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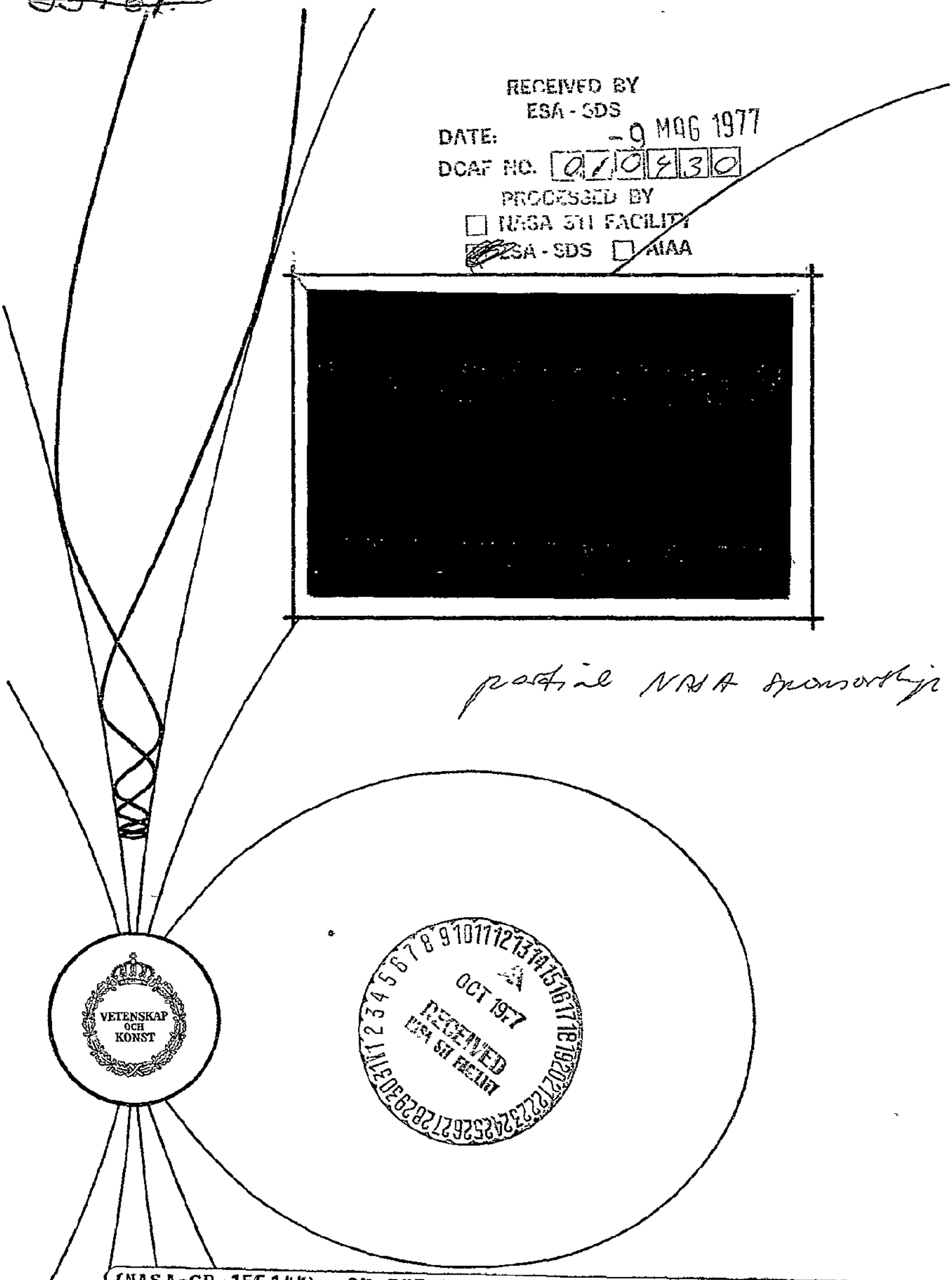

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ON THE ROLE OF MAGNETIC MIRRORING IN THE AURORAL PHENOMENA

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Abstract. On the basis of field and particle observations, it is suggested that a bright auroral display is a part of a magnetosphere-ionosphere current system which is fed by a charge-separation process in the outer magnetosphere (or the solar wind). The upward magnetic-field-aligned current is flowing out of the display, carried mainly by downflowing electrons from the hot-particle populations in the outer magnetosphere (the ambient cold electrons being depleted at high altitudes). As a result of the magnetic mirroring of these downflowing current carriers, a large potential drop is set up along the magnetic field, increasing both the number flux and the kinetic energy of precipitating electrons. It is found that this simple basic model, when combined with wave-particle interactions, may be able to explain a highly diversified selection of auroral particle observations. It may thus be possible to explain both "inverted-V" events and auroral rays in terms of a static parallel electric field, and the electric field may be compatible with a strongly variable pitch-angle distribution of the precipitating electrons, including distributions peaked at 90° as well as 0°. This model may also provide a simple explanation of the simultaneous precipitation of electrons and collimated positive ions.

1. Introduction

One of the most puzzling problems in magnetospheric physics today is how to understand the complex processes that cause energization and precipitation of the auroral particles. A great variety of ideas have been presented in the literature to explain different observed phenomena, but so far very little has been achieved in getting a unified picture. For an illustration of the complexity of auroral particle observations, see, for example, O'Brien and Reasoner (1971).

The purpose of this paper is to emphasize the potential central role of magnetic mirroring in the complex auroral phenomena and to suggest that a proper consideration of the magnetic mirroring may greatly simplify the present picture. The reader who only wants a brief oriantation may read Sections 2, 15 and 16.

For reference purposes we need a rough division of current ideas about auroral particle acceleration. The main ideas may be grouped into the following three basic categories:

(a) The precipitating particles have already attained their final energy when leaving the equatorial region of the magnetosphere. It is frequently assumed that the auroral particles get their final energy by, for instance, betatron and Fermi acceleration during their drift motion into and filling of the plasma sheet reservoir with energetic particles. In order for a sufficient flux of the energized particles to reach down to the atmosphere, despite the strong mirroring effect of the geomagnetic field, a final pitch-angle scattering mechanism (by means of wave-particle interactions) may be needed. See, for instance, Kennel and Petschek (1966). Some measurements of the near-earth plasma sheet seem to indicate a sufficient energy flux of particles with appropriate energies for producing even the most intense auroral precipitation (Frank, 1971; Vasyliunas, 1970). For a very brief review of this kind of large scale energization, see Heikkila (1974).

(b) The precipitating particles in general, or at least some of them, gain additional energy at the expense of a trapped particle component through which they pass on their way down. Alternatively, this energy transfer may be from one precipitating component to the other. According to this view the energy yielding particles having an unstable velocity distribution produce plasma waves, the energy of which is absorbed by the precipitating particles in an ordered manner. A crucial point is then to have the precipitating particles increase preferentially their downward field-aligned velocity. For examples of these kinds of ideas see Gary _et al_ (1968), Laval and Pellat (1970), Perkins (1968) and Swift (1970).

(c) The precipitating particles fall through an electrostatic potential gradient along the magnetic field lines. This requires, of course, a drastic reduction of the parallel current-carrying capability of the magnetospheric and ionospheric plasmas relative to what has been normally assumed (cf. Alfvén, 1968). This can occur in several different ways, see e.g. Block and Fälthammar (1976). For instance, the behaviour of laboratory plasmas has led people to think in terms of current-driven plasma instabilities, producing double layers (e.g. Block, 1972; Swift,1975) or anomalous resistivity (e.g. Kindel and Kennel, 1971; Swift, 1965), as the means by which field-aligned currents are obstructed in auroral regions. Alternatively, the magnetic mirroring may play the key role in this respect, as demonstrated by Knight (1973) and Lemaire and Scherer (1974). The magnetic mirroring may, in principle, support a parallel electric field even in the absence of a field-aligned current, as discussed originally by Alfvén and Fälthammar (1963) and Persson (1963,1966). See also Whipple (1976).

2. Essential Features of a New Model

The model outlined in the present paper basically belongs to category (c), but important features of it are taken from (a) and (b). The basic line of thought is the following:

From curl $\bar{E} = 0$ it is seen that an electrostatic potential gradient along the geomagnetic field lines will be associated with an increased peak amplitude of $E_\perp$ at high altitudes. In order for the high-altitude $E_\perp$ to stay at reasonable values the region with a parallel potential drop of several kV must have a fairly wide spatial extent transverse to the magnetic field, in accordance with the observed latitudinal thickness of "inverted-V" events, which is typically 100-300 km. This means that thin auroral precipitation structures like auroral rays must be due to a local reduction of the parallel "resistivity", rather than due to a current-induced local increase of the resistivity. This problem may be solved in terms of the following model. The upward field-aligned portion of a magnetosphere-ionosphere current system will be associated with a depletion of ambient cold electrons at high altitudes and, hence, the upward current will be carried by downflowing hot and dilute magnetospheric electrons. As the parallel motion of these electrons is strongly hampered by the magnetic mirroring a large fraction of the total voltage produced by the magnetospheric "dynamo" will be projected along the magnetic field, increasing both the flux density and the kinetic energy of the downflowing hot electrons. The effective "resistivity" may then be locally reduced either by a local increase of source electrons or by a local transfer of electron gyroenergy into electromagnetic wave-energy, for instance. In this manner very thin substructures of increased precipitation may occur, energized by the parallel electric field, that is in reality by the magnetospheric "dynamo".

This paper emphasizes the merits of this model in explaining a large variety of observed phenomena, but it does not discuss the detailed physical conditions for the formation of thin precipitation structures.

3. Some Observational Indications of a Large $(\Delta V)_{||}$

The observation traditionally considered as indicative of field-aligned potential gradients is that of a "nearly monoenergetic" peak in the energy spectrum of precipitating electrons (Albert and Lindstrom, 1970; Arnoldy et al,1974; Choy et al, 1971; O'Brien and Reasoner, 1971; Westerlund, 1969).

The frequently observed collimation (along $\bar{B}$) of auroral electron distributions is often interpreted in terms of a field-aligned acceleration at low altitudes which may be due to a $(\Delta V)_{||}$ (Ackerson and Frank, 1972; Arnoldy et al, 1974; Bosqued et al, 1974; Hoffman and Evans, 1968; O'Brien and Reasoner, 1971; Whalen and McDiarmid, 1972). Detailed measurements of pitch-angle versus energy have also led to an interpretation in terms of field-aligned potential gradients (Arnoldy et al, 1974), or even more specifically in terms of double layers (Albert and Lindstrom, 1970).

The large amount of satellite data on "inverted-V" precipitation structures (e g, Frank and Ackerson, 1971) and associated irregularities in the convection electric field (e.g. Cauffman and Gurnett, 1972) observed in the poleward part of the auroral ovals also seem to point in a direction of potential gradients along the magnetic field. These observations will be more extensively discussed in the Section "Comparison with Observations". A direct evidence for a large $(\Delta V)_{||}$ above an auroral form has been found recently from the drift motion of a barium plasma jet injected along the magnetic field lines (Wescott et al, 1976). While the barium plasma beyond 1 R_E experienced flux tube splitting and rapid dispersion the plasma at lower altitudes remained unaffected.

4. Magnetic-Field Aligned Currents

Among the different theories of auroral particle acceleration, those involving parallel electric fields seem to be particularly encouraged by the existence of magnetic-field aligned currents. This can be seen by the following arguments.

According to the viewpoints (a) and (b) listed in the Introduction, the auroras are in fact produced by a magnetospheric electron gun. The negative charge carried by the electron beam need not give rise to a net field-aligned current, however, because the negative charge thus deposited deep within the ionosphere will enable ionospheric electrons in the topside region to escape outwards along the beam (together with backscattered and secondary electrons). Actually, this is what we should expect according to the kinetic model discussed by Lemaire and Scherer (1973a and 1974). In this way a net field-aligned current may not appear until the precipitation flux density exceeds the flux density of freely escaping ionospheric electrons, which is quite high, maybe as high as $10^{11}/cm^2s$ (or more) at ionospheric altitudes (cf Lemaire and Scherer, 1973a and 1974). In the absence of precipitated negative charges the outflowing ionospheric electrons are tied to the much slower positive ionospheric ions (ambipolar diffusion).

The situation is quite different when we consider the viewpoint (c). A potential gradient along magnetic field lines in a direction to accelerate precipitating electrons is an efficient barrier to the upward escaping thermal electrons from the ionosphere (actually a potential barrier of only a few volts will do, cf Lemaire and Scherer, 1973a and 1974) as well as a barrier to backscattered and secondary electrons. Consequently, if the flux of precipitating protons is negligible as compared with the electron flux (as is normally the case, cf e.g. Frank and Ackerson, 1971), the net $i_{||}$ has to be in the upward direction and at least as large as the current density carried by the precipitating electrons (not including the downflowing electrons that have been reflected by the potential barrier).

On the other hand, if the net $i_{||}$ is found to be at least as large as the precipitation current density, the most immediate interpretation is that the ionosphere, at the point of deposit of negative charge, stays at a positive potential of at least a few volts relative to the adjacent magnetosphere. This potential distribution is easy to understand if the precipitating electrons are passive carriers of current. However, as discussed in Section 8 the energetic precipitating electrons do not readily act as passive current carriers, unless they are forced to by an $e(\Delta V)_{||}$ which is at least of the same order of magnitude as the kinetic energy of the electrons. The reason for this is the magnetic mirroring in the geomagnetic field. A $(\Delta V)_{||}$ of this magnitude will evidently appreciably increase the energy of the electrons at the same time.

The permanent existence of east-west extended field-aligned current sheets in all local time sectors of the auroral ovals is fairly well established (Armstrong and Zmuda, 1970; Zmuda et al, 1970; Zmuda and Armstrong, 1974). It is interesting that an upward $i_{||}$ (downgoing electrons) measured by means of its distortion of the geomagnetic field is very often seen directly associated with precipitating electrons and auroral arcs and that the current density is seemingly at least as high as defined by the precipitation flux density (Armstrong et al, 1975; Arnoldy et al, 1974; Berko et al, 1975; Choy et al, 1971; Cloutier et al, 1973; Park and Cloutier, 1971).

5. Some Crucial Properties of a Large $(\Delta V)_{||}$

When discussing magnetospheric electric fields in the light of the behaviour of laboratory plasmas, we have to consider the entirely different boundary conditions in the magnetosphere. For an illustration of this, see Figure 1. The left part of the figure, a, is a rough sketch of the familiar electric field generated at a resistant section of an otherwise good conductor, when a current is flowing. The medium outside of the conductor is assumed to be a vacuum. The conductor in Fig 1a may be an unmagnetized plasma column contained wihtin a glass tube, and the "resistant" section may be a potential double layer (cf Block, 1975). The plasma confinement may as well be due to an external axial magnetic field.

Consider now Fig 1b. This is a sketch of the formal magnetospheric analogue of Fig 1a. For simplicity the total magnetic field (geomagnetic field and superposed field due to the current) is assumed to be vertical and homogeneous, $B \equiv B_z$. A current is flowing upward along $\bar{B}$, carried by downflowing electrons and having a density i_z. This current is obstructed by a region of reduced parallel "conductivity" $\sigma_{||}$. The word "conductivity" here simply means the quantity i_z/E_z.

In the magnetospheric case there is obviously no vacuum outside of the current path. Hence, the fan-shaped equipotentials in Fig 1a transform into magnetic-field-aligned equipotentials as indicated in Fig 1b. Suppose that the wavy contour in Fig 1b indicates the smallest possible box containing the region with $E_z \neq 0$. Evidently, E_x is not confined to the immediate vicinity of the box as in Fig 1a but penetrates infinitely far out along $\bar{B}$.

Further assume

$$\text{curl } \bar{E} = 0 \qquad (1)$$

If we take the line integral of $\bar{E}$ around any closed contour and apply Stoke's theorem to Eq. (1) we get

$$\oint \bar{E}\cdot d\bar{s} = 0 \quad (2a)$$

With reference to Fig. 1b this can be written as

$$\left| E_x(z_2) - E_x(z_1) \right|_{max} \approx \left| \frac{V(z_1) - V(z_2)}{\Delta x} \right|_{max} \quad (2b)$$

Hence, if we know the extreme values of the transverse electric field $E_\perp$ at high altitudes, we also know the highest possible values of $(\Delta V[x])_{||}/\Delta x$, where $(\Delta V)_{||}$ is the potential drop along $\bar{B}$. That is, the larger $(\Delta V)_{||}$ is, the larger is Δx.

This result can easily be generalized to a case with a dipolar total magnetic field where $E_{||}$ is arbitrarily distributed along a magnetic field line. If we integrate the longitudinal component of (1) along a magnetic field line from the equatorial plane down to the ionosphere, utilizing orthogonal dipolar coordinates (cf e.g. Cummings et al, 1968), we get after some algebra:

$$\left(\frac{\partial}{\partial s_\perp} \Delta V_{||} \right)_{ia} = E_{\perp ia} - \frac{R^2_{ep}}{R^2_{ia}} f(\theta)\, E_{\perp ep} \quad (2c)$$

The symbol $E_\perp$ is used here for the southward component of the transverse electric field. The index "ia" denotes an ionospheric altitude and "ep" the equatorial plane. R is the respective radial distance from the centre of the earth. $\Delta V_{||} = V_{ep} - V_{ia}$ and $s_\perp$ is the southward horizontal $(\perp\bar{B})$ length-coordinate at the ionospheric altitude. The symbol θ is the magnetic co-latitude of the ionospheric intersection of the field line, and

$$f(\theta) = (1 + (1/4)\tan^2\theta)^{1/2} (2 \sin\theta\cos\theta + (1/2)\tan\theta\sin^2\theta)^{-1}$$

that is, $f(\theta) \approx 0.7$ with $\theta \approx 20^\circ$.

As a consequence of Equations (2a) - (2c) we may face an unattainable compromise when trying to apply a particular model of a current-driven plasma instability to the magnetospheric problem. This is because on one hand the instability may require a high value of i_z, while on the other hand (2a) - (2c) require the parallel electric field to be spread out, and the capability of the ionosphere to carry horizontal currents is limited:

$$\bar{i}_\perp = \sigma_p (\bar{E}_\perp + \bar{v}_n \times \bar{B}) + \sigma_H \bar{B} \times (\bar{E}_\perp + \bar{v}_n \times \bar{B})/B \qquad (3)$$

The symbols σ_p and σ_H denote the Pedersen and Hall conductivities, respectively, and v_n denotes the neutral gas velocity (cf Boström, 1964).

If we integrate (3) with respect to altitude, we get the total current per meter that can be fed into the ionosphere by means of a field-aligned sheet-current density $I_{||}$. Roughly speaking, we may equate for instance $\Sigma_p E_\perp$ to $2\Delta x \; i_{||}$, where Σ_p is the height integrated σ_p, and Δx is defined by Fig 1b. The largest possible value of Σ_p is probably about 40 mho (Boström, 1964). According to satellite measurements (Cauffman and Gurnett, 1972) $E_\perp$ at 500 - 2500 km alt is at most 150 - 200 mV/m, which would thus imply $I_{||} = \Sigma_p E_\perp \lesssim 8$ A/m. However, this is probably far too much, because $E_\perp$ tends to be reduced where Σ_p (and Σ_H) is large (Aggson, 1969; Potter, 1970; Wescott *et al*, 1969). A more realistic maximum value of $I_{||}$ is rather an order of magnitude lower, in accordance with the magnetic measurements made by Zmuda *et al*, 1970. These authors infer the values 0.02 - 0.7 A/m for $I_{||}$. The highest values of $i_{||}$ ever reported are about 2×10^{-4} A/m^2 (Whalen and McDiarmid, 1972). Using this value for $i_{||}$ and 0.7 A/m for $I_{||}$ we get $2\Delta x \sim 3$ km. That is, with $V(z_1) - V(z_2) = 5$ kV in Eq. (2b) we have $|E_x(z_2) - E_x(z_1)| \sim 3$ V/m. Hence, we may, for instance, conclude that any instability that does require $i_{||}$ of at least 10^{-4} A/m^2 to be operating in the topside ionosphere is highly unlikely to be the actual cause of a $(\Delta V)_{||}$ of several kV.

From Eq.(2b), for instance, we further conclude that the common ray structure in visible auroras cannot be directly related to the spatial (transverse to $\bar{B}$) distribution of $(\Delta V)_{||}$. In fact, the ray structure might indicate $\Delta x < 50$ m in Fig. 1b (cf Chamberlain, 1961). With a typical electron kinetic energy of 5 keV the right-hand member of Eq.(2b) is thus 100 V/m. That is, neglecting $E_x(z_1)$ we have $E_x(z_2) > 100$ V/m. In a dipolar magnetic field this would correspond to $E_\perp > 40$ V/m at an altitude of 1 R_e above the ionosphere and $E_\perp > 1.5$ V/m in the equatorial plane at a distance of 10 R_e from the earth (cf Eq.(2c)). These values of $E_\perp$ are at least a factor of 100 to 300 larger than the largest $E_\perp$-field observed so far (cf Cauffman and Gurnett, 1972; Jeffries et al, 1975; Wescott et al, 1976). Even if $E_\perp$-fields of this magnitude do occur they do not automatically imply that $(\Delta V)_{||}$ is confined within a very thin flux tube, however. The confinement of $(\Delta V)_{||}$ also requires that these strongly concentrated $E_\perp$-fields are supported by the magnetospheric dynamo (cf. Section 14), which appears rather unlikely. The small spatial scale of these $E_\perp$-fields is obviously much smaller than the gyroradius of a 5 keV proton, for instance. Hence, if the auroral electrons do indeed fall through a large electrostatic potential gradient the auroral ray most likely represents a substructure within a much wider region of non-zero $E_{||}$. It should be noted that even though Equation (1) may not be strictly fulfilled, a region of large $(\Delta V)_{||}$, which is confined within a thin magnetic flux tube, in general has to be associated with large values of $E_\perp$.

In summary, the magnetospheric case may require a large $(\Delta V)_{||}$ to be maintained at current densities that are too low to generate a current-driven instability. The mechanism responsible for $(\Delta V)_{||}$ may, however, allow local enhancements of the precipitation within the region of non-zero $E_{||}$. As will be discussed below the magnetic mirroring may seem to provide a basic solution of these problems.

6. A Simple Illustration

The simple model presented below will serve as a further illustration of the previous section. As our à priori information about $E_\perp$, we will assume a simplified horizontal distribution that is basically similar to the $E_\perp$-distribution seen at auroral latitudes by a polar orbiting satellite at around 500 - 2500 km altitude, cf for instance Cauffman and Gurnett (1972).

Fig 2 refers to the local evening side of the northern auroral zone. The z-axis points vertically upward, the x- and y-axis point geomagnetically northward and westward, respectively. Again the total magnetic field $\bar{B}$ is assumed to have straight and vertical field lines.

Suppose that we know the convection at altitude z_b in the upper ionosphere to be magnetically eastward and westward, that is parallel to the y-axis, with $E_\perp$ equal to the step function $E_x(x,z_b)$ in Fig 2. What will E_x then look like at other altitudes? Suppose that $\sigma_{||} = i_z/E_z$ is constant above a certain altitude z_b - h well above the E- and F-layers, and that $\sigma_{||} \sim \infty$ throughout the lower part of the ionosphere. The last assumption enables us to get the height-integrated form of Eq. (3) by simply writing Σ_P and Σ_H instead of σ_P and σ_H, provided that

$$v_n \approx 0 \tag{4}$$

The Pedersen and Hall conductivities are assumed to be horizontally homogeneous.

Further assume that

$$\frac{\partial}{\partial y} = 0 \tag{5}$$

We now solve Eq. (1) with $E_x(x,z_b)$ and Eq. (3) - (5) as boundary conditions, recalling that

$$\text{div } \bar{i} = 0 \tag{6}$$

As the Pedersen current in this geometry has a divergence around $x = 0$ we get a field-aligned current flowing upward at the field reversal. Due to the finite $\sigma_{||}$ the step in $E_x(x,z_b)$ is completely smoothed out in $E_x(x,z_b - h)$ giving a finite i_z. In flying through the field reversal at altitude $z_b + h$ we would see an $E_\perp$ profile according to $E_x(x,z_b + h)$ and at even higher altitudes the "spikes" on each side of the reversal would be even larger.

We see from Fig 2 that, although the field-reversal is infinitely sharp at z_b, we get a certain finite characteristic thickness of the associated field-aligned current sheet equal to 2Λ, where

$$\Lambda = \sqrt{\frac{h \cdot \Sigma_P}{\sigma_{||}}} \qquad (7)$$

That is, to get $\Lambda = 0$ we must have $\sigma_{||} = \infty$ everywhere. This is due to the fact that $E_\perp$ has a finite amplitude at z_b (as well as all other altitudes).

It is important to notice, that as $\sigma_{||}$ decreases (increasing Λ) the potential drop along the magnetic field is reached at the expense of the transverse potential drop at low altitudes, provided of course that $E_\perp$ (z_b) does not increase. In Fig. 2 $(\Delta V)_{||}$ between $z_b - h$ and z_b evidently has a maximum of $\Lambda \cdot E_o$ at $x = 0$.

We further notice that the parallel electric field E_z, as well as the current density i_z, has an "inverted-V" profile. This is of great interest, as this electric field having an upward direction on the evening side of the earth, at a "regular" field reversal, would be able to accelerate auroral electrons downwards, producing the typical "inverted-V" shape of mean energy versus latitude that is seen at the field reversal at local evening (Gurnett and Frank, 1973). This is further discussed in Section 14.

7. A Self-Consistent Model of a Static $E_{||}$

Figure 3 is a refinement of Fig. 2 in that the field-aligned "resistivity", that is, the quantity E_z/i_z, is increased only within the field-aligned current sheet. In Fig. 3 z_b is 1500 km and h = 500 km. The assumed boundary value $E_x(x,z_b)$ is not a step function here but a smooth profile, cf the curve labeled z = 1500 km. The altitude-averaged parallel field $\tilde{E}_z$, defined by ,

$$\tilde{E}_z(x) = (V(x,z_b - h) - V(x,z_b))/h$$

has been introduced here, as well as the altitude averaged "anomalous resistivity" $\tilde{\rho}_{||}$ that is

$$\tilde{\rho}_{||} = \tilde{E}_z/i_z$$

(the field-aligned current is assumed divergence free above the E- and F-layers). Below $z_b - h = 1000$ km $\tilde{\rho}_{||}$ is assumed small (normal) in accordance with most theoretical models (e.g. Block, 1972; Kindel and Kennel, 1971).

The function $\tilde{\rho}_{||}$ (x) defined by the bottom curve in Fig 3 is simply an à priori assumption about the quantity $\tilde{E}_z/i_z$ (the peak value 10^2 ohm · m is chosen to give a reasonable current density). This assumption together with Eq (3) - - (5) with Σ_p = 10 mho has been used to solve Eq (1) and (6) for $\tilde{E}_z(x)$, $i_z(x)$ and $E_x(x,z)$. The resulting distribution of $i_z(x)$, the top curve of Fig. 3, then also defines $\tilde{\rho}_{||}$ as a function of i_z. This enables a better assumption about $\tilde{\rho}_{||}$, which can be used to recalculate i_z, and so on. By this iterative process it is possible to get the desired relation between $\tilde{\rho}_{||}$ an i_z.

The dashed E_x-profiles in Fig. 3 show what $E_\perp$ would look like at z = 2000 km and 2500 km in case $\tilde{\rho}_{||}$ had the same average value throughout this upper altitude region.

This again illustrates the fact that the amplitude of $E_\perp$ has to be an increasing function of altitude near the reversal due to the presence of a strong $E_{||}$. Of course, this will only be true up to a certain altitude, because $(\Delta V)_{||}$ is finite. Above this altitude we expect $E_{||}$ to be small (in general) and the amplitude of $E_\perp$ to be decreasing with increasing altitude, due to the diverging magnetic field lines.

Despite the obvious difference between the two models, the quantity Λ according to (7) again gives a good measure of the latitudinal width of the $\tilde{E}$-profile in Fig. 3 with the peak value 10^2 ohm · m inserted for $\sigma_{||}^{-1}$. Also, the maximum potential drop between z = 1000 km and z = 1500 km is again at least of the same order of magnitude as $\Lambda \cdot E_o$.

In Fig. 3 Σ_p is still horizontally homogeneous, but an assumed profile $\Sigma_p(x)$ can be introduced in the model to give a modified i_z and E_z, which then helps make a better assumption about $\Sigma_p(x)$. Provided that the energy of the electrons before acceleration by $(\Delta V)_{||} = h \cdot \tilde{E}_z$ is specified. In this way the model can be made self-consistent. The main effect of a locally enhanced $\Sigma_p(x)$ at the base of a field-aligned current sheet, when $\sigma_{||}$ is small and $E_\perp$ is given at a certain high altitude, is just a corresponding local reduction of $E_\perp$ at low altitudes, as has been shown in a previous paper (Lennartsson, 1973a; cf also Section 14). The local increase of Σ_p will also have a feed-back effect on the magnetospheric "dynamo", which this simple model cannot account for, however. Neither can this model in an adequate manner account for the auroral electrojet, which requires a three-dimensional geometry.

It may be noted that if we try to extend this simple model to very high altitudes (utilizing (2c), for instance) we can no longer neglect the (unknown) transverse current that is feeding the current loop (the "dynamo current").

8. "Anomalous Resistivity" and the Magnetic Mirroring

Suppose for a moment that we can neglect the mirroring effect of the geomagnetic field where $E_{||}$ is large. Consider Fig. 1b. It is quite obvious that an electron that has gained the energy $e \cdot (V_1 - V_2)$ by falling from z_2 to z_1 at the same time has made its maximum possible contribution to a short-circuiting current. That is, a freely falling electron in this case represents an extremely high conductivity per particle. In order for the potential jump $V_1 - V_2$ to be maintained, the number flux of these electrons thus has to be limited in one way or another. It is commonly assumed that the ionospheric and magnetospheric plasmas are dense enough to short-circuit any $E_{||}$ in the classical sense, but due to the high relative drift velocity between electrons and ions, some plasma instability is generated that may strongly limit the number flux of electrons, in analogy with the behaviour of laboratory plasmas. The main different modes of plasma instabilities that are considered in this respect are turbulent wave-particle interactions (e.g. Kindel and Kennel, 1971; Swift, 1965) and electrostatic potential double layers (e.g. Block, 1972 and 1975; Kan, 1975; Swift, 1975). However, as discussed in Section 5 the magnetospheric plasma may not provide the appropriate boundary conditions for this kind of instability. The problems seem to be particularly severe with respect to turbulent "resistivity". In this case the electrons falling from z_2 to z_1 in Fig. 1b may possibly be a minority group of either "runaway" electrons or hot magnetospheric electrons passing by unaffected by the wave field, but the theory does require a certain minimum drift velocity of the thermal electrons. That is, with an assumed plasma density the theory does require a minimum parallel current density being carried by thermal electrons $i_{||}$ (thermal).

Consequently, a certain minimum fraction of the electrostatic energy (provided by an external "dynamo") being released per unit area per second, $i_{||} \cdot (V_1 - V_2)$, has to be converted into random motion, that is into heat (Block, 1975). With at least $i_{||}$ (thermal) ~ 10^{-5} A/m^2 (Kindel and Kennel, 1971) $V_1 - V_2 = 5$ kV, $z_2 - z_1 = 10^4$ km (see Fig. 1b) and a density of thermal electrons and ions of $10^9/m^3$, we get a heating rate of 30 eV per second per thermal particle, to be compared with the original thermal energy of less than 1 eV per particle (cf Block, 1975). A certain fraction of this energy may possibly be radiated away by plasma waves, but there is anyway no theory disproving that the auroral plasma temperature would get drastically increased, as far as the author knows (in the theory by Buneman, 1959, this heating is a desired effect; cf also Biskamp and Chodura, 1973). We notice here that as the temperature is increased the maintaining of the plasma drift instabilities demand a higher $i_{||}$, which means that we immediately get into conflict with Section 5, even if the initial conditions are favourable.

The theory of double layers, on the other hand, does not suffer from this heating dilemma, according to Block (1972, 1975), because the particle motion is basically laminar at a double layer. The theory of double layers will not be discussed in the present paper, however. The reader is referred to the papers by Block (1972, 1975) as well as the papers by Swift (1975) and Kan (1975) on oblique double layers (electrostatic shocks).

Apart from the heating problem there is also a problem of plasma depletion connected with any theory that requires a strong (upward) $i_{||}$ to be carried by a cold background plasma of ionospheric origin. Suppose for instance that the density n of cold electrons at an altitude of 3000 kms is $10^2/cm^3$ (cf Lemaire and Scherer, 1973b) and that n decreases proportionally to B upwards, giving n ~ 0.1 - 1/cm^3 at the equatorial point of the magnetic field line. This may well give an overestimation of the cold-plasma content in a typical flux tube, as mass spectrometer data (Chappell, 1972) frequently show a total ion density of only $0.1/cm^3$ in the plasma sheet. An upward field-aligned current with $i_{||} \sim 10^{-5}$ A/m^2 at topside altitudes, carried by downward-moving electrons, would deplete all available cold electrons above 3000 kms altitude within about 2 - 5 minutes (provided that the current sheet does not have a persistent horizontal motion relative to the plasma). Within a few more minutes even the topside ionosphere would suffer a strong depletion. If $i_{||}$ as high as 10^{-4} A/m^2 is required by the theory, the depletion problem gets extremely critical. We cannot really expect the cold plasma to be supplied from adjacent flux tubes by convection, as the convection is generally found to be along auroral arcs (e.g. Armstrong _et al_, 1975; Gurnett and Frank, 1973; Wescott _et al_, 1969). At $i_{||}$ as high as 10^{-5} - 10^{-4} A/m^2 we can also neglect the contribution from upward-moving protons, even though these can, in principle, be continously supplied by the topside ionosphere. This proton current cannot be stronger than allowed by the escape flux (10^{-7} - 10^{-6} A/m^2, cf Lemaire and Scherer, 1973a and 1974), that is, it is "temperature-limited". The "spacecharge-limited" proton current is even many orders of magnitude weaker (Block, 1967). Consequently, the only available carriers of a persistently intense upward $i_{||}$ are the hot electrons from the outer magnetosphere.

Now take into account the magnetic mirroring effect _within_ the acceleration region. The previous statement about the high "conductivity" of "freely falling" electrons does not hold true anymore because the magnetic mirror tends to obstruct the parallel current by deviating the parallel motion of the electron into transverse motion (without changing the particle energy). Apparently, this may even constitute the only necessary mechanism for obstructing

$i_{||}$ and maintaining a large total potential drop along the geomagnetic field lines, provided that the density of the charge carriers is not too large. In view of the fact that an upward current (downgoing electrons) may have to be carried mainly by electrons from the dilute and hot plasma in the outer magnetosphere, this mechanism seems to have been somewhat overlooked over the years.

Consider the simplified case with an isotropic and mono-energetic source distribution of electrons in the outer magnetosphere, at point 1. In this case the electron flux density at ionospheric altitudes, at point 2, is proportional to $\sin^2\alpha_{max}$, where α_{max} is the maximum pitch angle at point 1 of electrons capable of reaching point 2. If the potential difference between points 1 and 2 is $(\Delta V)_{||} > 0$, the constancy of the magnetic moment gives

$$\sin^2\alpha_{max} = \frac{B_1}{B_2}\left(1 + \frac{e(\Delta V)_{||}}{\frac{m_e}{2} v_1^2}\right)$$

where B_1 and B_2 are the magnetic field strengths at points 1 and 2, respectively, and $(m_e/2)v_1^2$ is the electron kinetic energy at point 1. Hence, the field-aligned current density at ionospheric altitudes due to precipitation is given by

$$i_{||2} = n_1 v_1 \frac{e}{2}\left(1 + \frac{e(\Delta V)_{||}}{\frac{m_e}{2} v_1^2}\right) \qquad (8)$$

where n_1 and v_1 are the density and velocity of downgoing electrons at point 1. Eq.(8) is valid for $e(\Delta V)_{||} \lesssim$ $\lesssim (m_e/2)v_1^2 B_2/B_1$. For larger $(\Delta V)_{||}$ the current becomes saturated. If the electrons at point 1 have a Maxwellian distribution, for instance, Eq.(8) takes on a different algebraic form (Knight, 1973), but (8) is still a good approximation, with v_1 denoting an average value. As a numeric example, with $2n_1 = 0.1$ cm^{-3} and $(m_e/2)v_1^2 = 500$ eV, a current density $i_{||2}$ of 10^{-6} A/m^2 requires $(\Delta V)_{||} \approx 9$ keV.

It may be noted that the $(\Delta V)_{||}$ required to drive a certain high $i_{||2}$ will increase with increasing energy (at constant density) of the source plasma, as long as $n_1 e v_1 < i_{||2}$.

Knight (1973) and Lemaire and Scherer (1973a, 1974) have used more sophisticated models to calculate the relation between $i_{||}$ and $(\Delta V)_{||}$ in a collision-free magnetospheric plasma under steady state conditions. These authors find, by assuming reasonable ionosphere-plasmasheet parameters, that an upward $i_{||}$ of the order of 10^{-5} A/m^2, for instance, may readily require a total $(\Delta V)_{||}$ of 1 - 10 kV, as a result of the magnetic mirroring of plasmasheet electrons (see for instance Fig. 3, p. 745, in the paper by Knight). Knight has neglected the ionospheric ion contribution to $i_{||}$, while this is included by Lemaire and Scherer, but the difference is obviously insignificant when $i_{||} \gtrsim 10^{-5}$ A/m^2.

Unfortunately, the model by Knight provides only the total voltage $(\Delta V)_{||}$ (as does Eq. (8)) while $E_{||}$ remains undetermined. The model by Lemaire and Scherer does provide $E_{||}$ numerically but the case of a strong upward $E_{||}$ is not explicitly shown.

It should be noted that these models rely upon the outer magnetosphere providing a steady supply of isotropic electrons. The need for a high $(\Delta V)_{||}$ will evidently be larger if the magnetospheric particle source is depleted of electrons with small pitch angles. A second important point that has to be considered is that the outflux of positive ions from the ionosphere may become strongly reduced by space-charge effects when the cold electrons are depleted at high altitudes (cf Block, 1967).

9. The Transverse Spatial Distribution of $E_{||}$ and the Ray Structure of Auroras

In view of Sections 5 - 7 it may seem difficult to reconcile auroral fine structures like visible auroral rays (and very thin current sheets) with a particle acceleration due to a large $(\Delta V)_{||}$. This is particularly true of current-driven instabilities as we then would expect the cross-sectional dimensions of a current sheet or current beam to directly map the transverse dimensions of the $(\Delta V)_{||}$ - region, cf Fig. 1b. This may thus strongly favour the magnetic-mirroring as the actual current obstructing mechanism, according to the following arguments.

As seen above the magnetic mirror may support a large $(\Delta V)_{||}$ even at a small current density. Eq. (8) assumes an isotropic distribution of source electrons at point 1, however. If the source electrons all have large pitch angles $(\Delta V)_{||}$ may be high even with no net $i_{||}$ being carried by the hot electrons (cf Alfvén and Fälthammar, 1963, pp 162 - 167; Persson, 1963 and 1966). Given the potential difference $(\Delta V)_{||}$ along a certain field line the parallel current density $i_{||}$ may thus vary over a wide range with different density and pitch-angle distribution of the source electrons. We therefore suggest the following basic model.

By the magnetic mirroring of incoming electrons the hot plasma at high altitudes remains at a large negative potential relative to the cold plasma at the ionospheric end of the flux tube (see Section 14 for the driving "dynamo"). The resulting parallel electric field is distributed within a high-altitude region that may have large dimensions transverse, as well as parallel, to the magnetic field, and net field-aligned currents may be flowing preferably in thin field-aligned subregions.

This model is compatible with the requirements in Section 5, and it permits thin auroral rays to be energized by a $(\Delta V)_{||}$.

What remains is a mechanism for producing thin precipitation structures. It is conceivable that such a mechanism may be associated with the supplying of electrons at high altitudes, but the above model also offers the possibility of transforming a uniform source distribution of electrons into a non-uniform distribution of precipitating electrons. That is, a local increase of the precipitation may, in principle, be accomplished by a local reduction of the magnetic mirroring effect on electrons. Hence, with the above model it may be possible to reduce the problem of auroral ray formation to the problem of finding a wave-particle interaction by which electrons can lose gyroenergy in a spatially selective manner. This problem will not be further analyzed here, however, but it may be kept in mind that there are, in fact, a number of plasma wave modes already known that resonate with the gyromotion of electrons (see e.g. Helliwell, 1967; Kennel and Petschek, 1966; Perkins, 1968; Stix, 1962). It should be noted that this kind of wave-particle interaction does not necessarily have to occur within the $E_{||}$-field-regions to produce a ray structure in the precipitation but may well occur at lower altitudes where $E_{||} = 0$, if the magnetic mirror ratio is still large below.

10. The Parallel Spatial Distribution of $E_{||}$

The distribution along the magnetic field of $E_{||}$ in a magnetic mirror configuration is a problem that has been treated in certain aspects by, among others, Persson (1966). He finds, for example, that in a stationary state with no field-aligned currents and with "almost isotropic" distributions (isotropic except for a loss cone) for both electrons and ions the parallel electric field is given by

$$E_{||} \propto \mathrm{grad}_{||} B \qquad (9a)$$

This particular form of $E_{||}$ will be used in Sections 11 and 13 for quantitative calculations. The results obtained there are qualitatively true with a rather wide range of $E_{||}$- fields, however. Although (9a) was derived by

Persson in a case with no net $i_{||}$ it can be seen to be compatible with a large $i_{||}$ as well, at least in a restricted sense. In fact, (9a) is the unique solution of Eq.(8) under the following conditions.

Suppose Eq.(8) is valid at any point 2 along the magnetic field line below point 1 ($B_2 > B_1$). This implies that the electrons are monoenergetic with an isotropic pitch-angle distribution on the interval $[0^\circ, 90^\circ]$ at every point below point 1. Then if s is the length-coordinate along the field line, Eq.(8) is differentiable with respect to s at point 2. Since $i_{||}(s) \propto B(s)$ the derivative of (8) gives

$$E_{||} = -\kappa \frac{dB}{ds} \qquad (9b)$$

with $\kappa = \mu_{crit}/e$, μ_{crit} being the magnetic moment of the electrons that maintain a pitch angle $\approx 90^\circ$.

Hence, (9b) is the electric field that barely maintains a saturated current at every pont, given an isotropic and monoenergetic source distribution of electrons at point 1 with energy equal to $\mu_{crit}B_1$. If the electrons at point 1 have a distribution of energies the electric field (9b) provides an asymptotically saturated current as $B(s)/B_1 \to \infty$.

The actual distribution of $E_{||}$ is subject to quasi-neutrality of the plasma as well as to the magnetic mirroring of the charge carriers, however. In the problem considered by Persson Eq.(9b) is consistent with quasi-neutrality, but only trapped particles are present ($\mu_e > e\,\kappa$). In the auroral case the distribution of $E_{||}$ is necessarily influenced by the ionospheric particles. Consider Fig.4. Suppose the high-altitude region 1 is devoid of cold electrons and $E_{||}$ is defined by (9a) in this region. Suppose further that the cold plasma still remains in the low-altitude region 3, where the plasma density n_3 is much larger than the plasma density n_1 in region 1, $n_3 \gg n_1$. In region 3 the electric field (9a) cannot be valid and we assume $E_{||} = 0$ throughout this region. The intermediate region 2 is a transition region with some à priori unknown distribution of $E_{||} \neq 0$. In going from the low-altitude region 3 into the $E_{||}$-field at higher altitudes the cold protons (or other positive ions) p_3, rapidly decrease in density and soon become comparable in density with the hot protons p_1. In region 1 the two proton populations p_1 and p_3 together may thus (chiefly) match the negative charge due to the hot electrons e_1. At lower altitudes in region 3 the hot electrons e_1 are a minority group and the protons p_3 are matched by cold electrons there. In the intermediate region 2 $E_{||} \neq 0$, however, and no cold electrons can exist where $E_{||} \neq 0$. The only negative particles that can conceivably match the protons p_3 throughout region 2 are the backscattered and energetic secondary electrons e_3 from below. Hence, the transition region 2 either has a quasi-neutral plasma, with a density gradient defined by the energy distribution of the backscattered and secondary electrons or it has an unbalanced positive charge in the lower section. The former case allows a smooth density gradient while the latter case obviously requires a steep density gradient, defined by some characteristic Debye length, and a locally strong $E_{||}$. The latter case also requires a region of unbalanced negative charge above the positive charge. This negative charge may be partly due to the electrons e_3 and partly due to energetic electrons e_2 that have become trapped between region 1 and the magnetic mirror below during the initial growth of $(\Delta V)_{||}$. Both the gradual transition and the "double layer" are conceivable, but the "double layer" may seem the most likely since it does not require any particular velocity distribution of the electrons (Block, private communication). It should be noted that such a "double layer" is not a result of a strong current, but is a result of the magnetic mirroring of the current carriers.

From these considerations it is obvious that the parallel electric field cannot be entirely determined by the <u>local</u> magnetic field gradient at every point along the flux tube.

Below some altitude, which may vary with time, the electric field will be "screened out" by the cold plasma still remaining there. This also means that there has to be a transition region where $E_{||}$ is determined by local plasma parameters, as well as by the magnetic mirror ratio below the transition region. At least if this mirror ratio is large the partial potential difference $(\delta V)_{||}$ across the transition region may be a considerable fraction of the total potential difference $(\Delta V)_{||}$, cf. Fig 4. At higher altitudes the $E_{||}$-field may or may not be able to adjust to the local magnetic-field gradient, depending on the actual particle population. However, even if $E_{||}$ does not have a smooth distribution like (9a), for instance, it still has to extend to high enough altitudes to ensure a sufficient precipitation flux of source electrons, according to Eq. (8). This problem will be discussed further in a forthcoming paper.

11. The Collimation of Electron Bursts

Suppose $E_{||}$ is given by (9b) with κ being a positive constant along a certain field line. The equation of motion along the field line for an electron is then

$$m_e \frac{dv_{||}}{dt} = (e\kappa - \mu) \frac{dB}{ds} \tag{10}$$

where $\mu = m_e v_{\perp}^2/2B$ is the magnetic moment. In going from point 1 where $B = B_1$ to point 2 where $B = B_2 > B_1$ an electron increases its total kinetic energy according to

$$\frac{m_e}{2} (v_2^2 - v_1^2) = e(V_2 - V_1) = e\kappa (B_2 - B_1) \tag{11}$$

As long as μ is constant we then have

$$\frac{v_{\perp 2}^2 - v_{\perp 1}^2}{v_2^2 - v_1^2} = \frac{\mu}{e\kappa} \tag{12a}$$

That is, if $B_2 >> B_1$ $(v_{\perp 2} >> v_{\perp 1})$

$$\sin^2 \alpha_2 = \frac{{v_{\perp 2}}^2}{{v_2}^2} \lesssim \frac{\mu}{e\kappa} \qquad (12b)$$

Hence, given an electron with $\mu < e\kappa$ its pitch angle remains smaller than or equal to a constant determined by the magnetic moment of the electron. Such an electron increases its parallel velocity along the path, according to (10), and the increase is faster the smaller μ is. The associated velocity despersion due to different α at given energy is quite large. Suppose for instance that (9b) is valid down to an altitude of h = 0.5 earth radii above the earth on a magnetic field line with L = 10 and $(\Delta V)_{||}$ = 1keV. If electrons with 10eV energy start at L = 10 in the equatorial plane, an observer at altitude h will find a time delay of about 4 sec between the arrival of electrons with $\alpha = 0^{\circ}$ and $\alpha = 45^{\circ}$. An observer in the lower ionosphere will find this time delay to be only 1 sec, if $(\delta V)_{||} = 0$ below h, but this is more than one order of magnitude larger than would be expected if the electrons started from altitude h with 1 keV energy. A sudden increase of the number of electrons with $\mu < e\kappa$ at high altitude is then expected to show up as a burst of electrons with small pitch angles at lower altitudes, in agreement with auroral particle observations (e.g. Arnoldy <u>et al</u>, 1974; O'Brien and Reasoner, 1971).

An increase of the number of electrons with $\mu < e\kappa$ does not have to involve an actual particle injection, it may as well be accomplished by a transfer of electrons in velocity space from large to small magnetic moments. That is, a gyroresonant wave-particle interaction may be a solution in this case, too. A transfer of electron gyroenergy into electromagnetic wave energy may also, in principle, produce a collimated beam of electrons by itself, without involving velocity dispersion. If the interaction occurs within the electric field (9b) the field serves to preserve the collimation, according to Eq (12b).

These considerations are based on the exact relation (9b), but they are essentially applicable to any upward $E_{||}$ that is distributed along the magnetic field with $\int eE_{||}\,ds \sim \mu\Delta B$ over finite intervals Δs.

12. Comments on the Electron Energy Spectrum

Consider Eq.(11). If the initial energy at point 1 is small compared to $e(V_2 - V_1)$, only a small total amount of kinetic (gyro) energy has to be removed by wave-particle interactions at point 1 to create a large enhancement of the elctron energy flux at point 2. On the other hand, any electron that is being mirrored at a point close to point 2, between points 1 and 2, can lose all its gyroenergy and arrive at point 2 virtually without any energy. In other words, as long as we do not specify in detail the process of wave-particle interactions, there is a wide range of possible precipitation spectra associated with any given total potential drop $(\Delta V)_{||}$.

Obviously, there may also be certain wave-particle interactions connected mainly with the parallel motion of the electrons (cf Stix, 1962). Since the precipitating electrons will be streaming through a population of upflowing positive ions from the ionosphere there may be favourable conditions for the two-stream instability, for instance. The different kinds of possible wave-particle interactions thus seem likely to generate a component of the precipitating electrons having a degraded energy, as compared with the "free-fall" component. More generally, wave-particle interactions may cause the electrons to diffuse in velocity space, preferably towards smaller velocities, although some precipitating electrons may gain energy in this way (cf Perkins, 1968). As the backscattered and numerous secondary electrons will be reflected downwards by $(\Delta V)_{||}$ (Evans, 1974) the total energy spectrum of precipitating electrons at low altitudes may thus, in principle, look fairly smooth even with a large $(\Delta V)_{||}$ present, which may also be the case with a fluctuating $(\Delta V)_{||}$.

The extent of energy degradation of the primary electrons will probably be a function of the spatial structure of the precipitation, as indicated by straightforward calculations (cf for instance Hess et al, 1971). That is, a widely extended structure is seemingly particularly susceptible to instabilities in velocity space because it allows unstable traveling waves to grow for extended periods of time. By the same token a spatially strongly limited plasma may thus be more stable against this kind of wave growth. In fact, both artificial generation of thin "auroral" electron beams (Hess et al, 1971) and theoretical investigations (Jones and Kellogg, 1973) do indicate that a thin structure of precipitating electrons is very stable to energy degradation by wave-particle interaction. This finding has an important implication with respect to the present auroral model. Suppose the number of electrons with $\mu < e\kappa$ is increased in a narrow spatial region at high altitudes, by gyroresonant wave-particle interaction, for instance. When continuing downwards these electrons will form a thin structure of increased number density (consider Eq.(11) and $nv_{||} \sim B$) that may thus become stable against further energy degradation, leading to a bright auroral form and a pronounced "monoenergetic" peak in the energy spectrum (cf O'Brien and Reasoner, 1971; Westerlund, 1969). That is, in principle the "monoenergetic" peak in the electron energy spectrum may have a spatial (horizontal) fine-structure within the horizontal region covered by a large $(\Delta V)_{||}$.

13. A Generalized "Loss Cone" for the Electrons

Since an electron with a large magnetic moment will mirror, there may often be a tendency towards negative charge-accumulation on a closed field line with upward currents. This may tend to quench the magnetospheric dynamo current (cf next section) leading to a "loss cone" distribution of electrons. This "loss cone" will be larger for electrons having a smaller total energy than for the more energetic electrons. Suppose $E_{||}$ is given by (9b) above a certain altitude, called the altitude of penetration of $E_{||}$, where $B = B_{pen}$, and $E_{||} = 0$ below. Then, given a point on a closed magnetic field line, where the magnetic field strength is $B \leq B_{pen}$, the half-angle α_{le} of the local loss cone is defined by

$$\sin^2\alpha_{le} = \frac{B}{B_{max}} + \frac{e\kappa B}{\frac{m_e}{2}v^2}\left(\frac{B_{pen}}{B_{max}} - \frac{B}{B_{max}}\right) \tag{13}$$

where B_{max} is the magnetic field strength at the altitude of the low ionosphere. For $B_{pen} < B \leq B_{max}$ the constant κ is zero. No electrons with $m_e v^2/2 \leq e\kappa B(B_{pen} - B)/(B_{max} - B)$ will remain on the field line. Eq.(13) follows from Eq.(11) and the constancy of μ.

The corresponding equation for the proton "loss cone" is analogous to (13) with the plus sign changed to a minus sign. This is then applicable to protons with $m_p v^2/2 \geq e\kappa(B_{pen} - B)$. Protons with lower energies will have no "loss cone".

If the low-altitude region where $B \geq B_{pen}$ has an upward $E_{||} \neq 0$ with a large $(\delta V)_{||}$ associated with it the change of Eq.(13) may be approximated by a reduction of B_{max}, $B_{max} \rightarrow B_{pen}$. In the case of the protons B_{max} will effectively increase.

If the electric field is increased, that is if κ is increased to $\kappa' > \kappa$, electrons will start precipitating again with pitch angles given by

$$\frac{\kappa}{\kappa'} \leq \sin^2\alpha \leq 1 \tag{14}$$

at the altitude of the low ionosphere. The half-angle of the apparent "loss cone" at ionospheric altitudes will thus rapidly decrease from 90° to the lower limit determined by (14) and then slowly increase again. Provided that the electric field has a negligible growth time, the time scale of the initial decrease of this "loss cone" will be roughly defined by the time it takes an electron with a low initial energy to fall from an altitude of one earth radius above the altitude of penetration of $E_{||}$, that is typically of the order of a second or less. The time scale of the subsequent increase of the "loss cone", on the other hand, will be determined by the travel time from the outer magnetosphere of the lowest-energy electrons, which may be several tens of seconds (with initial energies of the order of 100 eV or less).

Under certain conditions the increase of $E_{||}$ will lead to a transiently field-aligned precipitation flux which has a hardening energy spectrum towards smaller pitch angles, as observed at low altitudes. Consider, for instance, the case $\kappa' \gg \kappa$ (κ may be zero). Suppose the average electron energy at any altitude is much smaller than $e\kappa' B_{pen}$ prior to the increase of $E_{||}$. After the electric field is "turned on", a given electron from the precipitating population will reach the low ionosphere at a smaller pitch angle and a higher energy, if it is initially at a higher altitude, as seen from Eq.(11) and the constancy of μ. Furthermore, as a consequence of the velocity dispersion an electron from a higher altitude (higher final energy) will reach the low ionosphere with a certain pitch angle at the same time as an electron from a lower altitude (lower final energy) with a larger pitch angle. This apparent relation between energy and pitch angle will thus gradually disappear as electrons from larger and larger distances appear at 90° pitch angle. Since a larger $(\Delta V)_{||}$ will cause a larger number of electrons to precipitate, the velocity dispersion will also be associated with a field-aligned number flux at low altitudes. It should be kept in mind that the effect of velocity dispersion may be very strong with an electric field that is distributed over a large distance (cf Section 11). Also in the case of gradually increasing $(\Delta V)_{||}$ the velocity dispersion will have similar effects, as discussed in Section 15. These results are basically true with any $E_{||}$ that is both distributed along the magnetic field line and compatible with preserved magnetic moments of the electrons.

14. The Magnetospheric Dynamo

The current configuration of Fig. 2 and 3 may be part of current loops like those sketched in Fig. 5. The view of Fig. 5 is in the direction towards the sun. We may think of Fig. 2 and 3 as pictures of a small region around point D. In this particular case Pedersen currents are flowing in towards the upward current sheet both from the north and the south side. The poleward downward current may flow either from A′ to D′ or from W down the dotted line (that is, close to A-D), or probably both ways. This symmetric situation may not at all be the typical case in reality, where we may even have multiple field-aligned current sheets (e.g. Aubry *et al*, 1972).

A magnetospheric dynamo driving a current down to the ionosphere and back up basically is a continuously progressing charge separation in the outer magnetosphere, driven by e.g. inertia forces on the charged particles. The dashed current loop in Fig. 5, for example, may be accomplished by the ionospheric drag (in a hydromagnetic sense) on the solar wind flow via open (merged) magnetic field lines. This case is a "voltage-generator", where the charge separation between A and A′ is produced, basically, by solar wind protons displacing their gyrocenters in a direction opposite to (and the electrons in the same direction as) $\bar{E}_\perp$, when entering a region of reduced $E_\perp$ (reduced E x B-drift), cf e.g. Alfvén (1975). That is, kinetic energy associated with E x B-drifting solar wind protons (and electrons) is converted into electrostatic energy. If the solid current loop in Fig. 5 is on closed magnetic field lines the driving charge separation between A and B may, for instance, be due to gradient-B drift of energetic particles across inhomogeneities in their density and temperature distributions, as in the model by Jaggi and Wolf (1973). This case is more like a "current-generator", although far from strictly. Indirectly, the solar wind is the driving agent in this case, too, as the solar wind flow is what causes the internal magnetospheric convection (sunward). This convection carries the charged particles into the earth's magnetic field, leading to betatron and Fermi acceleration of the particles (cf e.g. Alfvén and Fälthammar, 1963).

Consider, for instance, the current loop ABCDA in Fig 5. Suppose the dynamo current A-B is due to a differential drift of hot electrons and protons (or other positive ions) across the magnetic field lines. This drift tends to accumulate electrons at A and protons at B. Then the positive space charge at B will enable the ionospheric electrons at point C to escape at a higher rate than allowed by the normal polar wind flux of both ions and electrons. Since the flux density of freely escaping ionospheric electrons is as high as 10^{10} - $10^{11}/cm^2s$, corresponding to $i_{||} \sim 10^{-5}$ - 10^{-4} A/m^2 (cf Lemaire and Scherer, 1973), it is reasonable to believe that the current B-C typically flows without a significant potential drop. That is, point C will remain at nearly the same potential as point B. A Pedersen current from C to D in the ionosphere will thus charge point D positive with respect to point A. The negative space charge at A, on the other hand, does not release a corresponding increase in the outflux of positive ions from point D. The upward positive-ion flux from the ionosphere will be either "temperature limited" by the natural thermal outflux of topside ions, giving a contribution to $i_{||}$ of only 10^{-7} - 10^{-6} A/m^2 (cf Lemaire and Scherer, 1974) or "spacecharge limited", giving an even smaller contribution (cf Block, 1967). The potential difference $(\Delta V)_{||}$ between A and D will thus easily grow to a level where a large fraction of the hot electrons arriving at A are forced through the magnetic mirror and precipitate at D with increased energy. Given the initial (average) kinetic energy K_e of the electrons at A, the magnetic mirror may support a $(\Delta V)_{||}$ which is as large as $(K_e/e) \times (B_D/B_A)$, where B_D and B_A are the magnetic field strengths at D and A, respectively (see Section 8). This is valid provided most of the electrons from A preserve their magnetic moments during transit to D, of course.

By these arguments we emphasize the magnetic mirroring effect as the presumable basic cause of a large $(\Delta V)_{||}$. That is, the primary effect of the mirroring is to obstruct a discharge along the magnetic field line. However, the actual distribution of $E_{||}$ is subject to the quasi-neutrality of the plasma and this may well impose the formation of spacecharge layers where $E_{||}$ becomes much stronger than the local mirror forces (cf. Section 10).

It may be noted that the acceleration conditions along A-D may also be influenced by changes in the magnetic energy stored in the current loop. This will not be discussed in this paper, however.

15. Comparison with Observations

The convection electric field in the altitude range 500 - 2500 km has been extensively explored by polar orbiting satellites (Cauffman and Gurnett, 1972; Frank and Gurnett, 1971; Gurnett and Frank, 1973; Gurnett and Akasofu, 1974; Heppner, 1972 and 1973). It is found that the convection is generally antisunward over the polar caps down to the poleward edge of the auroral ovals (at 70° - 80° magnetic lat) and sunward between this region and the plasmasphere (except for stagnation lines near noon and midnight). The transition between antisunward and sunward convection is generally observed as a fairly sharp reversal of $E_{\perp}$, and adjacent to the main reversal the $E_{\perp}$-field is often strongly fluctuating (as seen by the moving spacecraft) with pronounced peaks. It has further been established (Ackerson and Frank, 1972; Burch et al, 1976; Frank and Ackerson, 1971; Gurnett and Frank, 1973) that on the evening side this field reversal is frequently associated with bands of intense "inverted-V" events, that is field-aligned sheets (probably east-west oriented) of precipitating electrons characterized by an "inverted-V" profile of mean energy versus latitude, as seen by a satellite crossing the sheet. From Sections 6 and 7 we would expect such an "inverted-V" event associated with the field-reversal on the evening side, where the associated $i_{||}$ is upward, in contrast with the morning side (cf Fig. 5).

The basic results of Sections 6 and 7 only require a pronounced horizontal gradient in $E_\perp$, that is, "inverted-V" events may as well be associated with the irregularities in $E_\perp$ adjacent to the main reversal, in accordance with the observations. The real situation, however, may be strongly complicated by horizontal gradients in Σ_P (and Σ_H), in particular when the precipitation structure is moving. A further complication is introduced by the (generally) unknown neutral gas velocity, which may also slightly displace the "inverted-V" structure relative to the observed inhomogeneity in $E_\perp$ (cf Lennartsson, 1973a). That is, we might expect some ambiguity when interpreting the observations. As long as Pedersen currents are the major source of the upward $i_{||}$ and the gradient in $E_\perp$ is mainly responsible for $i_{||}$ the $E_\perp$-gradient has to be in a certain direction, of course. That is, more $E_\perp$-field lines have to point toward the upward current sheet than away from it. The occasional observation of "inverted-V" events in the field-reversal region in the morning sector we thus interpret as due to the presence of a $\mathrm{grad}_\perp E_\perp$ with the "right" sign close to the main reversal. This seems to be in full agreement with data from the Ion Drift Meter (Hanson <u>et al</u>, 1973) on Atmosphere Explorer C, according to Burch (private communication).

We note from the simple models in Sections 6 and 7 that the "inverted-V" shape is the simplest possible latitudinal distribution of $(\Delta V)_{||}$ we may expect at an upward field-aligned current sheet, when the parallel "conductivity" is finite.

The "inverted-V" events in general are fairly thick sheets of precipitation, typically 100 - 250 km (Burch <u>et al</u>, 1976) which obviously is in full agreement with Section 5 (cf Eq. (2b)). It is even observed that in the direction from early to late local evening the "inverted-V" precipitation bands grow more energetic <u>and</u> wider (e.g. Gurnett and Frank, 1973), which is in qualitative agreement with Eqs (2b-c) under the assumption that $E_\perp$ at large distances from the earth (the "dynamo field") stays fairly constant; cf also Eq.(7) and the two subsequent paragraphs in Section 6; note that a decreased "$\sigma_{||}$" may, for instance, be due to an increased temperature of the hot source plasma, according to Eq.(8).

Often very pronounced peaks with opposite signs in $E_\perp$ are observed at each border of an "inverted-V" event. According to Burch (private communication) the ion drift data from Atmosphere Explorer C (Hanson et al, 1973) show such pronounced peaks to be in the "right" sense in all cases examined, that is with $E_\perp$ pointing toward the center of the "inverted-V" event. Besides, Burch found one pair of opposite $E_\perp$ peaks where $E_\perp$ pointed outwards, and this single case was seen to be associated with a three orders of magnitude dropout in the electron precipitation flux between the $E_\perp$-peaks as compared with the surrounding flux. Even if the satellite is observing the uppermost $E_\perp$ curve in Fig. 3, for instance, a large fraction of the observed $E_\perp$ is evidently due to the low-altitude field needed to carry the Pedersen currents towards the upward current sheet. That is, we do not expect the integral of $E_\perp$ along the satellite trajectory to be a true measure of the $(\Delta V)_{||}$ below the satellite. The "asymptotic" $E_\perp$-field on both sides of the reversal in Fig. 2 and 3 in reality may well go to zero within a short distance from the reversal, associated with the downward $i_{||}$-sheets (upflowing ionospheric electrons) as sketched in Fig. 6. This means that the satellite may at times observe two apparent "spikes" in $E_\perp$ even if it is actually observing only the low-altitude $E_\perp$.

Observations indicate that $E_\perp$ is reduced within auroral arcs due to the enhanced Σ_p and Σ_H (e.g. Aggson, 1969; Potter, 1970; Wescott et al, 1969). This is in full formal agreement with a large $(\Delta V)_{||}$, as shown in an earlier paper (Lennartsson, 1973a), and may be qualitatively understood as the low altitude $E_\perp$ adjusting to gradients in Σ_p to avoid a too high $i_{||}$; that is, to avoid a too high $(\Delta V)_{||}/\Delta x$ according to Eq (2b). This is, of course, provided that $E_\perp$ at high altitudes (the "dynamo field") is not allowed to increase. This is also illustrated in Fig. 6, where the low-altitude $E_\perp$ is very weak within the upward current sheet (precipitating electrons).

As mentioned in Section 4 observations often indicate that $i_{||}$ as inferred from magnetic measurements, is equal to or even larger than the current density inferred from the detected precipitation (see references at the end of Section 4). We found (Section 4) that this is seemingly the same as keeping the ionosphere at a higher potential than the adjacent magnetosphere. Obviously, this is easily understood in terms of a large $(\Delta V)_{||}$ in a direction to accelerate electrons downwards (along A-D in Fig. 5).

The above comments apply in principle to any large $(\Delta V)_{||}$. Now consider some observations that may favour a combined model of magnetic mirroring and plasma waves.

We recall that the "inverted-V" structures are often fairly wide in latitude and, hence, often associated with average $i_{||} \sim 10^{-6}$ A/m^2 (or less) at ionospheric altitudes (see references at the beginning of this section). This evidently places a severe restriction on a current-driven instability being the cause of $(\Delta V)_{||}$. On the other hand, the interpretation in terms of magnetic mirroring is, in principle, not affected at all, as $(\Delta V)_{||}$ in this case will be determined by the overall supply of electrons with small magnetic moments provided the outflux of ionospheric ions is not too large, and, in principle, $(\Delta V)_{||}$ may be large even with no $i_{||}$ at all flowing (Alfvén and Fälthammar, 1963; Persson, 1963; cf Section 13). With this model we then allow very sharp auroral arcs to be associated with intensified substructures of $i_{||}$ within wider regions of weak (upward) i (cf Armstrong et al, 1975; Hallinan and Davis, 1970). the intensification of $i_{||}$ being due, for instance to local reduction of the "magnetic resistance", that is, due to local transfering of electrons from the mirroring population to the precipitating population by means of gyroresonant wave-particle interaction.

According to Sharber and Heikkila (1972) no systematic variation with altitude of the auroral particle energies has been observed from a few hundred kms altitude to a few thousand kms. This is well compatible, within the accuracy of comparing observations of different events, with a widely distributed $E_{||}$. The most straightforward interpretation is, however, that $E_{||}$ does not normally penetrate to these altitudes.

We note that $E_{||}$ according to (9a), for instance, allows us to apply, in a qualitative manner, the model by Evans (1974), where he gives an explanation of the low-energy "continuum" spectrum of auroral electrons in terms of secondary and backscattered electrons from the ionosphere being reflected downwards by a $(\Delta V)_{||}$. In Evans' model all primary electrons have energies equal to or larger than $e(\Delta V)_{||}$ (they have all fallen through the same potential $(\Delta V)_{||}$.) giving rise to a pronounced high-energy peak in the energy spectrum. According to the present model (see in particular Section 12) we may expect some of the electrons with lower energies to be primary electrons that have been degraded in energy by wave-particle interactions. As the intensity and spectral shape of the backscattered and secondary electrons with lower energies are rather insesitive to the energy of the primaries (the intensity may even tend to increase with decreasing energy of the primaries, cf Evans, 1974) we might expect essentially the same low-energy "continuum" if the primary high-energy peak is "smoothed out" by wave-particle interactions. Even outside the magnetic flux tubes with a high $(\Delta V)_{||}$ there will be a residual precipitation, and if the magnetic field lines are closed we might then find a somewhat similar low-energy "continuum" of electrons arriving from the conjugate ionosphere. In this manner it may be possible to reconcile the presence of a high $(\Delta V)_{||}$ with the frequent observations of a fairly stable low-energy "continuum" even when the high-energy peak is strongly fluctuating (O'Brien and Reasoner, 1971; Reasoner and Chappell, 1973; Westerlund, 1969).

A $(\Delta V)_{||}$ supported by magnetic mirroring will have a selective effect on a given source distribution of electrons incident at high altitudes. The electrons with lower initial energies have on the average smaller magnetic moments and will thus get more completely precipitated. As $(\Delta V)_{||}$ grows larger, more high-energy electrons will be precipitated, while the precipitation of the electrons with lower energies will become successively saturated. An observer going towards the center of an "inverted-V" event (cf Fig. 3) will thus see a progressively larger high-energy tail above the (increasing) energy defined by $e(\Delta V)_{||}$. This tendency may be further strengthened by wave-particle interactions causing the precipitating electrons to diffuse in velocity space (cf Section 12). Recent measurements (Burch et al, 1976) do show a similar behaviour of the electron energy spectrum at low altitudes.

As pointed out in Section 11, the common collimation of electron bursts to small pitch angles (Hoffman and Evans, 1968; O'Brien and Reasoner, 1971; Whalen and McDiarmid, 1972) may be understood in terms of a distributed $E_{||}$-field in combination with gyroresonant waves acting as triggers of bursts (rays).

Arnoldy et al, (1974) found field-aligned fluxes (bursts) of electrons to have distinctly lower peak energies than the accompanying isotropic and "monoenergetic" component. In at least one case even the field-aligned flux appeared to be "monoenergetic", although with a lower energy than the isotropic flux. It may be possible to explain these observations simply in terms of several electrons populations with different energies falling through a certain $(\Delta V)_{||}$, at least if all limitations of the instruments are taken into account. However, we note that these observations fit into a model where bursts and rays are triggered by a transfer of electron gyroenergy into wave energy. Such an energy transfer leads to a reduced total energy of the collimated electrons as compared with an undisturbed isotropic component. A "monoenergetic" beam of collimated electrons is conceivable as a result of electrons losing most of their energy, at least their gyroenergy, at a relatively well-defined altitude above the observer. At the same time, some electrons may lose energy by wave-particle interactions without getting effectively collimated (cf Section 12); that is, we may not expect to find a very simple general relation among observed energies and pitch angles, particularly not if velocity dispersion is likely to be important (cf Whalen and McDiarmid, 1972; cf also Section 13).

Venkatarangan et al, (1975) have studied the electron pitch-angle distribution within "inverted-V" structures by means of a spinning satellite (the low-altitude polar orbiting satellite Isis 2). They have frequently found the fluxes in all energy channels to peak at 90° pitch angle, while the lower energy flux has shown a secondary peak at small pitch angles. The fact than only the lower energy electrons show an increased flux at small pitch angles we may again (in principle) ascribe to a wave-triggered collimation, which is basically associated with a certain loss of particle energy. An apparent peak flux at 90° at all energies, as seen by the spinning spacecraft (with spin period ~20 sec) looking in only one radial direction at a time, may possibly be a temporal or spatial variation in the flux. Alternatively, the observations may be due to "loss cone" distributions on closed field lines, as described in Section 13, with some electrons being scattered into the "collimation-cone" (small magnetic moments) somewhere along the field-line, associated with energy loss.

Several authors (Dunckel _et al_, 1970; Gurnett, 1974; Kurth _et al_, 1975) have observed very intense bursts of electromagnetic "kilometric" radiation propagating away from the earth during the occurence of discrete auroral forms. By direction-finding technique (Gurnett; 1974; Kurth _et al_, 1975) the radiation source has been found to be located in the auroral zones, in particular in the local evening sector, at altitudes of about 1-2 R_e above the earth: The radiation spectrum has a peak intensity in the range 100 - 300 kHz, and the total instantaneous power of the radiation from the earth has been estimated to be as large as 1% of the maximum power dissapted by auroral particle precipitation (Gurnett, 1974). In view of the estimated altitude of the source the typical frequencies of this radiation are obviously compatible with a wave generation at the local electron gyrofrequency, in particular if we consider the effect of Doppler shifts. If auroral ray formation is indeed associated with a transformation of gyroenergy into wave energy this is obviously a kind of radiation we would expect.

Rosenberg _et al_, (1971) have observed a one-to-one correlation between bursts of VLF emissions and slightly time-delayed short bursts of x-rays (due to bursts of precipitating energetic electrons) at Siple station, Antarctica (L = 4.1). From, among other things, the frequencies of the VLF emissions (center frequency 2.5 kHz) Rosenberg _et al_ interpret these emissions as due to cyclotron resonance between the waves and energetic electrons at the equator, by which the wave energy is created at the expense of the electron gyroenergy. This is the same kind of wave-particle interaction as suggested in Section 9. However, the electron densities of main interest in the model may be smaller than the equatorial density in this case ($\sim 10/cm^3$).

Sharber and Heikkila (1972) have observed, using a spinning satellite (the polar orbiting satellite Isis 1), that the electron flux in the poleward part of the nighttime auroral ovals is frequently field-aligned with a hardening of the energy spectrum at small pitch angles ("Λ" structures). When the range of the pitch angle scan is sufficiently wide, a more or less empty "loss cone" may show up ("top-less Λ" structures). They reject parallel electric fields as being involved and interpret their observations in terms of Fermi acceleration on closed field lines. As their observations seem to be directly related to "inverted-V" events, their interpretation is evidently incompatible with the above model. We are thus forced to suggest a different interpretation, although this may be somewhat ambiguous. We first notice that a hardening of the electron energy spectrum with decreasing pitch angles to a certain extent can be attributed to the "loss cone" being larger for low energies than for high (cf Fig.7, p 3406, in the paper by Sharber and Heikkila). Such an energy dependent "loss cone" is suggested by Eq (13). (Isis 1 has an apogee of 3522 km alt). A sudden increase of $E_{||}$ will, transiently (for some tens of seconds), lead to a narrowed empty cone, as suggested by Eq (14). In particular, if the increase in $E_{||}$ is relatively very strong, that is, like the case $\kappa' >> \kappa$ in Section 13 (κ may be zero), we may well expect the velocity dispersion to initially (within the first few seconds) cause an apparent electron energy spectrum where the peak energy is increasing towards smaller pitch angles. At the same time, the electron number flux will evidently be generally field-aligned (cf Eq.(11) and (12b)).

However, it may be argued that the spin period of Isis 1 (20.4 sec) is somewhat too long to really permit the latter explanation of the increasing energy towards small pitch angles and the field-aligned number flux. We may thus be forced to assume that the spinning spacecraft is also moving through a spatial ("inverted-V") structure at the same time, or that the spacecraft is measuring a mainly temporal change in the elctron energy and flux.

We further notice that even a gradually increasing $(\Delta V)_{||}$, which is distributed along the magnetic field line, may cause the most energetic electrons to have the apparently smallest pitch angles at low altitude. This is because the most energetic electrons will be the most recently accelerated at any time during the increase of $(\Delta V)_{||}$. This mechanism, basically due to different starting times at a given location, is an alternative to the mechanism in Section 13, which is due to different initial particle locations after a given sudden increase of $(\Delta V)_{||}$. During the increase of $(\Delta V)_{||}$ the velocity dispersion will also cause a field-aligned number flux. The time scales involved in the low altitude precipitation event will be determined both by the growth rate of $(\Delta V)_{||}$ and the actual instantaneous distribution of $E_{||}$ along the magnetic field line.

Effects that may be due to a temporal or spatial variation of $(\Delta V)_{||}$ are, of course, possible on both open and closed magnetic field lines, but the presence of a "loss cone" may seem to imply closed field lines.

The simultaneous observations of electron and (weak) proton precipitation, with even higher proton energies than electron energies, have often been used as an argument against any significant $(\Delta V)_{||}$ (O'Brien, 1970; Sharber and Heikkila, 1972). For the case of the protons and electrons originating from different regions along a magnetic field-line, Block (1972) has shown this to be surmountable in terms of certain distributions of $E_{||}$. We do not want to restrict the above model to this case, however, but rather allow protons and electrons to originate from the same regions. The protons that are observed precipitating along with the electrons thus have been decelerated by $(\Delta V)_{||}$ on their way down. The measured proton distribution does not, however, have a simple bearing on the "typical" energy distributions of protons in the source regions, as long as we do not know whether or not the charge-separation process (the "dynamo") in the outer magnetosphere is associated with energy dispersion. At times a large fraction of the precipitating protons may also be previously accelerated ionospheric protons as discussed further down. With an auroral proton energy typically at least as high as the electron energy (cf Sharber and Heikkila, 1972) we expect the proton number flux to be about 1/40 times the electron number flux, or larger , in the absence of a $(\Delta V)_{||}$. This may be compared with, for instance, Figures 1 and 2 (p. 3400 - 3401) in the paper by Sharber and Heikkila (1972), where the peak number flux of electrons is apparently at least three orders of magnitude larger than the simultaneous proton number flux. This evidently means that the number density of the precipitating protons is much smaller than the number density of the precipitating electrons (the proton energy seems to be somewhat reduced, too). A simple interpretation of this is that only the protons from the high-energy tail of the source distribution are able to reach lower altitudes, due to the presence of a large $(\Delta V)_{||}$ in a direction to accelerate the electrons and retard the protons. The local quasi-neutrality may, of course, be maintained by upward flowing ionospheric ions. At the altitude of this particular observation (around 3000 km) upward accelerating ionospheric (topside) ions may have an energy of a few keV or less, depending upon the actual penetration depth of $E_{||}$. However, in this particular case the spacecraft (Isis 1) was evidently looking in the upward direction only. The upflowing ionospheric ions will not readily be observed unless the observer is looking very close to the downward field-aligned direction (cf the discussion below).

According to Burch et al (1976) the data from Atmosphere Explorer C typically show the ratio of electron to proton energy fluxes to be strongly increased within "inverted-V" precipitation structures, as compared with the flux ratios outside. This is, of course, what we (generally) would expect if the electrons are being accelerated by a $(\Delta V)_{||}$.

The present model leads, however, to another interesting consequence regarding proton precipitation or, more generally, precipitation of positive ions. The parallel electric field will evidently accelerate positive ions upward from the topside ionosphere (while suppressing the ionospheric electrons). These ions will, in principle, get an extremely field-aligned velocity distribution both as a result of the diverging magnetic field lines and as a result of $E_{||}$. If the magnetic field line is closed, these energized ions may be able to precipitate in the conjugate ionosphere together with electrons, provided $(\Delta V)_{||}$ is smaller along the downward path. Since these ions may drift a considerable distance transverse to the magnetic field during transit, for instance due to E x B - drift, they may be able to precipitate in either hemisphere if $(\Delta V)_{||}$ has a horizontal gradient in the drift direction. A trapped population of these ions will precipitate whenever $(\Delta V)_{||}$ is reduced. That is, we may well expect energetic protons, as well as heavier ions (cf Shelley et al,1972), of ionospheric origin to precipitate now and then together with energetic electrons. The energy of these ions may occasionally be higher than the average electron energy, for instance when $(\Delta V)_{||}$ is rapidly decreasing in time.

An interesting property of these ions is that they tend to have a field-aligned distribution also when precipitating at ionospheric altitudes. In fact, provided the magnetic moment is preserved, these ions will not be isotropic unless their energy is $\lesssim K_o \times B_{max}/B_{pen}$, where K_o is the initial energy of the ions (< 1 eV) before acceleration and B_{max} and B_{pen} are the magnetic field strengths at the low altitude of observation and at the lowest altitude of penetration of $E_{||}$, respectively ($B_{pen} < B_{max}$). As a consequence, an observer at low altitudes will, on the average, find the field-alignment to be more pronounced the higher the energy is of these precipitating ions. In this manner the present model may be able to give a very simple alternative explanation of the fairly frequent satellite observations (ESRO/A and ESRO/B) of field-aligned fluxes of positive ions in the keV-range along with energetic (and typically isotropic) electron precipitation (Hultqvist, 1971), as far as these observations can be related to closed magnetic field lines. The field-alignment of these ions may, to some extent, be reduced by wave-particle interactions, of course (cf Section 12).

In the outer magnetosphere these energized ionospheric ions will presumably have a generally field-aligned distribution, even in the presence of a slight pitch-angle scattering, with energies of the same order as the "typical" energy of auroral electrons or lower $\left((\Delta V)_{||} \lesssim \text{typical electron energies}\right)$ Furthermore, an $E_{||}$ according to (9b), or more generally, any upward $E_{||}$ that is distributed along $\bar{B}$, being basically compatible with preserved magnetic moments of the protons, will suppress the development of the loss cone of lower-energy protons of magnetospheric origin, on closed magnetic field lines (cf Section 13). This may explain the "source-cone" distributions of positive ions at energies less than 10 keV frequently found by the geosynchronous satellite ATS-6 (DeForest, private communication; McIlwain, 1975).

According to DeForest (private communication) and McIlwain (1975) even the electrons sometimes show strongly field-aligned distributions at the geosynchronous orbit (ATS-6), although much less often than the positive ions. These field-aligned electron fluxes seem to be quite intense but rather fluctuating in amplitude (on a time scale of a quarter of a second, according to DeForest). The energy spectrum of these electrons is typically flat or slightly rising up to a break point somewhere between 0.1 and 10 keV, beyond which it rapidly decreases. It might be tempting to associate these electron "beams" with a downward current (upward moving electrons) like B-C in Fig. 5. This would then require some kind of obstruction of the escape flux of ionospheric electrons (cf Knight, 1973; Lemaire and Scherer, 1973a). One possible obstruction is a double layer (cf Block, 1972, 1975), another is strongly reduced plasma density at high altitudes, in which case the electron flux may become spacecharge-limited (cf Block, 1967). The latter case, for instance, may occur if the cold plasma at high altitudes has been previously depleted by a strong upward current (cf Section 8). However, it may not be necessary to associate the electron "beam" with a downward current. Consider, for instance, un upward electric field according to Eq.(9b). If this electric field is "turned off" it will enable energized electrons from lower altitudes to escape outwards, after mirroring, while transforming their gyromotion into directional (field-aligned) motion. Hence, if the total $(\Delta V)_{||}$ is strongly fluctuating it may thus cause a fluctuating beam of field-aligned energetic electrons to appear in the outer magnetosphere. Such a fluctuating $(\Delta V)_{||}$ is conceivable under certain conditions, since a current loop like ABCD in Fig. 5 is basically a "resonant circuit", the "inductance" being due to the encircled magnetic field and the "capacitance" being due to the charged-particle convection through the loop (cf Lennartsson, 1973b).

When the positive ions from the ionosphere reach the parallel electric field and become accelerated they also become reduced in density as compared with the density distribution during normal escape (for a review of the theory of escape flux, see e.g. the paper by Lemaire and Scherer, 1973b). Such a density reduction of the positive ions is also required to preserve quasi-neutrality, since the cold electrons will be depleted by the parallel electric field and replaced by a dilute population of precipitating, backscattered and (energetic) secondary electrons, cf the brief discussion in Section 10. Without a detailed study of the quasi-neutrality we are very limited in predicting the plasma distributions above auroral forms, however. As a very general consequence of the present model we would, nevertheless, expect to find anomalously low plasma densities at high altitudes above auroral forms. This qualitative prediction may seem to be compatible with electron density measurements made by the topside-sounding satellite Alouette II (Hagg, 1967). Ionograms recorded at high latitudes (L $\gtrsim$ 6) and high altitudes (1500 - 3000 km) often showed a beat-frequency modulation from which Hagg deduced accurate densities as low as 8 cm^{-3} in many cases.

It is worth noting in this context that also the downward field-aligned portion of a current loop, like ABCD in Fig. 5, may be associated with a plasma depletion, although in this case the depletion will occur at low altitudes. If the horizontal current C-D is a Pedersen current it is associated with a transport of positive ions away from point C (cf Boström, 1964). Since the current B-C will be associated with an outflux of electrons form point C the plasma density at point C may thus become appreciably reduced. This mechanism may seem to have potential applications to certain observations of density irregularities in the high-latitude ionosphere but it will not be further discussed here. For a theoretical discussion of plasma depletion by field-aligned currents, see Block and Fälthammar (1968).

16. Summary and Concluding Remarks

The existence of field-aligned currents associated with auroral precipitation (Section 4) suggests a process of charge separation (a "dynamo") in the distributions of "hot" particles in the outer magnetosphere and the magnetosphere-solar wind transition region (Section 14), leading to current loops like ABCD in Fig 5, for instance. The downward current B-C may generally be carried by escaping ionospheric electrons, charging point C positive to essentially the same potential as point B. A Pedersen current C-D will charge point D positive relative to point A. However, the upward current D-A will generally have to be carried by down-flowing "hot" magnetospheric electrons (Section 8), which do not readily flow because of the magnetic mirroring (Section 8). This may lead to a large $(\Delta V)_{||}$ along A-D, entirely due to adiabatic particle motion, that will increase the number flux of precipitating electrons as well as the kinetic energy (Sections

8 - 10). At the same time, this $(\Delta V)_{||}$ will energize outflowing positive ionospheric ions (Section 15). A region of high $(\Delta V)_{||}$ generally has to be rather wide in latitude, as well as longitude, (Section 5), which requires an additional mechanism for producing auroral fine structures. For this reason, we suggest, as one plausible mechanism, a wave-particle interaction by which the downflowing electrons can lose gyroenergy. Any such interaction that is spatially localized will automatically lead to a locally intensified precipitation, like an auroral ray (Section 9). If this interaction occurs at high altitudes, within the $E_{||}$-field, it may also cause strongly collimated bursts of precipitation (Section 11). An alternative mechanism would have to involve a corresponding spatial fine structure in the electron source at high altitude.

In this model the parallel electric field, that is in reality the "dynamo", provides the increased energy flux in auroral displays, whereas the spatial structure of individual auroral forms may be due to a modulating effect of certain kinds of plasma instabilities. These plasma instabilities may not provide "anomalous resistivity", however. On the contrary, these instabilities may just as well tend to limit the growth of $(\Delta V)_{||}$ by their thermalizing effect on the otherwise adiabatic particle motion.

The association of a net field-aligned current with precipitating electrons also suggests that the convection electric field $E_{\perp}$ is (generally) transverse to auroral arcs (cf observations made by Gurnett and Frank, 1973, and Wescott et al 1969) with steep gradients within the precipitation structure (Sections 6 and 7), particularly at altitudes of several thousand kms (cf Fig. 3 and Eq. (9a)). The resulting $E_{\perp} \times B$-drift pattern is likely to lead to different kinds of shear flow instabilities, similar to the Kelvin-Helmholtz instability, that may generate folds and vortex-forms (cf Haerendel, 1974; Hallinan and Davis, 1970). The frequent alignment of thin auroral forms along the $E_{\perp} \times B$-drift direction (cf e.g. Hallinan and Davis, 1970) hence might indicate that the auroral ray formation is closely related to such shear flow instabilities.

It may be noted that the parallel electric field in this model is due to a magnetic confinement of a negatively charged, hot and collision-free plasma. A transfer of electron gyroenergy into wave-energy obviously tends to weaken the confinement; and if this energy transfer becomes too strong, the parallel potential gradient will break down. Hence, from this model, in contrast with certain other models of parallel electric fields, we might expect only a small fraction of the total auroral particle energy to be transformed into electromagnetic wave-energy during the acceleration process. According to observations, the auroral precipitation is indeed associated with electromagnetic radiation of many different wavelengths, but the radiated power is seemingly small compared to the power carried by the precipitating particles. The most intense radiation discovered so far is the kilometric radiation, which still represents only approximately 1 percent of the total power dissipated by the auroral electrons (Gurnett, 1974).

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Figure Captions

Figure 1.(a) The schematic electric field lines and equipotentials created at a resistant portion of an otherwise good conductor when a current is flowing. The surrounding medium is vacuum.

(b) The formal analogue when the resistor is a subregion of low conductivity within a magnetized plasma.

Figure 2. The electric field and current distributions at different altitudes associated with a given distribution of $E_\perp = E_x$ at altitude z_b, where z_b is assumed to be in the topside ionosphere or low magnetosphere. The magnetic field is vertical and downward (antiparallel to the z-axis).

Figure 3. The analogue of Figure 2 when $E_\perp$ at z_b = 1500 km has a smooth distribution and the parallel resistivity (averaged over altitude) above $z_b - h$ = 1000 km is defined by the bottom curve.

Figure 4. The various plasma regions expected when a large $(\Delta V)_{||}$ is being supported by magnetic mirroring of the charge carriers e_1, which are hot electrons. The high-altitude region 1 is devoid of cold particles and $E_{||} \neq 0$ there, whereas the low-altitude region 3 has mainly cold particles and $E_{||} = 0$. Region 2 is a transition region where strong spacecharge effects are likely to occur. The $E_{||}$-field accelerates the electrons e_1, and precipitates some of them, while retarding hot protons p_1. At the same time $E_{||}$ accelerates ionospheric protons p_3 and reflects backscattered and secondary electrons e_3. The electrons e_2 are trapped by the $E_{||}$-field and the magnetic mirror below.

Figure 5. A possible configuration of a magnetosphere-ionosphere current system (projected onto the dawn-dusk plane). The current paths B-C, D-A and A′-D′ as well as the dotted path are parallel to the magnetic field, while the remaining current paths are in the transverse direction. The dashed current path A-W-A′ is within the solar wind.

Figure 6 A sketch of a case where the downward currents flow immediately outside of the upward current sheet (precipitating electrons). Only the upward current is assumed associated with a small $\sigma_{||}$. The low-altitude E_x is "shorted out" within the precipitation structure, as a result of the enhanced ionization.

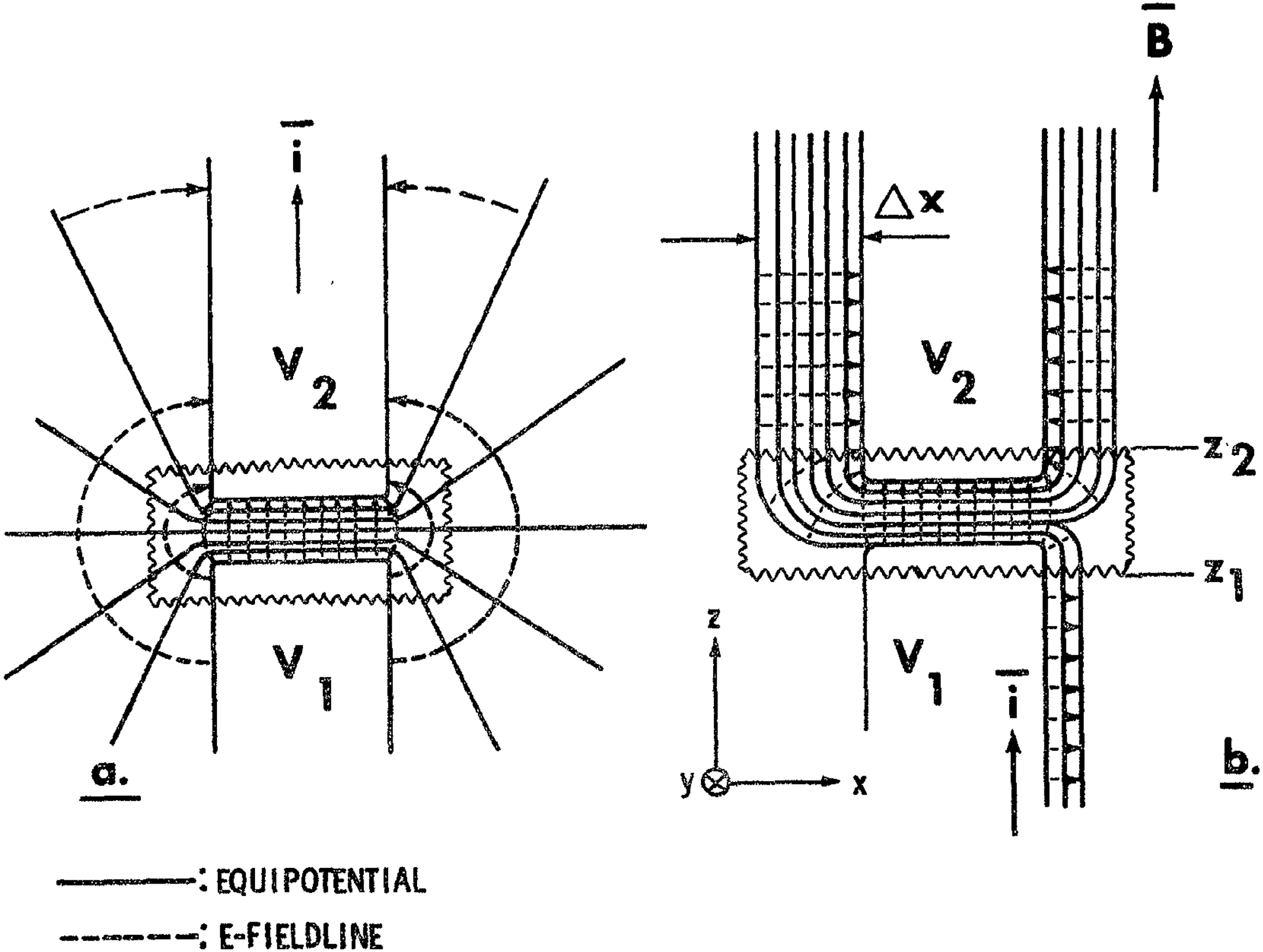
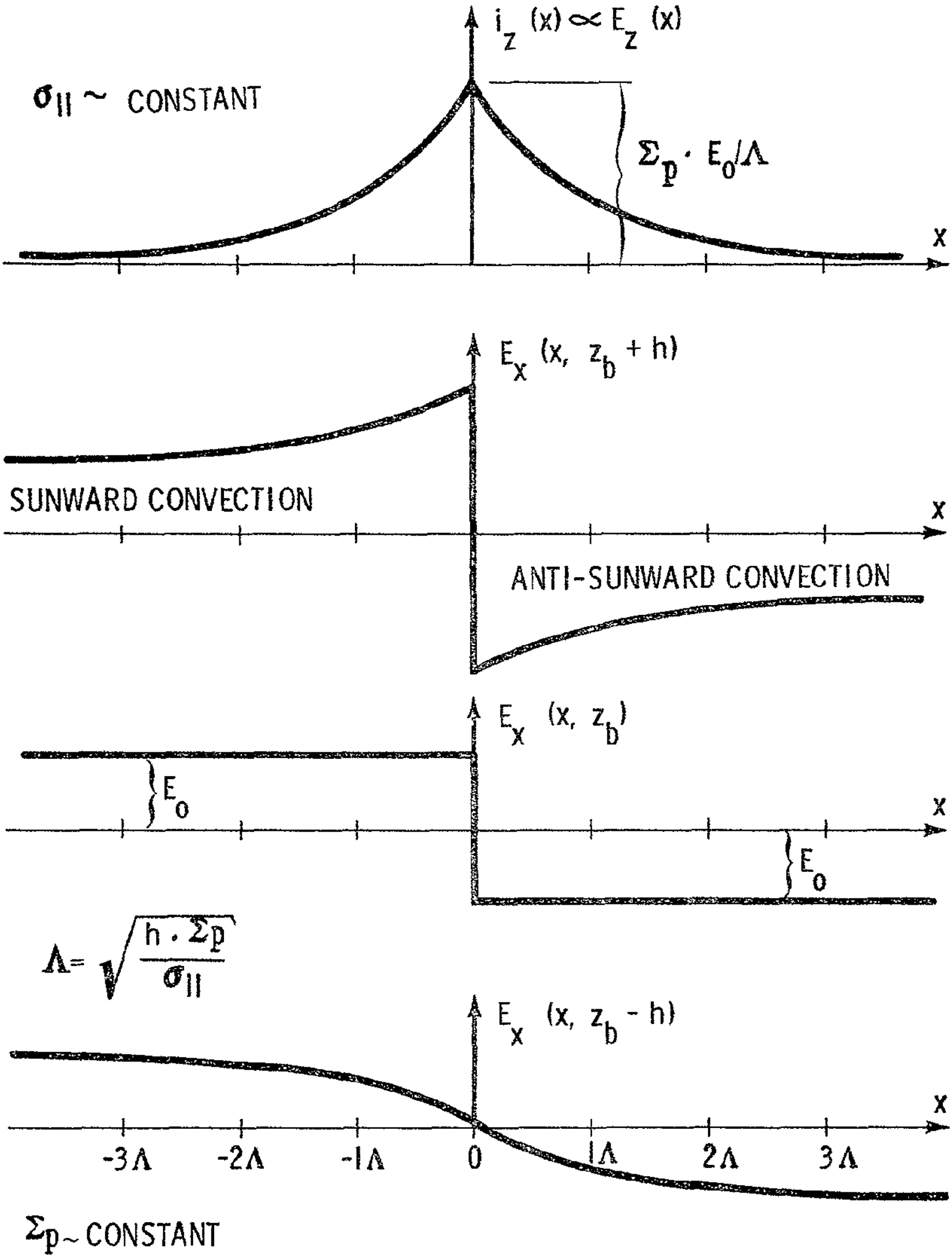
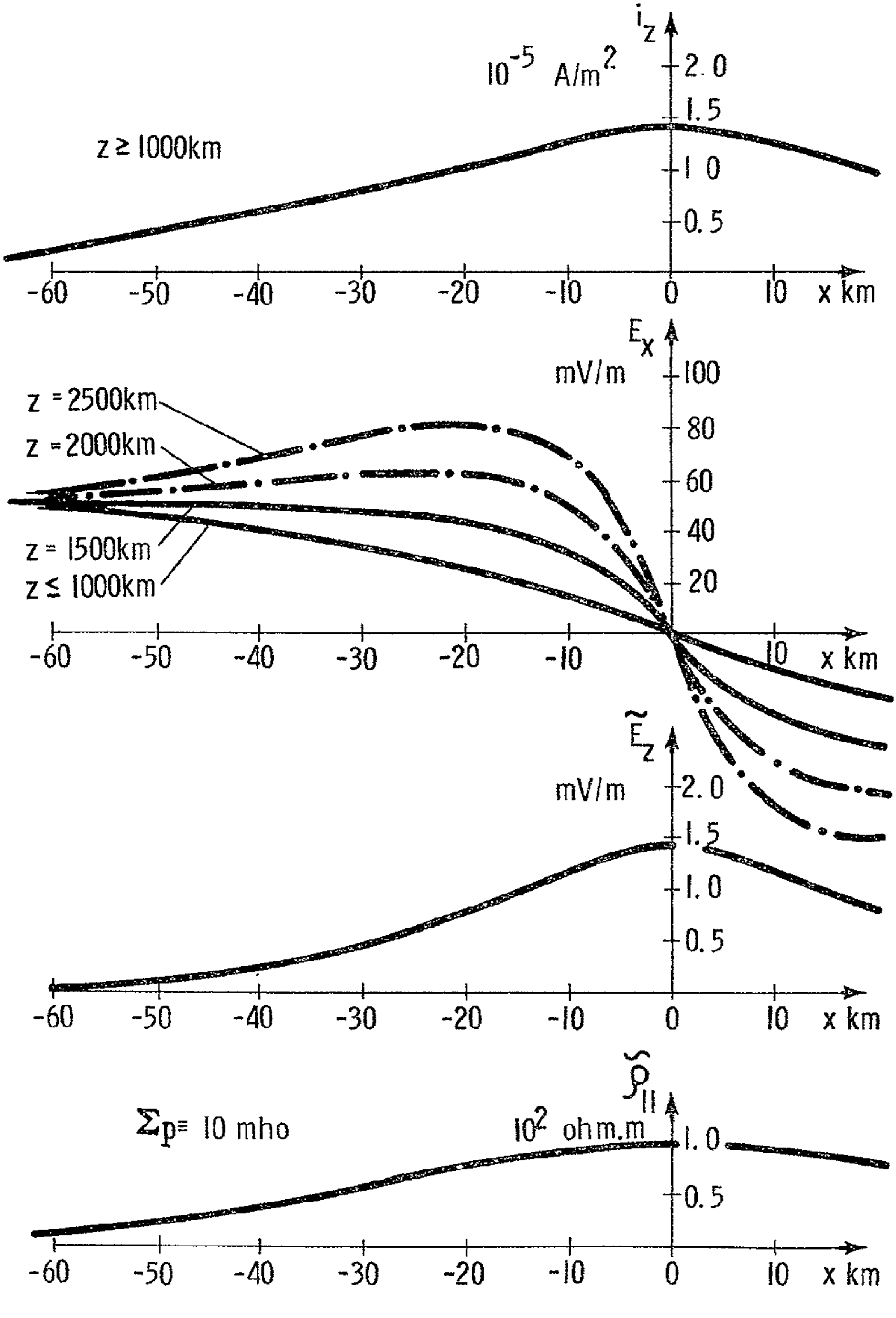


Figure 1



$i_z(x) \propto E_z(x)$
$\sigma_{||} \sim$ CONSTANT
$\Sigma_p \cdot E_0/\Lambda$
x
$E_x(x, z_b + h)$
SUNWARD CONVECTION
x
ANTI-SUNWARD CONVECTION
$E_x(x, z_b)$
E_o
x
E_o
$\Lambda = \sqrt{\frac{h \cdot \Sigma p}{\sigma_{||}}}$
$E_x(x, z_b - h)$
x
-3Λ
-2Λ
-1Λ
0
1Λ
2Λ
3Λ
$\Sigma p \sim$ CONSTANT

Figure 2



i_z
10^{-5} A/m^2
2.0
1.5
1.0
0.5
z ≥ 1000km
-60
-50
-40
-30
-20
-10
0
10
x km
E_x
mV/m
100
80
60
40
20
z = 2500km
z = 2000km
z = 1500km
z ≤ 1000km
$\tilde{E}_z$
mV/m
Σ_p = 10 mho
$\tilde{\rho}_{\parallel}$
10^2 ohm.m

Figure 3

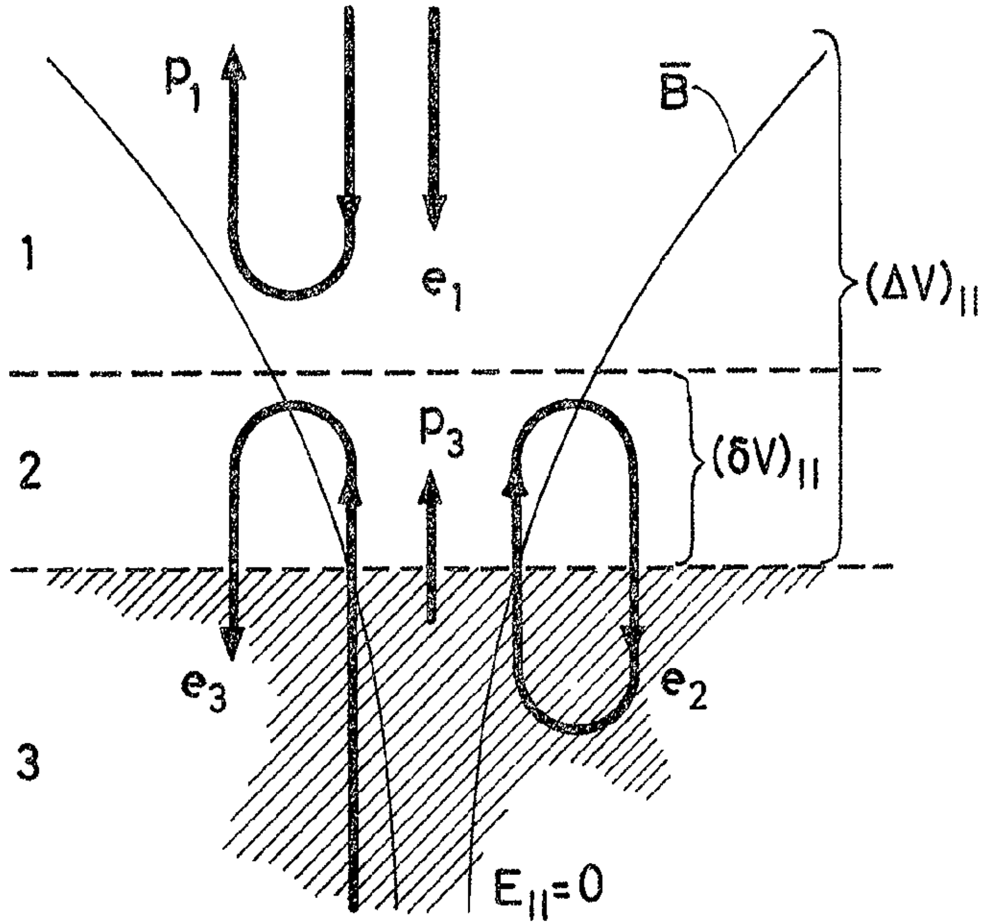

p_1
$\bar{B}$
1
e_1
$(\Delta V)_{\parallel}$
2
p_3
$(\delta V)_{\parallel}$
e_3
e_2
3
$E_{\parallel}=0$

Figure 4

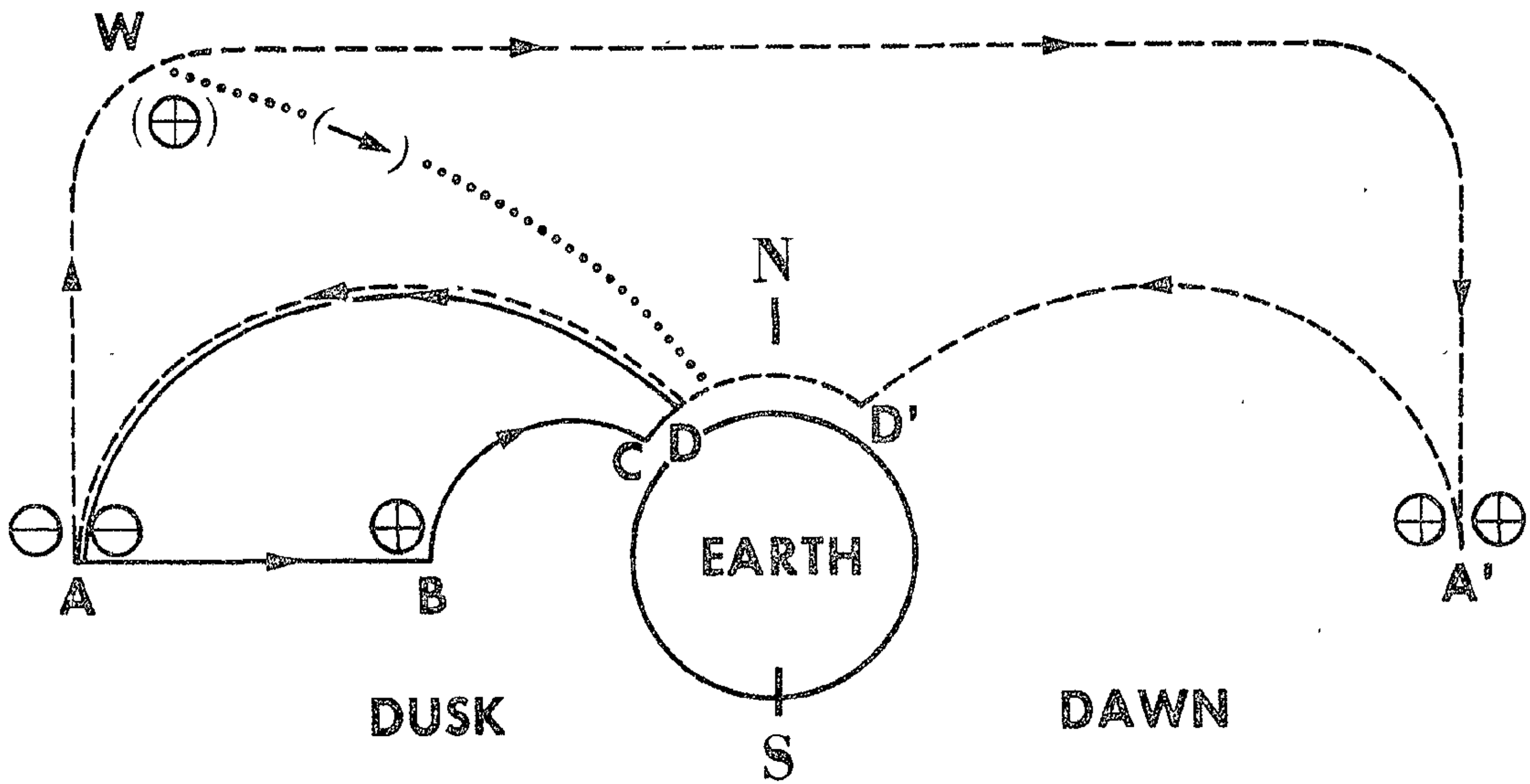


Figure 5

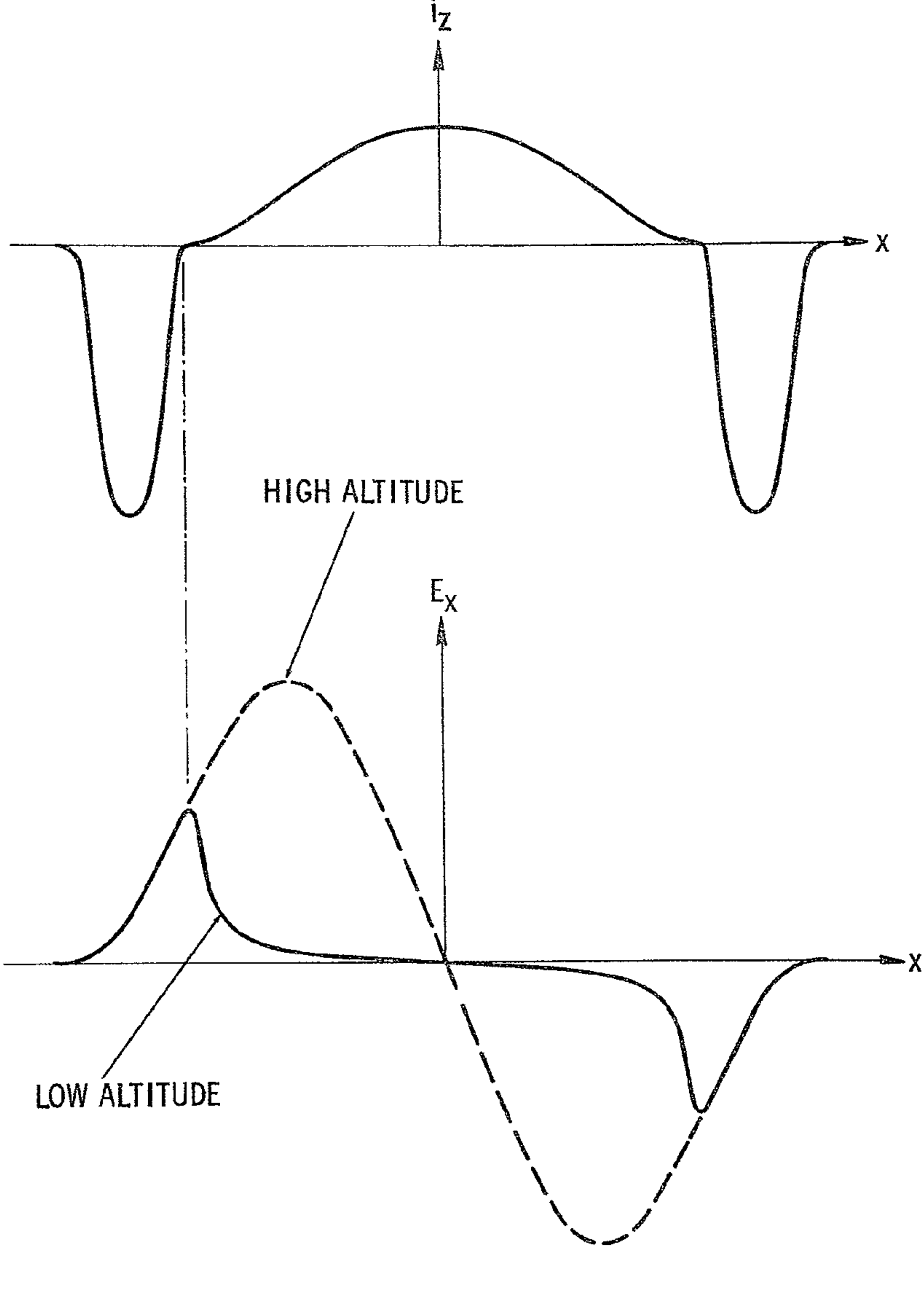


Figure 6

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ON THE ROLE OF MAGNETIC MIRRORING IN THE AURORAL PHENOMENA

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On the basis of field and particle observations, it is suggested that a bright auroral display is a part of a magnetosphere-ionosphere current system which is fed by a charge-separation process in the outer magnetosphere (or the solar wind). The upward magnetic-field-aligned current is flowing out of the display, carried mainly by downflowing electrons from the hot-particle populations in the outer magnetosphere (the ambient cold electrons being depleted at high altitudes). As a result of the magnetic mirroring of these downflowing current carriers, a large potential drop is set up along the magnetic field, increasing both the number flux and the kinetic energy of precipitating electrons. It is found that this simple basic model, when combined with wave-particle interactions, may be able to explain a highly diversified selection of auroral particle observations. It may thus be possible to explain both "inverted-V" events and auroral rays in terms of a static parallel electric field, and the electric field may be compatible with a strongly variable pitch-angle distribution of the precipitating electrons, including distributions peaked at 90° as well as 0°. This model may also provide a simple explanation of the simultaneous precipitation of electrons and collimated positive ions.

Key words auroras, magnetosphere, electric fields, Birkeland currents, magnetic mirroring, anomalous resistivity, double