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INVESTIGATION OF TURBULENT PROCESSES IN MAGNETOSPHERIC BOUNDARY LAYERS

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Final Technical Report

1. Summary of Results

1.1. Self-Consistent Slab Model of a Viscous LLBL

A self-consistent non-evolving two-dimensional slab model of a viscous low-latitude boundary layer (LLBL) coupled to the ionosphere was developed by Phan et al. [1989]. In the model, an exact balance is maintained between $\mathbf{j}\times\mathbf{B}$ forces and viscous forces generated by unidirectional shear flow, $\mathbf{v} = -\hat{\mathbf{x}}V(y)$, in the layer. Thus the structure and thickness of the layer do not evolve in the flow direction. The flow velocity V(y) has its maximum value, V_0, at the magnetopause edge of the layer and then drops to zero or to some magnetospheric sunward convection speed $\mathbf{v} = +\hat{\mathbf{x}}V_\infty$ at the inner edge. The magnetic field in the layer is determined self-consistently from the currents, the result being parabolic shapes of the field lines with the vertices pointing tailward and with the field lines adjacent to the magnetopause having the greatest curvature, those at the magnetospheric edge of the layer being straight. A qualitative sketch of the geometry is shown in Figure 1.

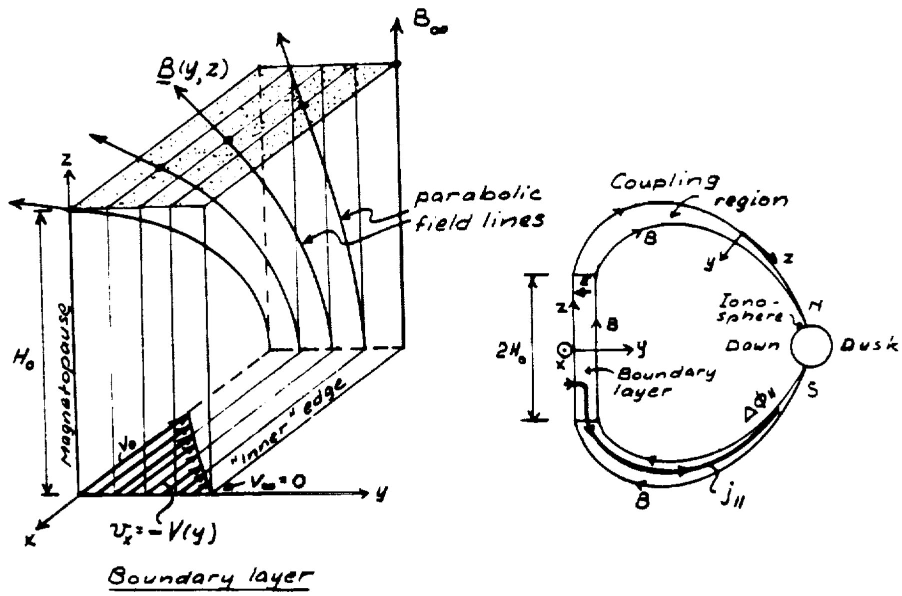

Figure 1. Model of non-evolving low latitude boundary layer and its connection to the ionosphere. [Phan et al., 1989]

More precisely, the magnetic field in the layer is found to be of the following exact form: $B_x = (z/H_0)B_{x1}(y)$, $B_y = 0$, $B_z = B_z(y)$, where $B_{x1}(y)$ is a maximum at the magnetopause, i.e., at $y = 0$, and $B_{x1}(y) \rightarrow 0$ as $y \rightarrow \infty$, i.e., at the magnetospheric, or "inner" edge of the layer. Also, $B_z(y)$ is a minimum at y = 0 and approaches its magnetospheric level, B_∞ as $y \rightarrow \infty$. The variation in magnetic pressure across the layer is balanced precisely by the plasma pressure in the boundary layer. The magnetic pressure is a minimum and the plasma pressure a maximum in the equatorial plane (z = 0) adjacent to the magnetopause (y = 0); as $y \rightarrow \infty$ or $|z| \rightarrow H_0$ the magnetic and plasma pressures both approach their magnetospheric levels, $B_\infty^2/2\mu_0$ and p_∞, respectively. At $|z| = H_0$ the current components j_z and j_x are continuous and are such that they form a net current that is exactly parallel to the magnetic field at each y value. The current component $j_y(y)$ which is nonzero and independent of z for $|z|<H_0$ is switched to zero abruptly at $|z| = H_0$. The viscous force is also switched off at that location so that the boundary layer model terminates there. However, the field aligned currents, $j_{||}$, are then mapped along **B** into the ionosphere by use of appropriate geometrical mapping factors. Field-aligned potential drops, $\Delta\phi_{||}$, governed by a simple conductance relationship, $j_{||} = \kappa\Delta\phi_{||}$, are allowed for and the field-aligned currents are then deflected into horizontal Pedersen currents in the ionosphere, which is modelled as a purely resistive substrate.

Numerical results from the model are presented in the paper by Phan et al. [1989] and the possible use of observations to determine the model parameters is discussed. The general predictions of the model in terms of region 1 currents and associated ionospheric signatures are similar to those obtained earlier by Lotko et al. [1987] and by Sonnerup [1980]. Those predictions are in qualitative and approximately quantitative agreement with a number of observations. The main new contribution of the study is to provide a better description of the field and plasma configuration in the LLBL itself and to clarify in quantitative terms the circumstances in which induced magnetic fields become important. In particular, it appears that for the low values of the field-aligned conductance expected on the duskside of the magnetosphere, these fields may remain relatively unimportant, at least in the noon to dusk segment of the LLBL.

1.2. Auroral Shear Layer Dynamics

The dynamical model developed by Lotko et al. [1987] was used by Lotko and Shen [1991] to examine two-dimensional dynamical processes of relevance to the LLBL with particular application to post-noon auroral shear layers. In this model, the magnetic field threading the layer is taken to be uniform. The plasma motion within the layer is incompressible and confined to planes perpendicular to the magnetic field. The equation of motion includes inertia effects, pressure gradients, the **j**×**B** force, and a viscous force; the current **j** is determined via coupling to the ionosphere with allowance for the effects of field-aligned potential drops. The approach taken by Lotko and Shen is to treat the distribution of field-aligned current generated in the LLBL proper as given, and ask what are the dynamical consequences of such currents in the lower altitude, low β region extending along magnetic field lines from the bottom of the LLBL to the ionosphere. Although the distinction between the LLBL region and the tenuous plasma region below it is somewhat artificial in Lotko and Shen's analysis, the fact that E×B shear flow instabilities tend to be suppressed by the strong magnetic shear that accompanies field-aligned currents in the higher β, LLBL region, and that the generation of currents by an enhanced viscous interaction is substantial in the LLBL relative to the tenuous plasma region below it, suggests that such a distinction is qualitatively meaningful. Given this distinction, the stability of the shear layer can be readily evaluated, as shown in the figure below.

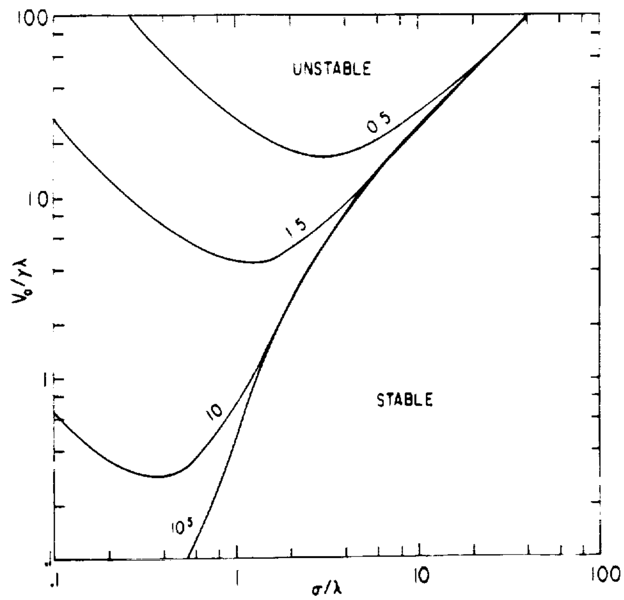

Figure 2. Neutral stability curves for effective Hartmann number M = 0.5, 1.5, 10, and 10^5. For a given value of M, the shear layer is linearly stable below the curve corresponding to that value of M and unstable above it.

The neutral curves depend on three nondimensional parameters related to the amplitude of the field-aligned current (or E×B velocity amplitude) produced by the LLBL, the scale size of the current distribution, and the so-called Hartmann number, which is a measure of the relative importance of resistive drag in the ionosphere proper and viscous drag in the viscous/polarization layer above the ionosphere. Numerical simulations of unstable cases show that (1) 2D quasi-steady rotational states arise when the shear layer is weakly unstable, (2) eddy shedding turbulent states can arise when the shear layer is more strongly unstable, and (3) the flow kinetic energy and energy dissipation by ionospheric Joule heating, production of field-aligned particle fluxes, and viscous heating are all reduced as a consequence of the instability. Power spectral densities are also evaluated along selected "satellite" cuts through the shear layer. The results of the study confirm the observed tendency for 2D rotational motion and periodic bright spots in post-noon auroral forms, although an important finding of the study is that typically observed electric current densities in post-noon auroral regions are sufficiently large to require a full inductive treatment, in which Alfvén waves may play a prominent role.

1.3. Magnetic Field Draping at the Magnetopause Boundary

Initial results from a magnetohydrodynamic simulation study of a flank-side magnetopause boundary configuration are described in the paper by Richard and Lotko [1990]. Effects of compressibility, scalar viscosity and electrical resistivity are included in the MHD equations. The geometry allows 2D variations of all three components of magnetic field and velocity, as well as the density and pressure, in the plane containing the boundary normal and initial magnetic field directions, i.e., variations in the downstream direction are not allowed. While dynamical effects are allowed in principle, the relatively low values of the mechanical and magnetic Reynolds numbers (300 - 1000) used in the simulations tend to suppress any large amplitude fluctuations that might arise after the initial transients have died away. Consequently, the results are illustrative of time-average properties. Boundary normal flows are imposed at the magnetosheath and magnetopause boundaries (a merging type configuration); a shear in the tangential (downstream) flow is also imposed by the boundary conditions. The major new finding of this study, as illustrated in the figure below, is the formation of a substantial "draping" field - the magnetic field component in the tangential downstream/upstream direction.

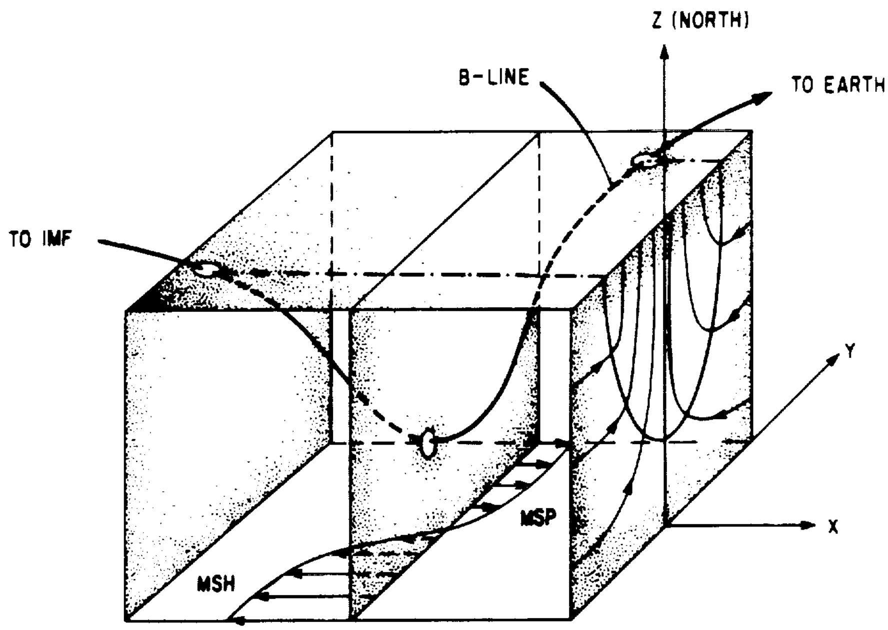

Figure 3. Schematic of the simulation geometry and normal field line draping. A draped, reconnected field line is shown along with its projection onto the yz plane. Projections of streamlines are drawn on the same plane, while tailward and sunward flows are indicated on the equatorial plane (the flow there has a small y component, but it has been omitted for clarity. The magnetosheath end of the reconnected field line is pulled anti-sunward relative to the magnetospheric end due to the shear in v_x. This effect generates a B_x component.

The currents responsible for the draping field appear to be consistent with the sense of direction of the region 1 currents that flow into/out of the ionosphere. However, the effects of the ionosphere, e.g., as represented by current closure in a conducting substrate, are not presently included in the model. Considerable effort has been expended in demonstrating that the phenomenon is robust, in particular for a variety of different inflow/outflow boundary conditions.

2. Bibliographic References of Publications (abstracts attached)

Lotko, W. and M. Shen, On large scale rotational motions and energetics of auroral shear layers, *J. Geophys. Res.*, in press, 1991.

Phan, T.D., B.U.Ö. Sonnerup and W. Lotko, Self-consistent model of the low-latitude boundary layer, *J. Geophys. Res., 94*, 1281, 1989.

Richard, R.L. and W. Lotko, Magnetic field draping at the low-latitude magnetopause, submitted to *J. Geophys. Res.*, August, 1990.

3. Student Support

Ian Gregory (graduate research assistant), 1/1/88 - 2/28/90.

On Large Scale Rotational Motions and Energetics of Auroral Shear Layers

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ABSTRACT

The stability, dynamics and energetics of an auroral shear layer are considered in the framework of incompressible, one-fluid magnetohydrodynamics, under conditions where current flow through the system is limited by the finite Pedersen conductivity and an enhanced field-aligned resistivity. The model includes a magnetospheric region where currents resulting from polarization electric fields and viscous forces are important, an ionospheric substrate of uniform conductivity, and a force-free acceleration region, characterized by a linear current-voltage relation and located at an intermediate altitude between the magnetospheric viscous/polarization layer and the ionosphere. It is assumed that the Alfvén wave transit time across the viscous/polarization layer is small compared with the eddy time. Neutral stability of the model system is determined for a class of one-dimensional equilibria in which a specified current distribution at the upper boundary of the viscous/polarization layer produces a potential structure with convergent, localized reversals in the transverse ($\mathbf{E} \times \mathbf{B}$) electric field. The calculated neutral curves depend on three nondimensional parameters related to the intensity of the imposed field-aligned current, the shear layer scale size, and the ratio of resistive to viscous drag at equilibrium. Numerical simulations of unstable configurations show that (1) 2D quasi-steady rotational states arise when the equilibrium is weakly unstable; (2) eddy shedding turbulent states can arise when the equilibrium is strongly unstable; and (3) the flow kinetic energy and energy input/dissipation rates in the model system are reduced as a consequence of the instability. Power spectral densities for the electric and magnetic fields are also evaluated along sample 'satellite' cuts through the shear layer. An application to post-noon auroral forms confirms the tendency for 2D rotational motion and periodic bright spots, although the observed intensity of the upward field-aligned current suggests that the effective resistivity of the system is not sufficient to suppress inductive fields in the vortex dynamics.

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Self-Consistent Model of the Low-Latitude Boundary Layer

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A simple two-dimensional, steady state, viscous model of the dawnside and duskside low-latitude boundary layer (LLBL) has been developed. It incorporates coupling to the ionosphere via field-aligned currents and associated field-aligned potential drops, governed by a simple conductance law, and it describes boundary layer currents, magnetic fields, and plasma flow in a self-consistent manner. Slab geometry is assumed, with no variations along the flow direction $-x$ and with the layer on closed field lines. The currents in the layer are regulated by coupling to the ionosphere. The magnetic field induced by these currents leads to two effects: (1) a diamagnetic depression of the magnetic field in the equatorial region and (2) bending of the field lines into parabolas in the xz plane with their vertices in the equatorial plane, at $z = 0$, and pointing in the flow direction, i.e., tailward. Both effects are strongest at the magnetopause edge of the boundary layer and vanish at the magnetospheric edge. The diamagnetic depression corresponds to an excess of plasma pressure in the equatorial boundary layer near the magnetopause. This pressure drops off both with increasing distance z from the equatorial plane and with increasing distance y from the magnetopause. It reaches the magnetospheric level for $z = \pm H$ as well as for $y \rightarrow \infty$. The boundary layer structure is governed by a fourth-order, nonlinear, ordinary differential equation in which one nondimensional parameter, the Hartmann number M, appears. A second parameter, introduced via the boundary conditions, is a nondimensional flow velocity v_0^* at the magnetopause. It is shown that for large M values the coupling to the ionosphere is weak; in that limit, or when v_0^* is small, the model reduces to that discussed by Lotko et al. (1987) in which induced magnetic fields are neglected. Numerical results from the model are presented and the possible use of observations to determine the model parameters is discussed. The general predictions of the model in terms of region 1 currents and associated ionospheric signatures are similar to those obtained earlier by Lotko et al. and by Sonnerup (1980). Those predictions are in qualitative and approximately quantitative agreement with a number of observations. The main new contribution of the study is to provide a better description of the field and plasma configuration in the LLBL itself and to clarify in quantitative terms the circumstances in which induced magnetic fields become important. In particular, it appears that for the low values of the field-aligned conductance expected on the duskside of the magnetosphere, these fields may remain relatively unimportant, at least in the noon to dusk segment of the LLBL.

Magnetic Field Draping at the Low Latitude Magnetopause

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Abstract

The structure of the low-latitude magnetopause is investigated for IMF conditions with a dominant southward component using magnetohydrodynamic simulations. The structure is self-consistently calculated as an initial-value problem in which the system is allowed to evolve to a quasi-steady-state. All components of the three-dimensional velocity and magnetic field as well as compressibility, resistivity and viscosity are included in the two-dimensional calculation. The boundary conditions sustain inflow from the magnetosheath and the magnetosphere, as well as a flow tangential to the magnetopause, sunward in the magnetosphere and tailward in the magnetosheath. The tangential flow leads to the draping of magnetic field lines in the magnetopause region. No draping (tailward or sunward) was included initially, while as the system evolved this component of the magnetic field became comparable in magnitude to the other two components. The resulting draping structure is found to be dependent sensitively on the ratio of the viscous and magnetic diffusivities.