Translationally hot ions, in particular $O_2^+$, may be able in collisions to efficiently excite $O_2(v)$. This latter process would be physically similar to Joule heating and maximum excitation would occur at ~ 125 km with negligible excitation below 110 km where the maximum [NO] enhancement

occurs [cf. reference 52 and Fig. 4.2]. The incorrect altitude variation and the observed ion composition preclude translationally hot ions as the source of $O_2(v)$. Whereas the precipitating electrons could excite $O_2$ in the appropriate altitude region, its source strength is not potent enough to overcome the severe quenching by O atoms to give high $T_v(O_2)$. High $T_v(O_2)$ is possible only if the O quenching rate were comparable to the slow $O_2$ and $N_2$ quenching rate at 300° K. We do note that Reid and Withbroe[63] suggest $O_2$ vibrational enhancement in the thermosphere from observations of solar UV radiation. A room temperature measurement of the O quenching rate would be decisive. On the basis of our present knowledge, it is unlikely that the O quenching rate is $\sim 10^{-18}$ $cm^3$ $sec^{-1}$ at 300° K and hence high $T_v(O_2)$ is improbable in auroral arcs where large [NO] enhancements are inferred.

## 4.4 SPECULATIVE CHEMISTRY

In light of our previous discussion our search for potent auroral NO sources must become more desperate. In conventional chemistry approximately 10 eV of energy must be expended to initiate odd nitrogen production. The reaction $N_2 + O_2 \rightarrow 2NO$ is only endothermic by $\sim$ 2 eV and a potential factor of 10 increase in the NO production efficiency is possible. There is no experimental evidence to indicate that this reaction occurs even with vibrationally excited $O_2$ and/or $N_2$. But if it were possible to form NO by this reaction, there would be no chemical cutoff in the production of NO as present in the conventional chemical cycle.

The reaction $N_2 + O \rightarrow NO + N$ could also be considered with rate constant $\sim 10^{-10} \exp\left(\frac{-38000}{T}\right)$ $cm^3$ $sec^{-1}$. To compete with conventional NO sources, $K \sim 5 \times 10^{-19}$ $cm^3$ $sec^{-1}$ or $T \sim 2000^0$ K. If $N_2$ were vibrationally hot and this energy were available to overcome the activation barrier, O atoms would quench $N_2(v)$ with a rate $\sim 3 \times 10^{-15}$ $cm^3$ $sec^{-1}$,[64] much faster than the rate at which N and NO would be produced. The calculations of Schunk and Hays[65] support the conclusion that $N_2$ must have a Boltzmann distribution for vibrational energy in the E-region during auroral bombardment. Anharmonicity effects at higher vibrational levels would not negate their conclusions. Reaction $N_2 + O$ cannot be the source of anomalous auroral [NO].

## 4.5 DRIZZLE REGION

The available evidence suggests that the auroral zone undergoes continual bombardment by soft energetic electrons and only occasionally do spectacular events occur.[65] The continual bombardment of the auroral regions will lead to an enhanced background NO concentration. With the model, an attempt was made to estimate this concentration in the absence of transport for an electron deposition rate that produces 1 kR of the auroral green line (5577 Å), its threshold for detection. This deposition rate is equal to 0.03 of that in Fig. 4.2. A continual increase in the NO concentration with time is obtained until the NO cutoff density is reached at a time $\gg 10^6$ seconds. After $10^5$ seconds, vertical transport effects will become important and severely limit the further NO buildup. However, peak NO

concentration $\sim 10^9$ $cm^{-3}$ would be possible if the above electron deposition rate were constant with time. With such concentrations, the [NO] inferred by Donahue et al.[47] and Swider and Narcisi[48] from ion composition measurements would be possible without exotic chemistry, although it could not explain the peculiar kink in their deduced [NO] profile. In the case of the mass spectrometer measurements of large [NO] this source of NO fails by at least one order of magnitude.

## 4.6 CONCLUDING REMARKS

On the basis of our analysis we conclude that [NO] enhancements in excess of $0.1[O_2]$ are exceedingly improbable in auroral arcs. As a consequence, we are very skeptical of mass spectrometer measurements that exceed this limit. Any [NO] enhancement past this limit would be inconsistent with the chemistry discussed here with one exception, NO formation by $N_2 + O_2$. We emphasize that there is no experimental support for its occurrence. All other chemical schemes have the same difficulty; the NO buildup stops abruptly when [NO] reaches $\sim 0.1[O_2]$, because NO is not directly formed from $N_2$. The $N_2$ must be first dissociated; then, the N atoms are oxidized. A maximum NO buildup <u>rate</u> is achieved under these conditions only if the reaction $N(^4S) + O_2 \rightarrow NO + O$ is fast. The most plausible mechanism is vibrationally hot $O_2$ but limited data at shock tube temperatures suggest that O quenching is too severe to permit a departure from thermal equilibrium. A room temperature measurement of $O_2(v = 1) + O \rightarrow O_2(0) + O$ is desirable.

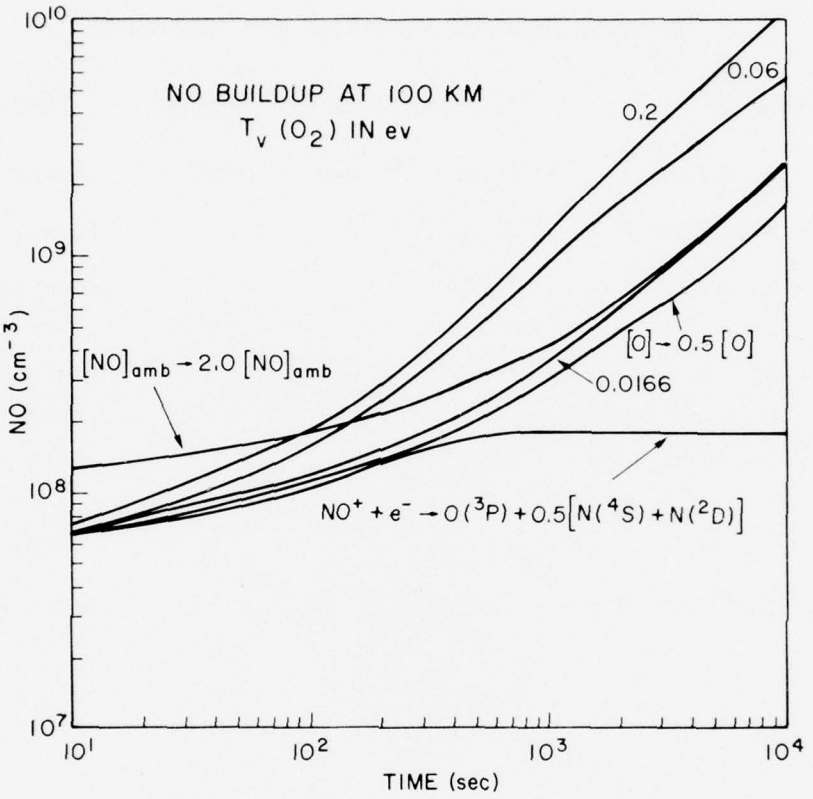



Fig. 4.3 — The [NO] buildup for various parameters as a function of time at 100 km where peak deposition occurs. For the standard run, denoted by 0.0166, only $N(^2D)$ is formed from $NO^+ + e$, $T_v(O_2)$ = 0.0166 eV = kinetic temperature, and [O] = $7 \times 10^{10}$ $cm^{-3}$ at 120 km. The label of the curve indicates the parameter varied. The labels, 0.2 and 0.6, denote the values of enhanced $T_v(O_2)$.

Table 4.1

Important Chemical Reactions for Auroral NO

| Reaction | Rate Constant* ($cm^3$ $sec^{-1}$) | Reference |
|---|---|---|
| $N(^4S) + O_2 \rightarrow NO + O$ | $1.1 \times 10^{-14} T \exp(-3150/T)$ | Garvin [1973] |
| $N(^4S) + NO \rightarrow N_2 + O$ | $2.7 \times 10^{-11}$ | Garvin [1973] |
| $N(^2D) + O_2 \rightarrow NO + O$ | $7 \times 10^{-12}$ | Slanger et al. [1971] |
| $N(^2D) + NO \rightarrow N_2 + O$ | $7 \times 10^{-11}$ | Lin and Kaufman [1971] |
| $N(^2D) + O \rightarrow N(^4S) + O$ | $1 \times 10^{-12}$ | Rusch et al. [1975]<br>Strobel et al. [1975] |
| $N_2^+ + O \rightarrow NO^+ + N(^2D)$ | $3.1 \times 10^{-8} T_i^{-0.44}$ | McFarland et al. [1973] |
| $N_2^+ + O_2 \rightarrow O_2^+ + N_2$ | $5.2 \times 10^{-8} T_i^{-0.8}$ | McFarland et al. [1973] |

*Temperatures in $^{\circ}K$

Section 5

# EFFECTS OF ANOMALOUS RESISTIVITY ON AURORAL BIRKELAND CURRENT SYSTEMS

Joel A. Fedder

In recent years it has become widely recognized that geomagnetic field-aligned, Birkeland, electric currents are of considerable importance to the physics of the high-latitude ionosphere and magnetosphere. Although their existence in association with aurora was orginally proposed by Birkeland,[66,67] their importance only became evident as a result of the great number of measurements of magnetic field perturbations in the auroral regions by rockets and satellites. The rocket measurements[68-71] have shown clearly the association of Birkeland currents with auroral arcs and bands. Whereas, the satellite measurements[72-76] have shown that the field-aligned currents occur over a much wider region associated within the whole auroral oval.

The Birkeland currents in the auroral region arise from two different mechanisms. Energetic plasma pressure gradients in the magnetosphere can lead to field-aligned currents as discussed by Vasyliunas.[77] Additionally, the ionosphere can drive field-aligned currents caused by an imposed electric field in the presence of conductivity gradients or by an ionospheric conductivity in the presence of electric field gradients. These Birkeland currents couple the magnetospheric and ionospheric electric fields and to some extent must modify the spatial distribution and magnitude of each.[78]

Models for the field-aligned currents and electric fields have been developed for auroral arcs and for the auroral region as a

whole. Bostrom[79] presented a model for electric fields and current in arcs making two limiting assumptions concerning the magnitude of the Birkeland current. In one case the Birkeland current was allowed to flow freely while in the other, it was taken to be negligible. Atkinson[80] also presented a model for an auroral arc in which the return ionosphere electron current was strongly limited. In this paper results are presented which are similar to theirs. Models for the electric fields and currents in the auroral regions and lower latitudes as well have been developed by Wolf,[80] Jaggi and Wolf,[81] Iwasaki and Nishida,[82] Karlson,[83] and others. In most of this work the conductivity of the plasma along the geomagnetic field has been taken to be large, and therefore they show no effects of field-aligned resistance on the derived Birkeland currents and electric fields. One exception to this is the model of Coroniti and Kennel[84] for the polarization of the westward electrojet in the midnight auroral oval, caused by anomalous resistance to field-aligned current. However, the idea of anomalous resistance to field-aligned currents did not arise as a result of comparing model results to data for auroral electric fields and current, but rather, from a desire to explain the acceleration of auroral energetic particles.

Swift[85] proposed the existence of the ion acoustic instability in the auroral plasma which could lead to anomalous resistivity, a field-aligned electric potential, and the acceleration of auroral electrons. Subsequently, Kindel and Kennel[86] showed that for auroral plasma parameters, the ion cyclotron instability had a lower threshold and therefore would be a more likely mechanism for the

anomalous resistivity. Furthermore, the threshold for this current driven instability is well within the range of Birkeland current densities inferred from measurements. A further study of the ion cyclotron instability by Palmadesso et al.[87] demonstrates the self-quenching character of the instability which results in marginal instability and considerably lower resistivity. In addition to the current driven plasma instabilities mentioned above Papadopoulos and Coffey[88,89] have proposed a beam driven parametric instability which also may provide resistance to auroral Birkeland currents. In this mechanism, a precipitating electron beam drives high-frequency plasma waves which interact parametrically to drive lower frequency waves and plasma density fluctuations. This parametric instability has the virtue that in addition to providing anomalous resistivity, it also stabilizes the beam plasma interaction and enhances the tail density in the thermal electron distribution to agree with auroral particle measurements.[90]

Mechanisms other than plasma instabilities and anomalous resistance have been suggested which could lead to field-aligned electric potentials. It would be expected that these mechanisms also would greatly affect Birkeland current systems. One of these is the possible formation of electrostatic double layers[91,92] which could lead to a large potential drop over a small distance along the magnetic field. The other is the possible formation of electrostatic shock waves between the magnetosphere and ionosphere. Kan[93] has discussed normal electrostatic shocks while Swift[94] has discussed the possible occurrence of oblique electrostatic shocks and their effects on

particles and electric fields.

In this section we attempt to discuss in considerable detail the effects of anomalous resistance on auroral Birkeland currents. We will illustrate and delineate these effects by showing a rather large selection of results from numerical model studies. In the following section the important features of the auroral model are presented. We also will present a simple model for the ionosphere-magnetosphere interaction with anomalous resistivity to field-aligned currents.

The section on results will demonstrate the effects of anomalous resistivity on Birkeland currents. Results are presented for both the minimum and maximum magnitude of resistivity which can reasonably be expected. Also to be presented are model results for the two most likely resistive mechanisms. We show the effect of treating the precipitating current separately from the ionospheric electron Birkeland current. These results are discussed and some conclusions will be drawn.

Since the simple model used to show the effects of anomalous resistivity is probably not very realistic for comparison to real auroral arcs, in the final section we will present and discuss the results of one model for the midnight region of the auroral oval. The complex current systems in this model will be discussed in some detail. We will also demonstrate that the electric fields derived from this model are in agreement with satellite electric field measurements.

## 5.1 MATHEMATICAL MODEL

To describe the auroral ionosphere, we solve the plasma continuity equation

$$\frac{\partial n}{\partial t} + \nabla_{\perp} \cdot (n\underline{v}_{\perp}) = P - \alpha n^2 \ , \tag{5.1}$$

the plasma momentum equation

$$\frac{q}{m} (\underline{E}_{\perp} + \frac{1}{c} \underline{v}_{\perp} \times \underline{B}) = \nu \underline{v}_{\perp} \ , \tag{5.2}$$

and the current continuity equation

$$\nabla \cdot \underline{j} = 0 \ . \tag{5.3}$$

In Eq. (5.1) we have neglected vertical transport of the plasma; in Eq. (5.2), the inertial terms; and in Eq. (5.3), charging effects. In Eq. (5.1), n, $\underline{v}$, P, and $\alpha$ are respectively the plasma density, the ion velocity, the plasma volume production rate, and the volume dissociative recombination rate; and the symbol $\perp$ applies to the geomagnetic field. The symbols in Eq. (5.2), q, m, E, c, B, and $\nu$ are respectively the electron or ion charge, and electric field in the ionosphere, the speed of light, the geomagnetic field and the electron- or ion-neutral collision frequency. The current density, in Eq. (5.3), is defined by

$$\underline{j} = en(\underline{v}_e - \underline{v}_i) \ , \tag{5.4}$$

where e is the electron charge and $\underline{v}_e$ and $\underline{v}_i$ are the electron and ion velocities.

These equations are solved on a cartesian coordinate system with the x-axis directed north-south; the y-axis, east-west; and the z-axis, vertical. In this paper, for simplicity, it is assumed that

all ionospheric properties are constant along the y-dimension. Additionally, the geomagnetic field is taken to be directed along negative z. Although these assumptions are not necessary to achieve a valid solution, they do make the results much easier to interpret.

In order to complete the set of Eqs. (5.1 - 5.4), it is necessary to prescribe the electric field. We define $\underline{E}$ in terms of the electric potential,

$$\underline{E} = \nabla \psi^{I} \quad , \tag{5.5}$$

which is defined by the magnetosphere-ionosphere interaction, Ohms Law;

$$\psi^{I} = \psi^{M} + J_{||} R \quad . \tag{5.6}$$

$\psi_I$ is the ionospheric electric potential, $\psi_M$ the prescribed magnetospheric potential on the same field line. $J_{||}$ is the field-aligned current leaving or entering the top of the horizontally conducting ionosphere (200 km altitude), and R is the resistivity integrated along a field line from 200 km altitude to the equatorial plane in the magnetosphere. Eq. (5.6) implies that the magnetosphere is an intrinsic source of electric potential which drives the ionosphere and Birkeland current systems. Although taking the auroral magnetosphere as a source of either electric field or current is not usual (see discussion by Wolf[78]), other workers have made such an assumption.[95,96]

Eqs. (5.1) - (5.6) are a complete set and may be solved self-consistently to yield the plasma density, electric field, and current system provided that P (in Eq. (5.1)) and $\psi_M$ and R (in Eq. (5.6)) are specified. The production rate, P, was chosen to

closely resemble the 3914 Å emission data of Romick and Belon.[97] Using typical values for the recombination rate and the collision frequencies,[98] the maximum Pedersen conductivity in the auroral arc is enhanced a factor of 5.2 over that outside, and the Hall to Pedersen conductivity ratio is 2.4. We judge that these values are typical of many auroral arcs. $\psi_M$ is chosen to yield an electric field perpendicular to the arc, in the x direction, which has a strength of 25 millivolts per meter. This is the simplest situation for the electric field about an auroral arc, and therefore allows us to more clearly show the effects of the resistance on the Birkeland current. The resistance function has been chosen differently for each result and will be described with the results.

To obtain a self-consistent result, it is necessary to obtain a simultaneous solution of (5.1) - (5.6). The results presented here were obtained as follows:

a. Using assumed $\psi_M$ , obtain $\underline{E}$ from (5.6) and (5.5) with $J_{||}(t = 0) = 0$ ,

b. Obtain $\underline{v}$ from (5.2),

c. Advance n in time with (5.1),

d. Obtain $J_{||}$ using (5.3 and (5.4),

e. Compute $\underline{E}$ from (5.6) and (5.5),

f. Repeat b - e until a steady state is achieved.

The equations are solved for the altitude range, 95 - 200 km, where the perpendicular ionospheric currents occur. The results include n and $\underline{j}$ throughout this region, and $\psi_I$ and $J_{||}$ at 200 km altitude.

## 5.2 RESULTS

In this section the effects of anomalous resistivity on auroral Birkeland currents are explored by consideration of a group of examples. We first consider the effect of the magnitude of the resistivity on the amplitude of the Birkeland current density and on the electric field perturbation. We next consider the results of anomalous resistivity for two of the proposed plasma mechanisms; the current driven ion cyclotron instability and the beam driven parametric instability. Finally, results are shown for a number of cases in which the precipitating current is resistance free and only the return currents experience resistivity.

Figure 5.1 shows the result for the minimum amount of resistivity that can be expected along an auroral field line. The resistance was chosen at a constant value of $3.5 \times 10^{-4}$ e.s.u. This value is the Spitzer[99] resistance of a 1 $cm^2$ flux tube above 200 km at auroral latitudes. The Birkeland currents peak strongly at the edges of the arc while the electric field perturbation is negligible. The maximum current density has the value $5.4 \times 10^{10}$ el $cm^{-2}$ $sec^{-1}$ ($8.65 \times 10^{-5}$ amp $m^{-2}$) which is considerably larger than current densities normally observed. This result is quite similar to one originally discussed by Bostrom.[79]

Figure 5.2 shows a contrasting result to Figure 5.1. In this case the resistance is again constant but now is the maximum value that can reasonably be expected along auroral field lines. Its value is $2 \times 10^4$ larger than the Spitzer value and is comparable to that used in previous work by Coroniti and Kennel.[84] For such a large value of

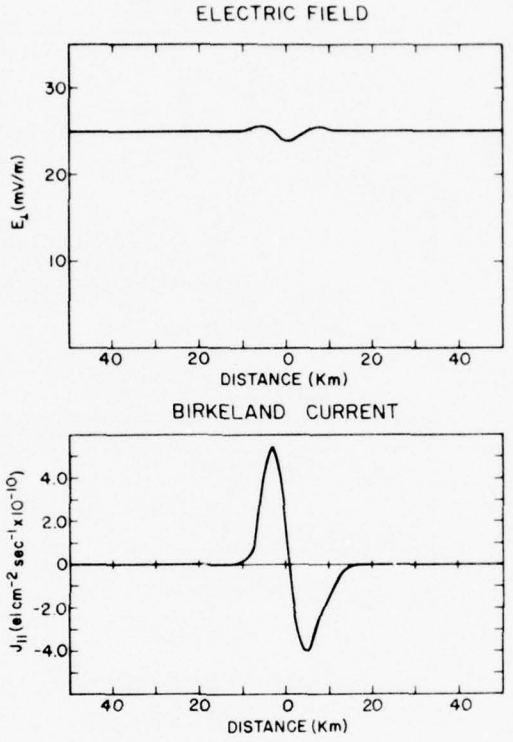



Fig. 5.1 — Electric field and Birkeland current density for a very small resistance to field-aligned current. The resistance, R = 0.00035 esu, (the Spitzer resistance of a 1 $cm^2$ flux-tube above 200 km altitude) is spatially constant. For this small resistance the electric field perturbation is small in the auroral arc while the Birkeland current density is very large, up to $8.65 \times 10^{-5}$ amp $m^{-2}$.

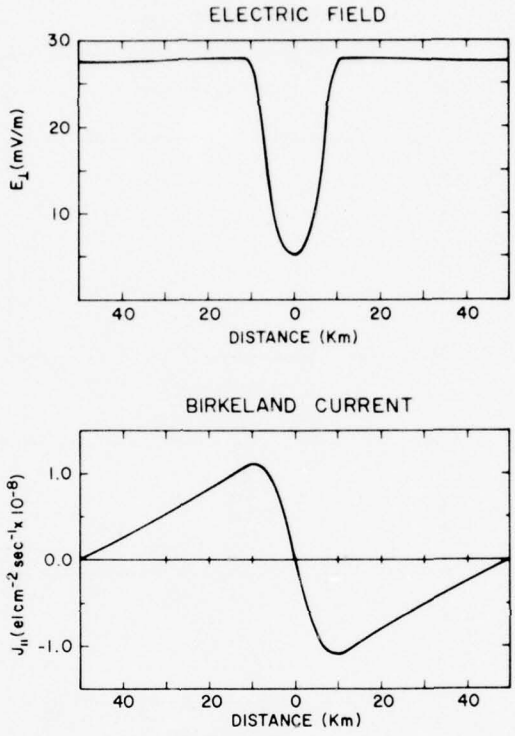



Fig. 5.2 — Electric field and Birkeland current density for a very large resistance. The resistance, 7 esu, is spatially constant and a factor of $2 \times 10^4$ larger than the Spitzer value. For this large resistance the Birkeland current density is 500 times smaller than in the previous case. Whereas, the electric field is greatly reduced inside the auroral arc.

resistance, the results show that the Birkeland current is small $1.1 \times 10^{8}$ el $cm^{-2}$ $sec^{-1}$ ($1.76 \times 10^{-7}$ amp $m^{-2}$) and that the electric field is greatly reduced in the auroral arc. The Birkeland current density is smaller than what is normally observed whereas the electric field strength is anti-correlated with the arc as has been observed.[100] As in the previous case, this type of situation has also been discussed by Bostrom.[79]

The results in Figure 5.3 are intermediate between those shown in the first two figures. In this case the resistance has the constant value 0.3 esu. The electric field and Birkeland current patterns are quite similar to those of the previous case. But here, the current density has a maximum of $4 \times 10^{-6}$ amp $m^{-2}$, which is more typical of measured values. In all of these cases where a constant resistance was chosen, the Birkeland currents maximize at the strong density gradients on this side of the auroral arc. On the other hand, the electric field shows a minimum in the center of the arc and tends to have maxima outside the arc structure.

For the next result, we attempt to model a marginally unstable current driven resistance mechanism. Marginal instability is a reasonable condition as the current driven instabilities are self-saturating. The marginal instability model assumes that the resistance on each flux tube is incrementally increased above the Spitzer value at each time step when the Birkeland current density exceeds a threshold of $3 \times 10^{9}$ el $cm^{-2}$ $sec^{-1}$.[84] The result is shown in Figure 5.4. The electric field is quite similar to that in the previous case, however, the Birkeland current is considerably different. The Birkeland current

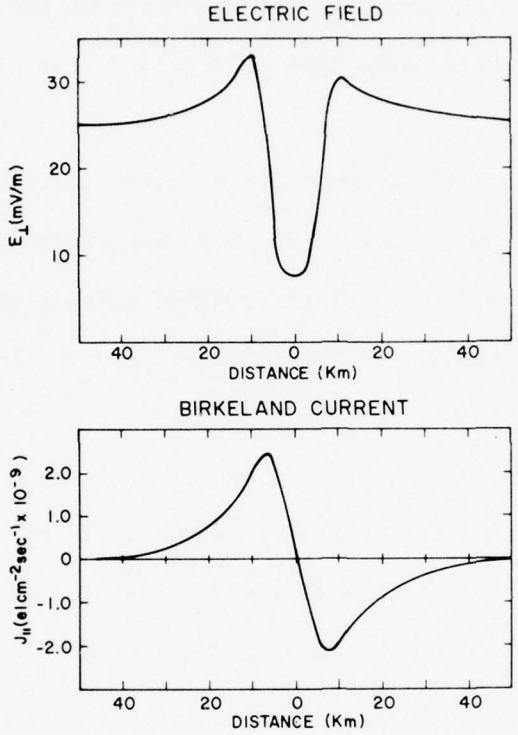



Fig. 5.3 — Electric field and Birkeland current density for an intermediate value of resistance. The resistance is spatially uniform and has a value of 0.28 esu. The Birkeland current density has a reasonable magnitude, about $4 \times 10^{-6}$ amp m$^{-2}$. The electric field is enhanced outside the auroral arc and considerably reduced inside.

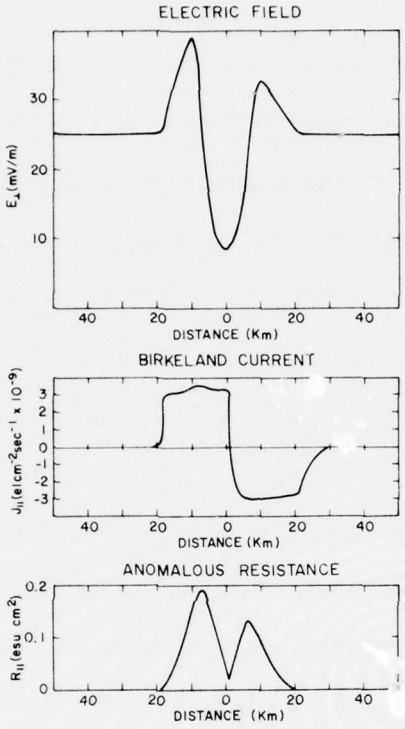



Fig. 5.4 — Electric field, Birkeland current density and anomalous resistance of 1 $cm^2$ flux tube for the current driven anomalous resistance mechanism. The resistance is uniform at the Spitzer value except where the current exceeds the instability threshold of $4.8 \times 10^{-6}$ amp $m^{-2}$, in which case the resistance increases rapidly. The Birkeland current density has a square wave character with the amplitude of the instability current threshold. The electric field is quite similar to that in Fig. 5.3.

has the shape of a square wave to either side of the center of the arc. The resistance of a 1 $cm^2$ flux tube is also shown. We see that it peaks at the steep density gradients on either side of the arc, and has a maximum value which is about 500 times larger than the Spitzer resistivity.

Figure 5.5 shows the results of a preliminary attempt to model the beam driven parametric resistance mechanism. Papadopoulos and Coffey[88] showed that the resistance is roughly proportional to the energy in the precipitating beam of electrons. Here we assume, similarly, that the resistance is proportional to the total ionization production rate in the auroral arc. This leads to a resistance which is large, 0.3 esu, at the center of the arc but has the Spitzer value immediately outside. The results show that both the Birkeland current and electric field peak very sharply in the small resistance region immediately outside the arc. To the author's knowledge, such strong peaking has not been observed in the auroral data.

In the preceding results both precipitating and cold ionospheric particle currents where treated identically. In all these cases the Birkeland current was balanced across the center of the auroral arc density enhancement and there was no evidence of an energetic precipitating current. The next three samples will show results in which the effect of the precipitating particles is clearly seen. In these cases it is assumed that only the cold, ionospheric particle return currents experience anomalous resistance. The precipitating particles carry current resistance-free.

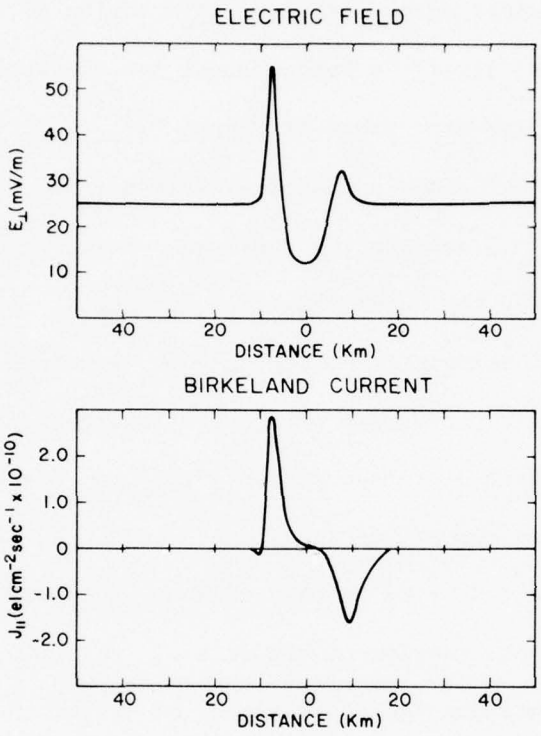



Fig. 5.5 — Electric field and Birkeland current density for the beam driven, parametric resistance mechanism. Here the resistance has the Spitzer value outside the auroral arc, but is very large and proportional to the precipitating energy inside. The Birkeland current density is small inside the arc but becomes large at the edges. The electric field is also very large at the border of the arc.

Figure 5.6 shows one of these results in which the resistance is large, 7 esu, but localized to the auroral arc field lines. In this case the precipitating particle current (short dash line) carries almost all of the Birkeland current inside the arc. The ionospheric electron return current exists outside the arc in a region of low resistance. These results are, likely, a better model for the beam driven parametric resistance mechanism than those of Figure 5.5.

Figure 5.7 shows a similar result but in this case the resistance is smaller, 0.3 esu, and is constant. Here, the precipitating current is shown by the short dash line, the cold, ionospheric return current, by the long dash line, and the net Birkeland current, by the solid line. Again, the effect of the precipitating particles is clearly evident in the total Birkeland current density. Nevertheless, the ionospheric return current is substantial inside the auroral arc and reduces the current density in that region. This effect becomes even more apparent in the results of Figure 5.8. For this result, the constant resistance was reduced a factor of 5 from that in Figure 5.7. The net Birkeland current density in Figure 5.8 no longer shows an extrema in the region of the arc precipitation and is, here again, balanced across the center of the auroral arc. Any further reduction in the anomalous resistance would lead to almost complete cancellation of the precipitating particle current by the cold, ionospheric return current.

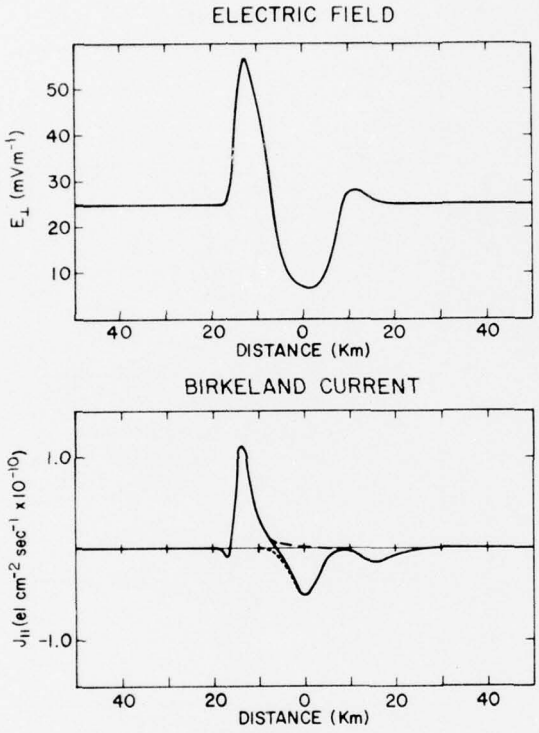



Fig. 5.6 — Electric field and Birkeland current density for resistance free precipitating particle current. The resistance to the ionospheric return current has the Spitzer value outside the auroral arc and is very large inside. The short-dash curve shows the precipitating current; the long-dash curve shows the ionospheric return current; and the solid line is the net current density. The precipitating energetic particles carry almost all of the electron current into the ionosphere. The return currents are strong in the Spitzer resistance region outside the auroral arc. This is likely a better result for the beam driven resistance mechanism than shown in Fig. 5.5.

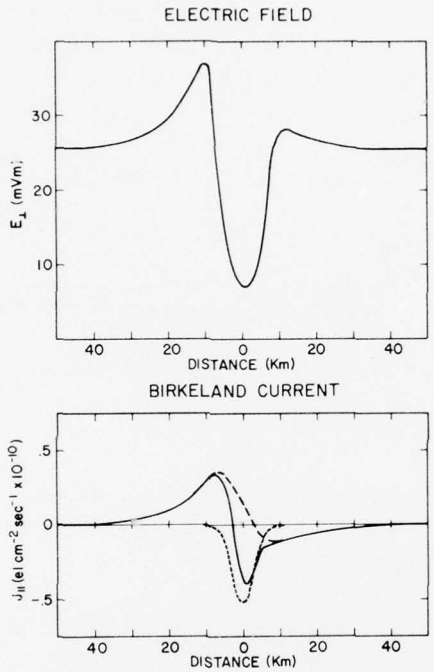



Fig. 5.7 — Electric field and Birkeland current density for a similar case to Fig. 5.6. Here the resistance is spatially uniform and has a moderate value, 0.3 esu. The presence of the resistance free precipitating current (short-dash curve) is evident in the net Birkeland current density (solid curve), however, it does not account for more than about half of the net downward electron flow. The electric field is similar to that in Figs. 5.3 and 5.4.

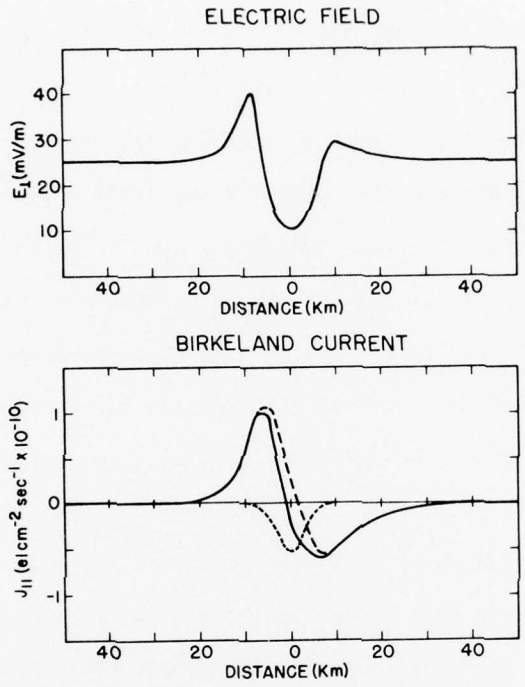



Fig. 5.8 — Results for the same conditions as in Fig. 5.7 except that the resistance is reduced a factor of 5. The contribution of the precipitating current to the net Birkeland current density is now much less obvious. The spatial distribution of the Birkeland current is similar to that in the first 3 figures. Further reduction of the anomalous resistance would lead to a result like Fig. 5.1.

## 5.3 DISCUSSION

In the preceding section a large number of examples were presented of the possible effects of anomalous resistivity by an auroral Birkeland current. The problem which remains is to sort out the effects and to develop some idea of their possible importance and relevance. That, we will now attempt to do.

We think that, taken as a whole, the results presented here are not in great disagreement with the available data on auroral Birkeland currents and electric fields. That is to say, using a model similar to that presented here which makes reasonable assumptions concerning the magnetospheric electric field and the anomalous resistivity mechanism can lead to a good fit between the model results and the auroral measurements. We therefore feel that there is some validity in applying the model results to the auroral currents and resistivity.

The model results indicate that the anomalous resistivity on auroral field lines is a factor of $10^2$ to $2 \times 10^4$ greater than the Spitzer value. There are a number of reasons for this. If the resistivity is too small, the Birkeland current density can easily exceed the observed range of the measurements, $1 - 20 \times 10^{-6}$ amp $m^{-2}$. Moreover, as was seen in the results of Figure 5.8, a small resistance allows the ionospheric return current to almost completely neutralize the precipitating electron current. The upper value of the resistivity is set by plasma instability considerations and has been discussed elsewhere.[88]

In addition, the model results would favor a resistivity which varies slowly in space. Rapid changes in the resistance of

adjacent flux tubes leads to sharp extrema in both the Birkeland currents and in the electric field. Spatial changes in the resistance are important, however, as they greatly influence the spatial distribution of the Birkeland current density. This is particularly well shown in the contrasting results of Figures 5.4 and 5.5. The effect of a spatially non-constant resistance is to alter the electric field so that the Birkeland current is stronger in regions of lower resistivity and weaker in regions of higher resistivity.

Finally, we would make an observation regarding the acceleration of auroral particles by geomagnetic field-aligned potential drops which are created by anomalous resistivity. For the results shown here, the largest field-aligned potential drop is 110 volts. Even if the magnetospheric electric field were 10 times stronger, it could not explain the energization of auroral electrons to more than 1 kilovolt. This does not mean that the mechanism does not occur, but only that it cannot occur on the scale size ($\sim$ 10 km) of a single auroral arc. In fact we will see an indication that it does occur in a more realistic model of auroral arcs which follows.

## 5.4 RESULTS FOR A MORE REALISTIC MODEL

The results shown and discussed in the previous sections were derived from a very simple model of an auroral arc and therefore would not be expected to describe accurately the fields and currents in an actual aurora. The simple model was used in order to show more clearly the effects of anomalous resistance on auroral Birkeland currents. Here we will attempt to show that anomalous resistivity is important in

the auroral oval by use of a more realistic model. This model was devised in an attempt to understand and explain the OGO-6 electric field measurements from the midnight region of the auroral oval presented by Maynard.[101]

The model requires the assumption of the magnetospheric electric field and energetic particle precipitation pattern along a north-south meridian through the premidnight auroral oval. The northward electric field chosen is 16 millivolts/meter, constant across the oval; and no northward field outside of the oval. The westward electric field is taken to be 25 millivolts/meter north of the oval, decreasing linearly to zero from the northern to southern border of the oval, and zero in the region south of the auroral oval. This choice for the magnetospheric electric field is somewhat unconventional and controversial, however it is in agreement, we think, with the flow pattern proposed for the plasma sheet by Rostoker and Bostrom[95] for the immediate premidnight region.

The precipitation pattern chosen, is shown as the short dash line in Figure 5.9. It features a broad (400 km wide) precipitation region in the southern and central regions of the oval and a structured region (containing 2 arcs or bands) at the northern border of the auroral oval. We would interpret the broad region as plasma sheet particle precipitation and the structured region as inverted - V precipitation. The precipitation pattern has been designed to be similar to the Ariel 4 particle data of Craven and Frank.[102]

Figure 5.9 also presents the resulting field aligned current systems when a uniform, large (7 esu) anomalous resistance is assumed.

The solid line shows the net field-aligned current density, the long dash line shows the cold ionospheric electron current, and the short dash line shows the precipitating current. The direction and strength of the net current is consistent with the TRIAD satellite date.[103] The important effect of the anomalous resistance is to cause the hot and cold particle currents to oppose each other in the broad precipitation region and to have the same direction in the structured precipitation region. Rocket magnetometer data have been interpreted to indicate that both hot and cold electrons flow downward into arcs [see Anderson and Cloutier[104] and references therein].

In addition to the cold ionospheric current the long dash line in Figure 5.9 is a plot of the field-aligned potential difference. The units in this case are kilovolts. In the structured region the potential is directed upward and becomes as large as 2 kilovolts. Presumably this potential could serve to accelerate electrons into the ionosphere. In the broad precipitation region the potential is downward and thus would discourage electron precipitation and encourage ion precipitation.

Figure 5.10 is a comparison between a measured electric field[101] and the model electric field result. The antenna for the measurement was oriented north-east south-west and therefore the model field was plotted on the same axis. In each case the major features of the field are the same. At the southern border the field is northward; it passes through zero at the Harang Discontinuity (Maynard's identification) and becomes northward through the central region of the auroral oval. At the northern border, both fields oscillate rapidly before

turning basically westward in the polar region. The agreement between the model electric field and the measurement is good.

In this paper we have shown that a model incorporating anomalous resistivity to field aligned currents can provide a description of auroral electric fields and currents, which is in reasonable agreement with auroral measurements. It was also shown that the effects of the resistivity were important to the Birkeland current densities derived therefrom. A better evaluation of resistivity and its effect on auroral fields and currents can be made only by incorporating the actual plasma mechanisms and their nonlinear behavior in the auroral model.

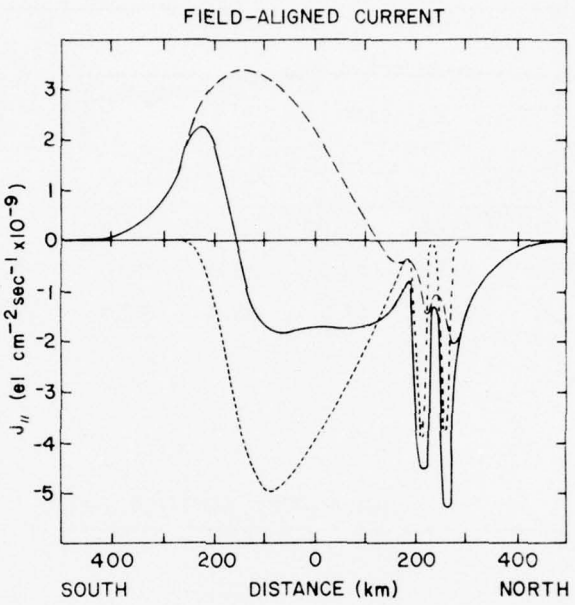



Fig. 5.9 — The field-aligned current density for a more realistic model of auroral arcs in the premidnight auroral oval. The short-dash curve shows the precipitating energetic electron current. It is composed of a broad precipitation region (plasma sheet particles) in the southern and central part of the oval, and two discrete, narrow precipitation structures (auroral arcs or bands) at the northern border of the oval. The long-dash curve shows the cold-ionospheric electron current. In the southern and central portions of the oval the hot and cold particle currents oppose each other, while at the northern border they are in the same direction. The solid curve shows the net field-aligned current density which results. In addition to the cold ionospheric current, the long-dash curve shows the potential drop along the geomagnetic field; the appropriate units are kilovolts. The potential is upward and accelerates precipitating electrons into the discrete precipitation region, while opposing electron precipitation in the broad region.

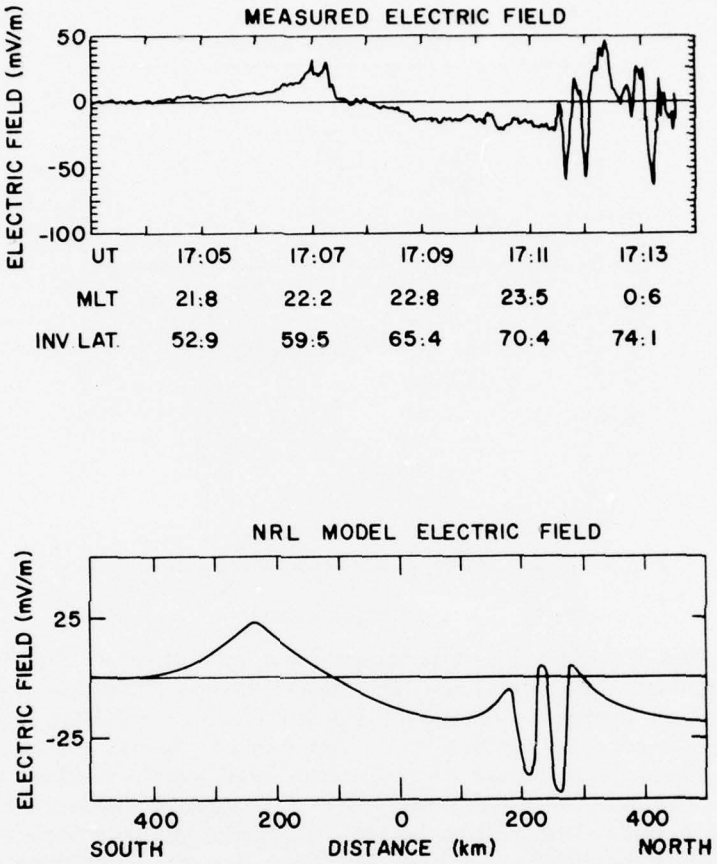



Fig. 5.10 — A comparison between a measured electric field [Maynard, 1974] and the model electric field for the currents of Fig. 5.9. Both the measured and model fields have the same features. The field is northward at the southern border of the auroral oval, becomes southwestward through the central oval, and shows similar structure in the discrete precipitation region at the northern border.

Section 6

# SUMMARY

In the introduction, we have pointed out the considerable similarities between the effects of a HANE and those of an auroral disturbance. These similarities include precipitation of energetic particles, generation of field-aligned current systems, atmospheric heating and generation of winds, radiation throughout the electromagnetic spectrum, along with other plasma phenomena. One result of these various processes is the creation of communications disturbances and interruptions which can be far reaching and of long duration. It is the study of these phenomena and their resulting effect on communications systems which is the motivation for the work reported here.

This is not to say that the aurora demonstrates these nuclear phenomena in the same magnitude and to the same extent as a HANE, but rather that the same physical laws and, therefore, similar models describe the effects in both events. The aurora can therefore be used, in the absence of nuclear testing, as a benchmark for nuclear phenomenology. Moreover, the physical models developed in the auroral program can be applied, with some modification, to the study of nuclear phenomenology. The auroral program, in this manner, is an integral part of the study of HANE effects on communication systems.

A program for developing an auroral model must address three fundamental technical areas: 1) the deposition of energy in the upper atmosphere by energetic electrons and protons 2) the chemical reactions initiated by the deposited energy and 3) the electrodynamical aspects

such as the structures of fields and currents. This program closely parallels the approach necessary in modeling HANE effects and provides valuable insights for the understanding of HANE phenomenology as well as serving as a measuring standard for our ability to model perturbations (or HANEs) in the upper atmosphere.

During the past year, significant improvements have been incorporated into the NRL proton deposition model. The number of atmospheric constituents in the model has been increased with the addition of O and $O_2$ to the $N_2$ already in the program. The photon energy degradation treatment, based on the continuous slowing down approximation, has been improved by the inclusion of the influence of the geomagnetic field on the particle energy loss.

Progress has also been made in electron energy deposition. The NRL electron transport code has predicted higher backscatter than other models because of the way the energy loss process is treated. A detailed study reveals high sensitivity of the backscattered flux to variations in the large angle scattering cross sections. The numerical solutions to the equation of transfer are shown to be accurate to at least three significant figures.

Auroral chemistry studies were focused on the large enhancements of NO concentration in auroral arcs inferred from observations. An analysis in terms of a model incorporating the possible channels of NO buildup has indicated that NO enhancements in excess of 10% of the concentration of $O_2$ would be improbable.

Improvements have been made in the auroral electrodynamics models. A detailed assessment of the importance of anomalous plasma

resistivity in modeling auroral electric fields and currents has been made. These model results have been shown to be in good agreement with auroral measurements.

The studies above have all contributed to other areas of the nuclear effects program. For instance, the proton energy deposition method has been modified to describe the deposition of nuclear debris ions and has given results which compare well with data from bomb test programs. It is now used as an important part of HANE simulations. Changes have also been made in HANE chemistry codes as a direct result of auroral chemistry studies. The auroral electrodynamics studies and models show promise of making important contributions in the near future as nuclear phenomenology studies are carried to later times. Much of the theoretical developments in the auroral models are directly applicable to the electrostatic evolution of the nuclear debris and ionized plasma which is of great importance in evaluating very late time effects of HANEs on defense satellite communications systems.

Future work will be devoted to studying the occurrence and development of plasma irregularities in the auroral ionosphere. The electrodynamic models used for this study are closely related to the late-time electrostatic models of HANEs. It is expected that these studies will allow a direct connection to be made between scintillations at auroral latitudes observed in the Wideband Satellite Experiment and those which would occur in the nuclear environment. The auroral modeling program is unique in allowing a direct connection to be made between naturally occurring scintillations and HANE effects on communications.

In conclusion, we point out that the auroral modeling program has made direct, important contributions to HANE phenomenology studies. Moreover, it is expected that such benefits will continue to accrue. As interest increases in nuclear disturbance effects at later times, the auroral modeling effort and the electrostatic methods and techniques developed through it will become a foundation of future developments in HANE phenomenology. In addition it will allow a connection to be made between nuclear weapons effects on communications and measurements which are conducted in the natural environment.

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