N87-23328

CONDITIONS FOR DOUBLE LAYERS IN THE EARTH'S MAGNETOSPHERE AND PERHAPS IN OTHER ASTROPHYSICAL OBJECTS

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ABSTRACT

Double layers (i.e., electric fields parallel to **B**) form along auroral field lines in the Earth's magnetosphere. They form in order to maintain current continuity in the ionosphere in the presence of a magnetospheric electric field **E** with $\nabla \cdot \mathbf{E} \neq 0$. Features which govern the formation of the double layers are: (1) the divergence of **E**, (2) the conductivity of the ionosphere, and (3) the current-voltage characteristics of auroral magnetic field lines. Astrophysical situations where $\nabla \cdot \mathbf{E} \neq 0$ is applied to a conducting plasma similar to the Earth's ionosphere are potential candidates for the formation of double layers. The region with $\nabla \cdot \mathbf{E} \neq 0$ can be generated within, or along field lines connected to, the conducting plasma. In addition to $\nabla \cdot \mathbf{E}$, shear neutral flow in the conducting plasma can also form double layers.

I. INTRODUCTION

Here I describe the large-scale, electrodynamical phenomena that give rise to the formation of double layers in the Earth's magnetosphere. I point out what I believe are the important features which might be found in association with other astrophysical objects, and which could produce double layers analogous to those associated with the Earth.

In the laboratory, double layers form if one tries to drive a current through a plasma that is greater than that which can be carried by the available charge particles in a plasma. The same situation occurs along auroral magnetic field lines. When the magnetosphere-ionosphere system tries to drive a current with a density greater than can be carried by the plasma available to flow along field lines, a field-aligned potential drop $V_{\parallel}$ forms. This $V_{\parallel}$ accelerates electrons toward the atmosphere, and the accelerated electrons form discrete auroral arcs.

In this discussion, I do not distinguish between double layers, where large $V_{\parallel}$'s occur across short distances, and smoothly varying potentials, where $V_{\parallel}$'s are distributed over large distances along field lines. The overall electrodynamics is the same for both situations.

II. CONDITIONS FOR DOUBLE LAYERS

Three critical features of the Earth's magnetosphere-ionosphere system are involved in the formation of significant ($\gtrsim 1$ kV) $V_{\parallel}$'s along auroral magnetic field lines. These are listed in Figure 1.

First, it is necessary to drive a current with a non-zero divergence. In the magnetosphere, the large-scale, convection electric **E** has $\nabla \cdot \mathbf{E} \neq 0$ across auroral field lines. This divergence in **E** maps along field lines to the ionosphere.

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Second, the ionosphere has a layer of high conductivity perpendicular to the magnetic field **B**. This conductivity results from collisions between ionospheric particles and the neutral atmospheric particles. Thus, an electric field with $\nabla \cdot \mathbf{E} \neq 0$ in the ionosphere drives Pedersen (parallel to **E**) currents $\mathbf{I}_P$ in the ionosphere with $\nabla \cdot \mathbf{I}_P \neq 0$. This divergence in $\mathbf{I}_P$ must be balanced by field-aligned currents to maintain current continuity in the ionosphere.

Third, if the intensity of the required field-aligned current density $j_\parallel$ exceeds that which can be carried by plasma flowing along field lines with $V_\parallel = 0$, then a $V_\parallel \neq 0$ must form.

Any astrophysical situation where an electric field drives a current **I** perpendicular to **B**, with $\nabla \cdot I \neq 0$, has the potential for forming $V_\parallel$'s along **B**. A layer with significant conductivity perpendicular to **B** would be an attractive candidate for having currents with $\nabla \cdot I \neq 0$.

To determine whether a $V_\parallel$ will form, we must evaluate the $j_\parallel$ versus $V_\parallel$ characteristics of magnetic field lines for $j_\parallel$'s of the magnitude expected from $\nabla \cdot \mathbf{I}$. Currents associated with aurora on the Earth typically have $j_\parallel \sim$ 1-10 $\mu A/m^2$. Two particle populations can contribute to this current: the ionospheric plasma moving up along field lines, and magnetospheric plasma (from the plasmasheet) which precipitates into the atmosphere. Only magnetospheric particles within the loss cone contribute to $j_\parallel$, since particles outside the loss cone mirror above the atmosphere.

Downward $j_\parallel$'s can result from ionospheric electrons moving upward and from the precipitation of magnetospheric ions. However, ionospheric electrons can generally supply a $j_\parallel > 10\ \mu A/m^2$ to a downward $j_\parallel$, so that $V_\parallel$'s do not generally form for downward $j_\parallel$'s.

On the other hand, the maximum $j_\parallel$ that can be carried by ionospheric ions is generally $<1\ \mu A/m^2$. Thus, the precipitation of magnetospheric electrons must be considered for upward $j_\parallel$'s. For typical parameters of plasmasheet electrons, the maximum $j_\parallel$ that can be supplied by the precipitation of magnetospheric electrons is $\sim 1\ \mu A/m^2$ for $V_\parallel = 0$. However, increasing $V_\parallel$ increases $j_\parallel$ by enhancing the flux of electrons in the loss cone. The relation between $j_\parallel$ and $V_\parallel$ along auroral field lines was obtained by Knight (1973), and is shown in Figure 2.

Figure 2 shows $j_\parallel$ versus $V_\parallel$ for an electron density $n = 1\ cm^{-3}$ and an electron thermal energy $K_{th} = 1$ keV, values which are reasonable for the plasmasheet. Results for other values of n and K_{th} can be obtained from the normalizations given in the figure. Curves are shown for various values of the ratio between the magnetic field in the ionosphere B_i and the magnetic field $B_{V_\parallel}$ at the top of the region where significant potential variation exists along field lines. Satellite obsevations (Gorney et al., 1981) indicate that $B_i/B_{V_\parallel} \approx 30$ is reasonable. Notice from Figure 2 that upward $j_\parallel$'s $\sim$ 1-10 $\mu A/m^2$ require the existence of $V_\parallel$'s $\sim$ 1-10 kV. Such $V_\parallel$'s are of the magnitude observed over auroras.

Figure 3 illustrates a way in which an **E** with $\nabla \cdot \mathbf{E} \neq 0$ develops in the Earth's magnetosphere. Both open, polar-cap field lines connected with the interplanetary field and closed, lower latitude field lines are shown. Solar wind flow across the open polar cap field lines forms a dawn-to-dusk electric field across the open field line region, and the electric field changes direction across the boundary between open and closed field lines. The boundary is thus charged as indicated in the figure. Mapping the electric field to the ionosphere gives $\nabla \cdot \mathbf{I}_P < 0$ and upward $j_\parallel$'s on the dusk side, and $\nabla \cdot \mathbf{I}_P > 0$ and downward $j_\parallel$'s on the dawn side. The magnitude of $\nabla \cdot \mathbf{I}_P$ gives large enough $j_\parallel$'s on the dusk side to require a $V_\parallel > 0$.

Similar situations as shown in Figure 3 should occur in the magnetospheres of other magnetized, solar system planets, and could exist in association with other magnetized, astrophysical objects. Also, regions of $\nabla \cdot \mathbf{E} \neq 0$ can be formed by plasma sources, such as Io, that move across field lines within a magnetosphere.

Figure 4 shows that the observed change in **E** across the dusk auroral zone can account for the observed magnitude of auroral $V_\parallel$'s and precipitation intensities. The observations (Gurnett and Frank, 1973) were from a low-altitude satellite. An electric field of 0.12 V/m was observed across the auroral region, and the equation for current continuity in the ionosphere was solved (Lyons, 1980) for an electric field of magnitude 0.06 V/m on each side of the reversal. The resulting values of $V_{\|}$ and precipitating electron energy fluxes are shown in Figure 4 as a function of latitudinal distance. These can be seen to compare well in magnitude with values obtained from electron observations on the satellite. The auroral observations in Figure 4 have more structure than that obtained from the simple solution to the current continuity equation. However, this type of structure, which is typical of discrete auroral arcs, can be explained as a result of more detailed structure in the magnetospheric electric field (Lyons, 1981; Chiu et al., 1981).

So far, the discussion here has been under the assumption that the velocity $\mathbf{V}_n$ of neutrals in the conducting layer is zero. Including $\mathbf{V}_n$, $\mathbf{I}_P$ may be written as the difference between the electric field drift velocity $\mathbf{V}_E$ and $\mathbf{V}_n$:

$$\mathbf{I}_P = \Sigma_P (-\mathbf{V}_E + \mathbf{V}_n) \times \mathbf{B} \quad ,$$

where Σ_P is the layer-integrated Pedersen conductivity. Since $j_{\|} = -\nabla \cdot \mathbf{I}_P$, the above relation shows that shears in $\mathbf{V}_n$, as well as shears in $\mathbf{V}_E$, can cause field-aligned currents within a conducting layer.

Generally, thermospheric neutral winds in the conducting region of the Earth's ionosphere are not sufficiently large to generate $V_{\|}$'s. However, this is not necessarily always the case. Recently, Lyons and Walterscheid (1985) proposed that neutral wind shear can drive waves of aurora (omega bands), with $V_{\|} > 0$, that occasionally occur on the poleward boundary of the post-midnight, diffuse aurora. In addition it has been proposed the neutral winds in the photosphere and lower chromosphere of the Sun can generate $V_{\|}$'s (e.g., Kan et al., 1983).

III. SUMMARY

Figure 5 summarizes conditions that might exist in other astrophysical objects and which could lead to the formation of significant $V_{\|}$'s in a manner analogous to what occurs in the Earth's auroral zones. A conducting layer carrying current **I** perpendicular to **B** with $\nabla \cdot \mathbf{I} \neq 0$ will force field-aligned currents. If the required field-aligned current density $j_{\|}$ exceeds the maximum $j_{\|}$ that can be carried along field lines by the available plasma with $V_{\|} = 0$, then a $V_{\|} > 0$ will form.

Two processes can drive Pedersen currents with $\nabla \cdot \mathbf{I}_P \neq 0$ within a collisional, conducting layer. The first is sheared plasma flow (i.e., $\nabla \cdot \mathbf{E} \neq 0$) applied anywhere along the magnetic field lines connected to the conducting layer. In this case, the sheared plasma flow will map along field lines to the conducting layer. The second process is a neutral flow with shear within the conducting layer. Such flow can drive divergent Pedersen currents without an electric field being applied to the system.

Acknowledgments. Preparation of this manuscript has benefitted from discussions with M. Schulz and J. F. Fennell. The work was supported in part by NASA grants NAGW-853 and NASW-861 and by the Aerospace Sponsored Research Program.

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THREE ASPECTS OF MAGNETOSPHERE - IONOSPHERE SYSTEM
INVOLVED IN FORMATION OF DISCRETE AURORAL ARCS

1. DIVERGENCE OF MAGNETOSPHERIC ELECTRIC FIELD

   A. DIVERGENCE REQUIRED TO DRIVE THE ARCS

2. CONDUCTIVITY OF THE IONOSPHERE

   A. WITHOUT CONDUCTING IONOSPHERE, THERE WOULD BE NO ARCS

3. CURRENT-VOLTAGE CHARACTERISTICS OF AURORAL FIELD LINES

Figure 1. Critical features of the Earth's magnetosphere-ionosphere system involved in the formation of significant $V_{\parallel}$'s.

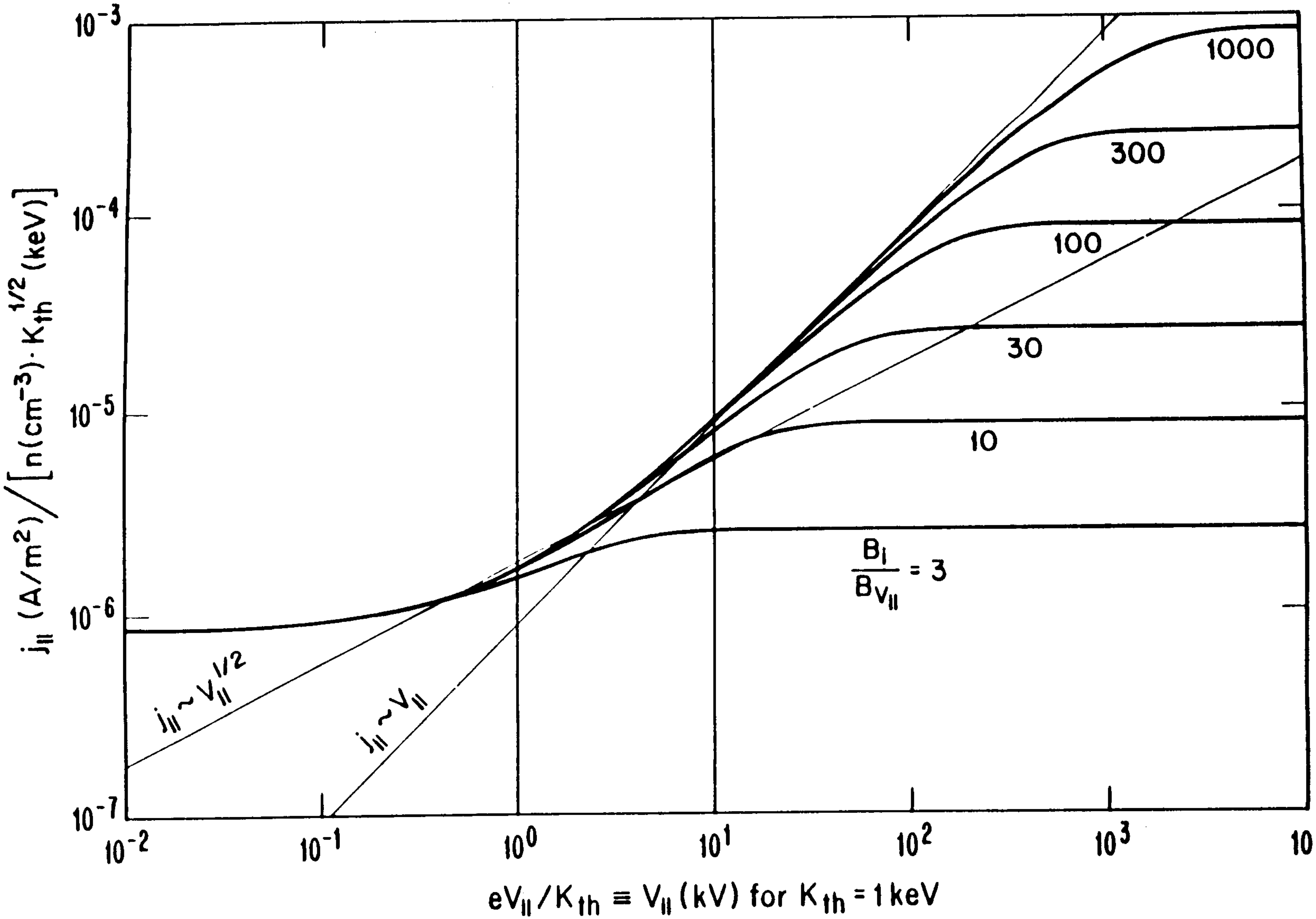


Figure 2. The $j_{\parallel}$ and $V_{\parallel}$ relation for uninhibited, single-particle motion along field lines for a high-altitude electron plasma with $n = 1\ cm^{-3}$ and $K_{th} = 1$ keV. Results for other values of n and K_{th} can be obtained by multiplying the current densities on the vertical axis by $n(cm^{-3})$. $K_{th}^{1/2}$ (keV) and the potential differences on the horizontal axis by K_{th} (keV). Curves are shown for $B_i/B_{V_{\parallel}}$ from 3 to 1000. Lines for $j_{\parallel} \sim V_{\parallel}^{1/2}$ and $V_{\parallel}$ and for $eV_{\parallel}/K_{th} = 1$ and 10 are shown for reference.

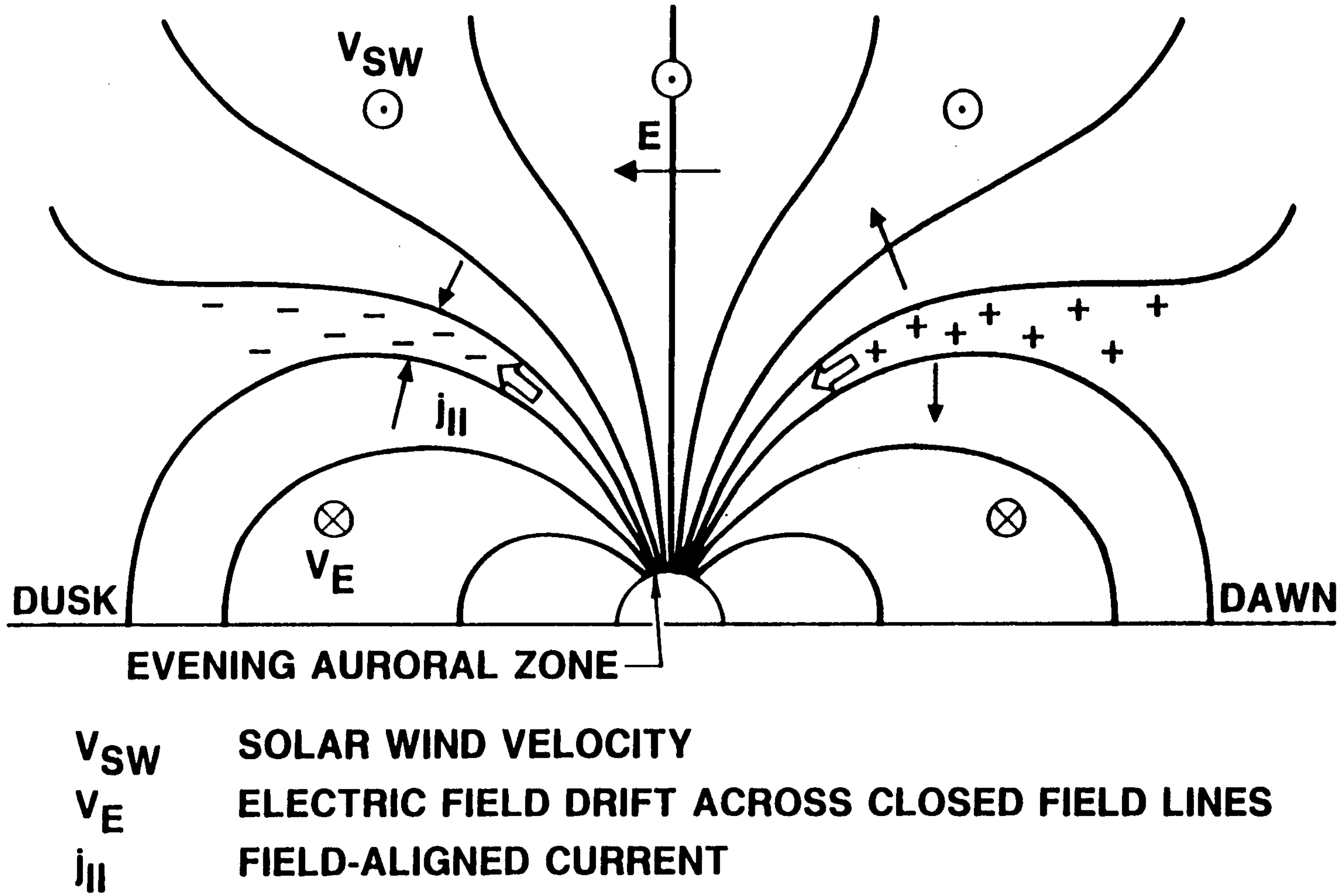


Figure 3. Schematic illustration of generation of **E**, with $\nabla \cdot \mathbf{V} \neq 0$, by the solar wind flow across the Earth's polar-cap field lines.

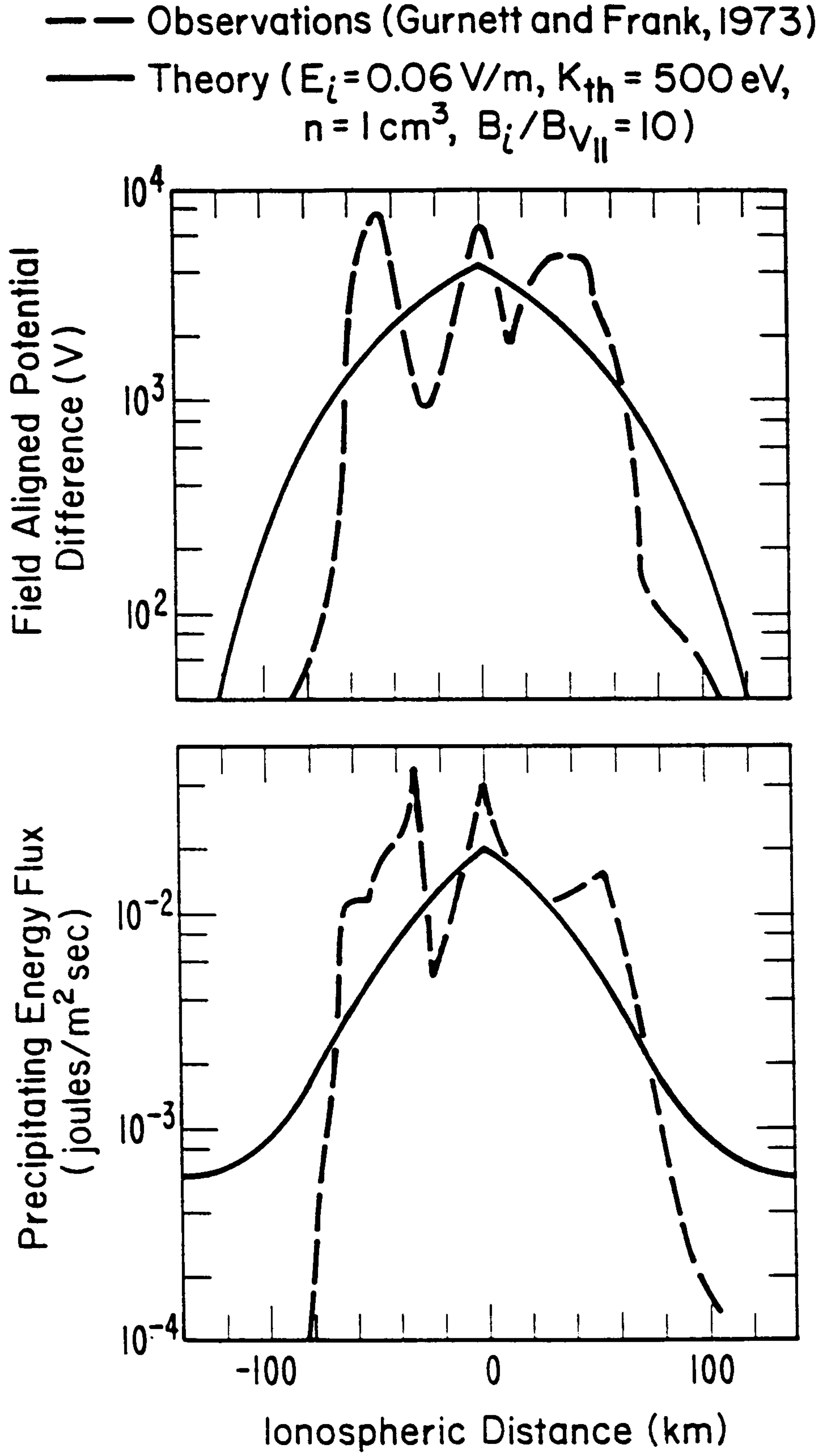
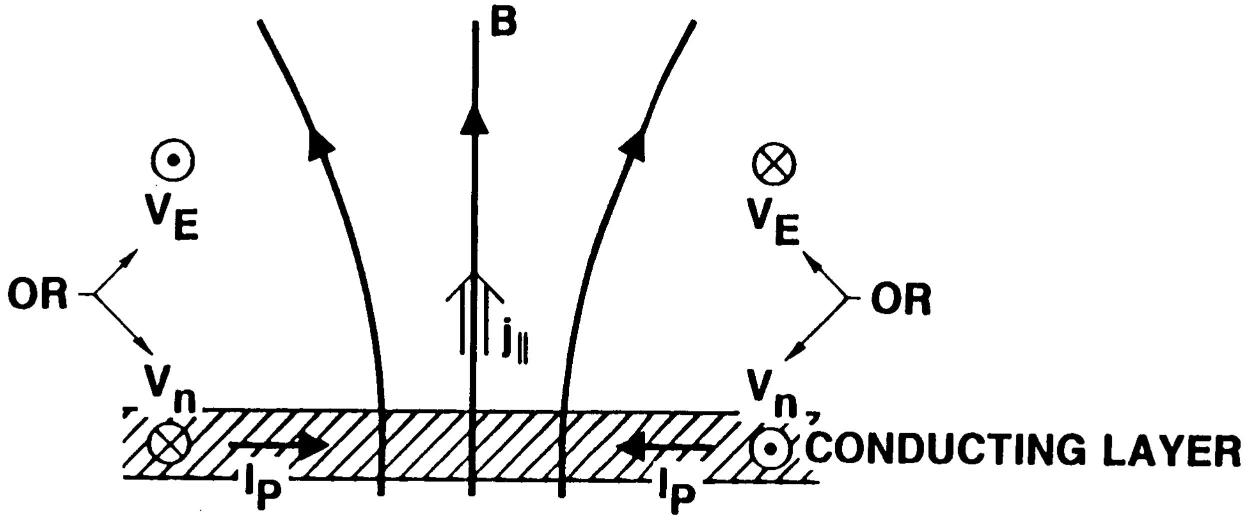


Figure 4. Comparison of the solution to the ionospheric current continuity equation (Lyons, 1980) with observations. The observations (Gurnett and Frank, 1973) were obtained over the auroral zone from a low-altitude satellite near 1800 LT.



- CONVERGING I_P CAN BE DRIVEN BY:
  1. SHEARED PLASMA FLOW V_E APPLIED ANYWHERE ALONG B
  2. SHEARED NEUTRAL FLOW V_n APPLIED IN CONDUCTING LAYER
- IF $j_{\|} >$ CRITICAL $j_{\|}$, GET $V_{\|}$

Figure 5. Summary of conditions that could lead to the formation of significant $V_{\|}$'s in a manner analogous to what occurs in the Earth's auroral zones.