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Structure of tangential discontinuities at the magnetopause: the nose of the magnetopause

by

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FOREWORD

The paper "Structure of tangential discontinuities at the magnetopause : the nose of the magnetopause" by M. Roth has been presented at the Symposium "Magnetopause Regions" held 7-10 September 1976 in Amsterdam as part of the Third meeting of the European Geophysical Society. This paper will be published in the Proceedings of the conference, and will appear in Journal of Atmospheric and Terrestrial Physics.

AVANT-PROPOS

L'article intitulé "Structure of tangential discontinuities at the magnetopause : the nose of the magnetopause" par M. Roth, a été présenté au symposium "Magnetopause Regions" qui s'est tenu du 7 au 10 septembre 1976 à Amsterdam dans le cadre de la 3ème réunion de la "European Geophysical Society". Il sera publié dans les comptes rendus du symposium qui paraîtront dans Journal of Atmospheric and Terrestrial Physics.

VOORWOORD

Het artikel getiteld "Structure of tangential discontinuities at the magnetopause : the nose of the magnetopause" door M. Roth, werd voorgedragen op het symposium "Magnetopause Regions" dat gehouden werd van 7 tot 10 september 1976, te Amsterdam, in het kader van de derde bijeenkomst van de "European Geophysical Society". Het zal gepubliceerd worden in Journal of Atmospheric and Terrestrial Physics.

VORWORT

Dieser Text "Structure of tangential discontinuities at the magnetopause : the nose of the magnetopause" von M. Roth wurde während des Symposium "Magnetopause Regions" der in Amsterdam im Rahmen der dritten Sammlung des "European Geophysical Society" zwischen 7 und 10 September 1976 gehalten wurde, vorgetragen worden. Dieses Artikel wird in die Proceedings des Symposiums heraugegeben, und in Journal of Atmospheric and Terrestrial Physics veröffendlicht.

STRUCTURE OF TANGENTIAL DISCONTINUITIES AT THE MAGNETOPAUSE : THE NOSE OF THE MAGNETOPAUSE

by

M. ROTH

Abstract

Observations show that the magnetopause can sometimes be represented as a tangential discontinuity in the magnetic field. In this paper, we use a theoretical model of steady-state tangential discontinuities to analyze the microscalestructure of the nose of the magnetopause. The boundary layer is described in terms of a kinetic theory based on the Vlasov-Maxwell equations for the charged particles and electromagnetic fiels. The general model represents the magnetosheath and magnetospheric sides as distinct regions with anisotropic displaced Maxwellian equilibrium states and allows the presence of a multi-components plasma whose ionic species have different concentrations, temperatures, anisotropies, ... For the nose region, these states reduced to isotropic Maxwellian states for an assumed hydrogen plasma. Transition profiles for the magnetic field, electric potential, electric field, charge separation and density are illustrated. The variations of the magnetic field direction in the discontinuity plane show a great variety of rotational structures in accordance with recent observations. The electric potential difference is seen to control the thickness of the magnetopause. When no electric potential difference applies between the two edges of the sheath, we recover a boundary layer similar to the classical Ferraro magnetopause where the electric current is mainly carried by the electrons. However, computations of drift and thermal velocities indicate that a two-stream instability occurs in the center of the sheath. The result will be a broadening of the layer leading by wave-particle interactions to an ion-dominated transition.

Résumé

Les observations montrent que la magnétopause peut quelquefois être représentée comme une discontinuité tangentielle du champ magnétique. Dans cet article, nous utilisons un modèle théorique de discontinuités tangentielles stationnaires afin d'analyser la structure à l'échelle microscopique du "nez" de la magnétopause. La couche frontière est décrite à l'aide d'une théorie cinétique basée sur les équations de Vlasov-Maxwell pour les particules chargées et les champs électromagnétiques. Le modèle général représente les côtés "magnetosheath" et magnétosphérique comme des régions distinctes en états d'équilibre représentés par des Maxwelliennes déplacées et anisotropes, et tient compte de la présence d'un plasma à plusieurs constituants dont les espèces ioniques possèdent différentes concentrations, températures, anisotropies... . Pour la région du "nez", ces états se réduisent à des états Maxwelliens isotropes pour un plasma que nous supposons d'hydrogène. Des profils de transition pour le champ magnétique, le potentiel électrique, le champ électrique, la séparation de charges et la densité servent d'illustration. En accord avec des observations récentes, les variations de la direction du champ magnétique dans le plan de la discontinuité indiquent une grande variété de structures de rotation. La différence de potentiel électrique contrôle l'épaisseur de la magnétopause. Lorsqu'aucune différence de potentiel électrique n'est appliquée entre les deux extrêmités de la transition, nous retrouvons une couche frontière similaire à la magnétopause classique de Ferraro dans laquelle le courant électrique est transporté principalement par les électrons. Cependant, les calculs des vitesses de dérive et d'agitation thermique montrent qu'une instabilité du type "two-stream" se produit au centre de la couche. Il en résulte un élargissement de cette couche conduisant, par interactions ondes-particules, à une transition de nature ionique.

Samenvatting

Uit de waarnemingen blijkt dat de magnetopauze soms kan beschouwd worden als een tangentiële discontinuïteit van het magnetisch veld. In dit artikel bezigen we een theoretisch model van een stationnaire tangentiële discontinuïteit ten einde op een microscopische schaal de structuur te bestuderen van de "neus" van de magnetopauze. De grenslaag wordt beschreven aan de hand van een kinetische theorie steunende op de Vlasov-Maxwell-vergelijkingen der geladen deeltjes en op de elektromagnetische velden. Het algemeen model stelt de twee zijden- de ene langs de kant der magnetische schede, de andere langs de magnetosfeer- voor als twee verschillende gebieden in evenwichtstoestand voorgesteld door verschoven en anisotrope Maxwelliaanse distributiefuncties, rekening houdend met de aanwezigheid van een plasma met talrijke bestanddelen waarvan deze van de ionische soort gekenmerkt zijn door verschillende concentraties, temperaturen, anisotropieën, enz. In het neusgebied worden deze gebieden herleid tot isotrope Maxwelliaanse toestanden van een plasma waarvan we aannemen dat het waterstof is. Overgangsprofielen, voor het magnetisch veld, de elektrische potentiaal, het elektrisch veld, de ladingsscheiding en de dichtheid illustreren dit. In overeenstemming met de waarnemingen, wijzen de richtingsveranderingen van het magnetisch veld in het vlak van de discontinuïteit op een grote verscheidenheid van rotatiestructuren. Het elektrisch potentiaalverschil bepaalt de dikte van de magnetopauze. Wanneer een potentiaalverschil aangelegd wordt tussen de twee uiteinden van de overgang, vinden we de grenslaag terug die overeenstemt met de klassieke voorstelling der magnetopauze volgens Ferraro waarin de elektrische stroom alleen veroorzaakt wordt door de elektronen. Uit de berekening van de driftsnelheid en de thermische agitatie blijkt evenwel dat een dubbelstroom labiliteit ontstaat in het midden van de laag. Hieruit volgt een uitzetting van deze laatste, die door een wisselwerking tussen golven en deeltjes, leidt tot een ionische overgang.

Zusammenfassung

Beobachtungen zeigen dass die Magnetopause manchmal als einer Tangentialunterbrechung des Magnetfeldes vorgestellt sein kann. In dieser Arbeit werden wir ein theoretisches Modell des stationären Tangentialunterbrechungen für die Analyse der mikroskopischen Struktur der "Nase" der Magnetopause benutzen. Das Grenz Gebiet wird beschrieben mit Hilfe einer kinetischen Theorie, die auf den Vlasov-Maxwell Gleichungen für geladenen Teilchen und elektromagnetischen Felden gegründet ist. Das allgemeine Modell wiedergibt die "magnetosheath" und magnetospherische Seiten als unterschiedene Gebiete, die durch verschiedene und anisotropischen Maxwellischen Verteilungen charakterisiert sind, und ist gültig für einem Plasma mit verschiedenen Komponenten, dessen die Ionen verschiedene Konzentrationen, Temperaturen, Anisotropie, ... haben. Im Gebiet der "Nase" beschränken sich diese Zustände zu einem isotropischen Maxwellischen Wasserstoffplasma. Ubergangsverteilungen des Magnetfeldes, des elektrischen Potentiales des elektrischen Feldes, der Ladungstremmung und der Dichte werden gegeben. In Ubereinstimmung mit neuen Beobachtungen, zeigen die Variationen der Richtung des Magnetfeldes eine grosse Abwechselung der Rotationstrukturen. Der elektrische Potentialunterschied kontrolliert die Dicke der Magnetopause. Wenn es kein Potentialunterschied zwischen beide Enden des Ubergangsgebiet gibt, ist das Grenzgebiet gleichartig zu der klassichen Magnetopause von Ferraro worin der elektrische Strom meistens durch die Elektronen transportiert ist. Jedock, zeigen die Berechungen der Driftgeschwindigkeiten und der thermischen Unruhe dass eine "two stream" Instabilität im Zentrum der Schichte stattfindet. Eine Ausfreitung der Schichte erfolgt und gibt, durch Welle-Teilchen Interaktionen, ein ionischen Ubergang.

I. INTRODUCTION

As a consequence of a too low time resolution, experimental observations of the internal structure of the magnetopause do not in general provide the detailed structure of this thin boundary layer. Nevertheless, most of the measurements have revealed that the magnetopause appears sometimes to be a tangential discontinuity in the magnetic field and occasionally a rotational discontinuity (Aubry *et al.*, 1971; Neugebauer *et al.*, 1974; Sonnerup, 1976). In this latter case, however, the time resolution of the measurements is often inadequate to ascribe with certainty a value for the component of the magnetic field normal to the magnetopause. Since rotational discontinuities are less frequently observed, it is reasonable to start constructing a theoretical model of tangential discontinuities.

The aim of this paper is to use this theoretical model for the description of the nose region of the magnetopause. To describe the different regions of the magnetopause, a model must include boundary conditions which permit plasma flows in the discontinuity plane and temperatures anisotropies at both sides of the sheath. Furthermore the model will be sufficiently general as to keep into account of the minor constituents of the solar wind and the presence of energetic particles. The theory of this general tangential discontinuity will be found elsewhere (Roth, 1976). This theory is only briefly summarized in Section II. In Section III, we describe the boundary conditions and we discuss the distributions of plasmas and fields across the layer. It is shown that by a suitable choice of the electric potential difference between the two edges of the layer, we can recover a current layer similar to the classical description of the Ferraro magnetopause where the electrons carry most of the current (Ferraro, 1952). However, this boundary layer happens to be unstable. Consequences of this instability for the magnetopause model are discussed in the conclusions.

II. THE THEORETICAL MODEL

The tangential discontinuity in the magnetic field is described in terms of a kinetic theory based on the Maxwell equations and the Vlasov equation for each particles species. The plasma contains p particles species, including the electrons. Each species is denoted by the superscript ν. $m^{(\nu)}$ and $Z^{(\nu)}e$ are the mass and the electric charge of the corresponding particle. The plane of the discontinuity is parallel to the Y - Z plane and all the variables are assumed to depend on the X coordinate only. The state of the plasma has distinct characteristics on both sides of the transition (at X = - ∞ and X = + ∞, denoted by subscripts 1 and 2): perpendicular temperatures ($T_{\perp_1}^{(\nu)}$, $T_{\perp_2}^{(\nu)}$)and parallel ($T_{\parallel_1}^{(\nu)}$ $T_{\parallel_2}^{(\nu)}$) temperatures, given densities ($N_1^{(\nu)}$,$N_2^{(\nu)}$)and given bulk velocity components (V_{y_1}, V_{y_2} and V_{z_1}, V_{z_2}). The magnetic field is parallel to the Y-Z plane and has given distinct intensities (B_1, B_2) and directions (θ_1, θ_2) at both sides. The polarization and induced electric field is along the X- axis since it is considered that there is no plasma transport across the discontinuity.

Evidently there is a great choice of velocity distribution functions which are solutions of Vlasov's equation. We have been guided in our choice by a generalization of a method introduced ten years ago by Sestero (1964; 1966) for contact discontinuities in collisionless plasmas. At each point in the transition, the velocity distribution function for each species is the sum of two different Maxwellians times step functions in the constants of motion, so that asymptotically one of these two Maxwellians becomes predominant over the other. At X= -∞ and X = + ∞, these functions have the same first order moments ($N_1^{(\nu)}$, $T_{\perp_1}^{(\nu)}$, $T_{\parallel_1}^{(\nu)}$, V_{y_1}, V_{z_1}; $N_2^{(\nu)}$, $T_{\perp_2}^{(\nu)}$, $T_{\parallel_2}^{(\nu)}$, V_{y_2}, V_{z_2}) as the actual velocity distribution functions on each side. This choice gives the simpliest description of a transition between two distinct anisotropic displaced Maxwellian states in a multi-components plasma. However, the state of the plasma at both ends of the transition does not uniquely determine the layer profile. The particular model chosen for the distribution functions determines the shape of the transition uniquely. The solution of the Vlasov's equation used here corresponds to one among many other possible solutions satisfying the same asymptotic conditions. However, due to their straightforwards mathematical forms, these distribution functions, give analytical expressions for the moments of any order.

In most cases, the Poisson equation for the electric potential can be replaced by the quasi-neutrality approximation for the charge density. The smallness of charge separation computed by evaluating the second derivative of the electric potential is a proof a posteriori of the validity of the charge neutrality assumption. Magnetic field components are obtained by numerical integration of the Maxwell equations (Roth, 1976).

In the next section we illustrate the method for the case of a hydrogen plasma with asymptotically isotropic temperatures and no flow velocities parallel to the tangential discontinuity on both sides of the magnetopause. The boundary conditions are pertaining to the nose of the magnetosphere where the flow of the solar wind tends to cancel.

III. AN IDEAL STRUCTURE FOR THE NOSE MAGNETOPAUSE

The asymptotic values of the physical parameters representative of the Maxwellian states at both sides of the sheath are given in table 1. These values are deduced either from observations either from the total pressure balance condition.

We assume in the following calculations, that there is no electric potential difference ($\Delta\phi$) between $X = -\infty$ and $X = +\infty$. If the total angle of rotation of the magnetic field through the sheath is an imposed boundary condition successive iterations are needed to fit the solution to the asymptotic conditions at $X = +\infty$ (the magnetosphere region). However, for isotropic conditions the asymptotic orientations (θ) of the magnetic field do not enter in the expressions of the distribution functions and the rate of rotation depends only on the boundary conditions and on the initial values for the potential vector components (a_y, a_z) we choose at $X = -\infty$ (the magnetosheath region). Therefore, for the isotropic conditions used in this example, it is not necessary to impose the orientation of the magnetic field at $X = +\infty$ (the magnetosphere region) to recover the corresponding asymptotic boundary conditions. The total rotation of the magnetic field depends only (other conditions at $\pm\infty$ being unchanged) on the initial ratio $\rho (= a_y/a_z)$ on the magnetosheath side. For the case analyzed here this ratio is chosen to be 0.5.

Figure 1 are hodograms of the magnetic field for the conditions listed in table 1. The X- axis is in the anti-solar direction, the Y and Z axes are arbitrary directions in the discontinuity plane. In the magnetosheath, the magnetic field has a 45^0 angle with the

TABLE 1 : Boundary conditions pertaining to the nose of the magnetosphere.

	Magnetosheath ($X = -\infty$)	Magnetosphere ($X = +\infty$)
N^- (cm^{-3})	30	1
N^+ (cm^{-3})	30	1
$T_\perp^-$ (K)	4×10^6	2×10^6
$T_\parallel^-$ (K)	4×10^6	2×10^6
$T_\perp^+$ (K)	5×10^5	3×10^5
$T_\parallel^+$ (K)	5×10^5	3×10^5
V_y ($m.s^{-1}$)	0	0
V_Z ($m.s^{-1}$)	0	0
B (nT)	5	68
θ (°)	45	87

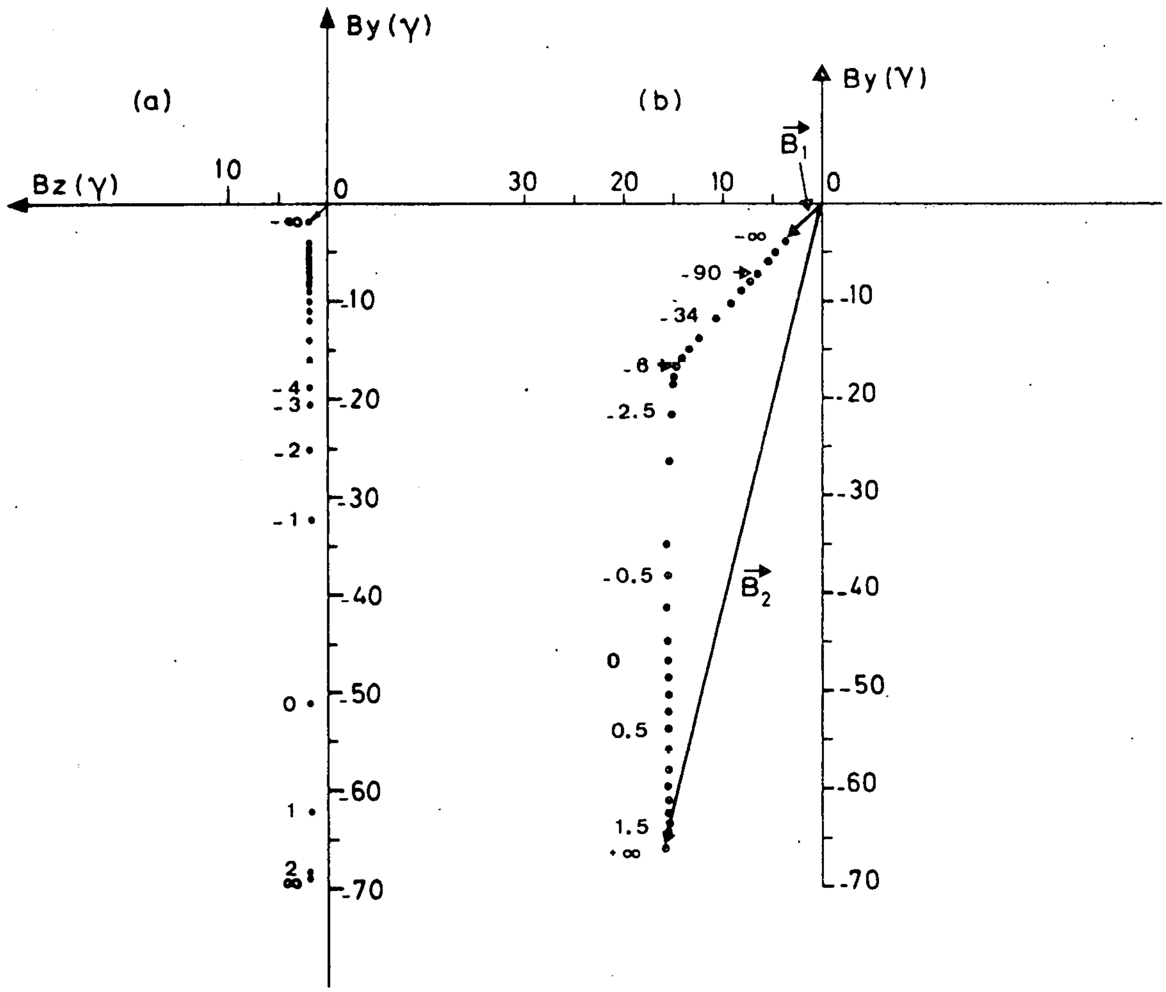

Fig. 1.- Hodograms of the magnetic field (nT or γ) corresponding to the boundary conditions listed in table 1 with $\Delta\phi=0$. (a) for $a_y/a_z = 0.5$, (b) for $a_y/a_z = 0.995$. Numbers from $-\infty$ to $+\infty$ are distances along the X-axis measured in electron skin depths (e.s.d.).

Z- axis. For the particular value (0.5) of the ratio a_y/a_Z used in figure 1a, the B_Z component remains constant (3.5 nT). In the magnetosphere, the angle with the Z- axis attains a value of 87° indicating that the total rotation is equal to 42°. Numbers from $-\infty$ to $+\infty$ are distances along the X- axis in units of electron skin depth which is the classical Ferraro thickness of the magnetopause (Willis, 1971, 1975). For magnetosheath values listed in table 1, this unit is of the order of 1 km. It can be seen that the asymptotic values of the magnetic field are rapidly attained in some kilometers. Figure 1b corresponds to a ratio $a_y/a_Z = 0.995$. In this case, both the Y- and Z components of the magnetic field change. The magnetic field has a 76° angle with the Z- axis in the magnetosphere, the total rotation being of 31°. In the same way, by changing the value of ρ, we can obtain any angle of rotation for the magnetic field. This agrees well with experimental magnetic field measurements (Sonnerup, 1976) for which the change in direction takes any value between 0° and 180°.

The curve (ϕ) of figure 2 shows the electric potential profile. It is assumed to be zero in the magnetosheath. Across the tangential discontinuity, the electric potential rises from its minimum value of - 20 V to its maximum value of 85 V in about 4 km which leads to the electric field shown in curve (E) of figure 2. The electric field changes sign across the transition. A maximum value of 67 mV/m is obtained in the center of the sheath. This rather sharp peak of the electric field however does not violate significantly the quasi-neutrality approximation. This is demonstrated in figure 3a which shows the relative charge separation $\Delta q/q$ in the center of the sheath (Δq is the charge excess and q the charge of the H^+ ions). The curve of figure 3a is obtained by calculating the divergence of the electric field and the corresponding charge number density according to the Poisson equation for the electric potential. The maximum relative electron charge excess does not exceed 2×10^{-3} which insures a posteriori that the electric potential determined by the charge neutrality equation is a good approximation.

Figure 3b shows the distribution for the number density. The concentration of charged particles of either sign has typical values of 30 cm^{-3} in the magnetosheath and 1 cm^{-3} in the magnetosphere. The transition occurs in a few electron skin depths. It is an example of an electron dominated layer in the sense that the electric current is mainly transported by the electrons as in the classical Ferraro magnetopause. This is clearly illustrated in figure 4

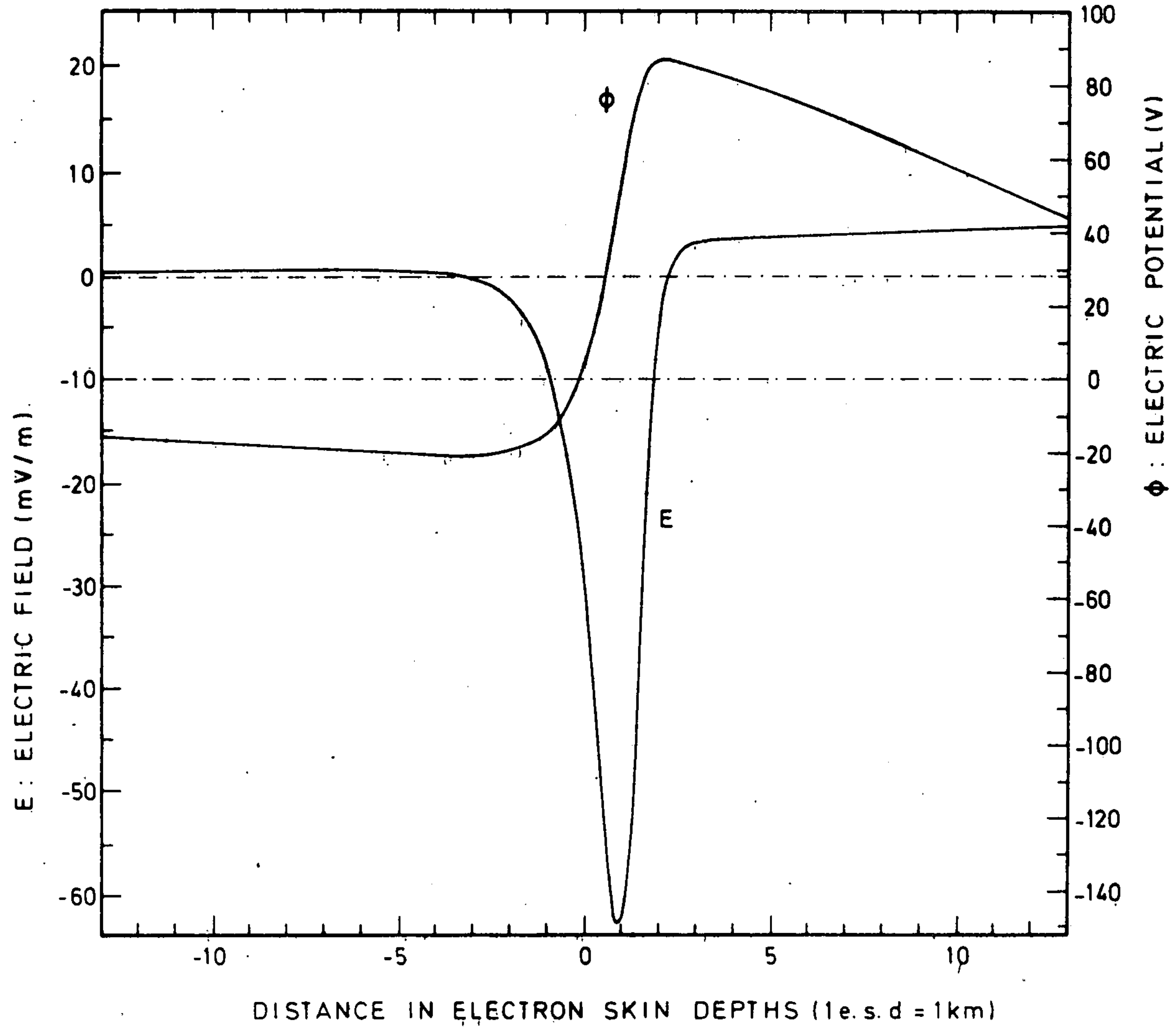

Fig. 2.- Electric potential (ϕ) and electric field (E) across the sheath corresponding to the boundary conditions listed in table 1 with $a_y/a_z = 0.5$.

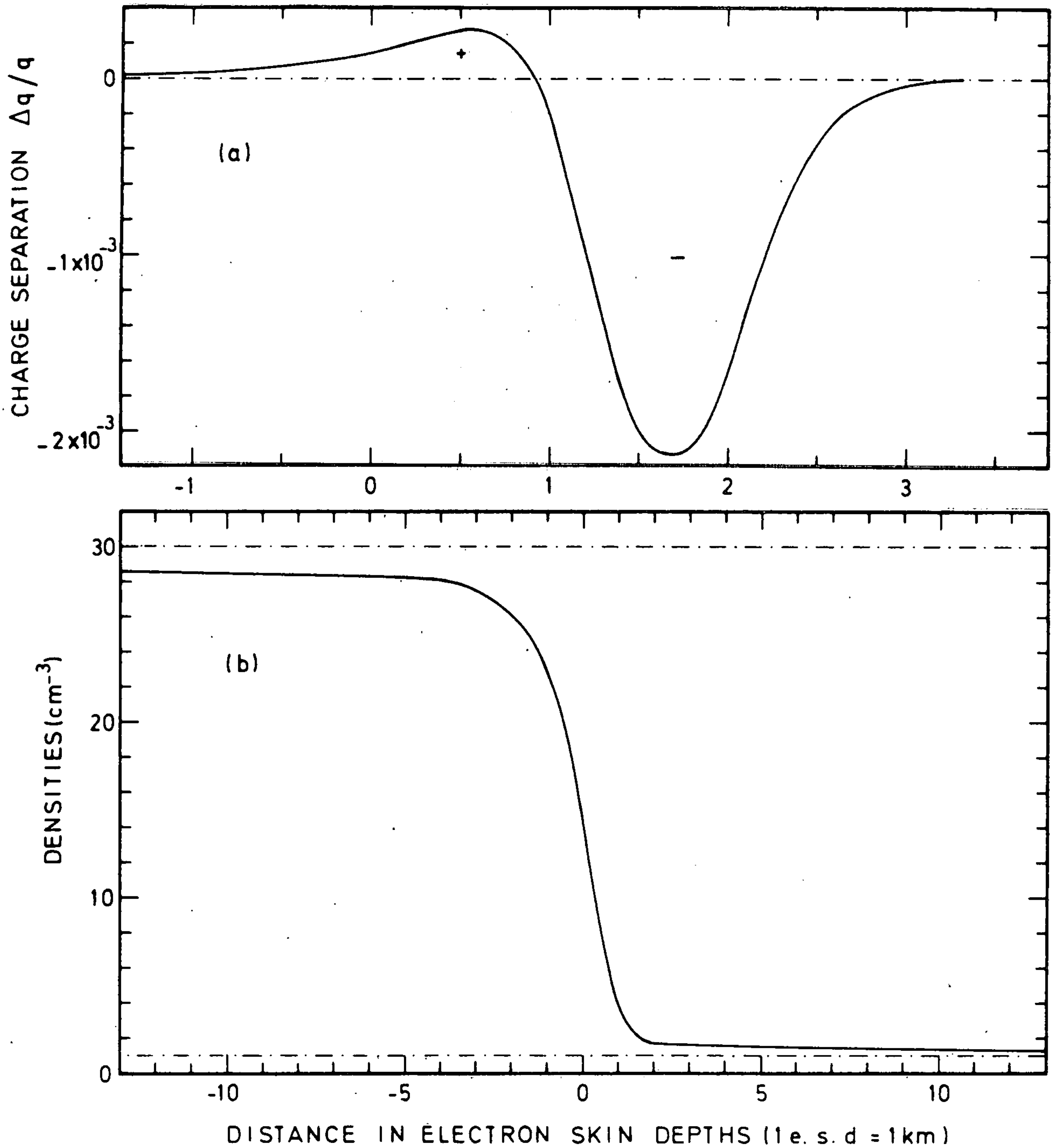

Fig. 3.- (a) relative charge separation $[\Delta q/q = -(\epsilon_0/ne)d^2\phi/dx^2]$ obtained from the Poisson equation and corresponding to the boundary conditions listed in table 1 with $a_y/a_z = 0.5$ and $\Delta\phi = 0$. The charge separation cancels at both ends of the sheath. (b) density of protons or electrons corresponding to the boundary conditions listed in table 1 with $a_y/a_z = 0.5$ and $\Delta\phi = 0$.

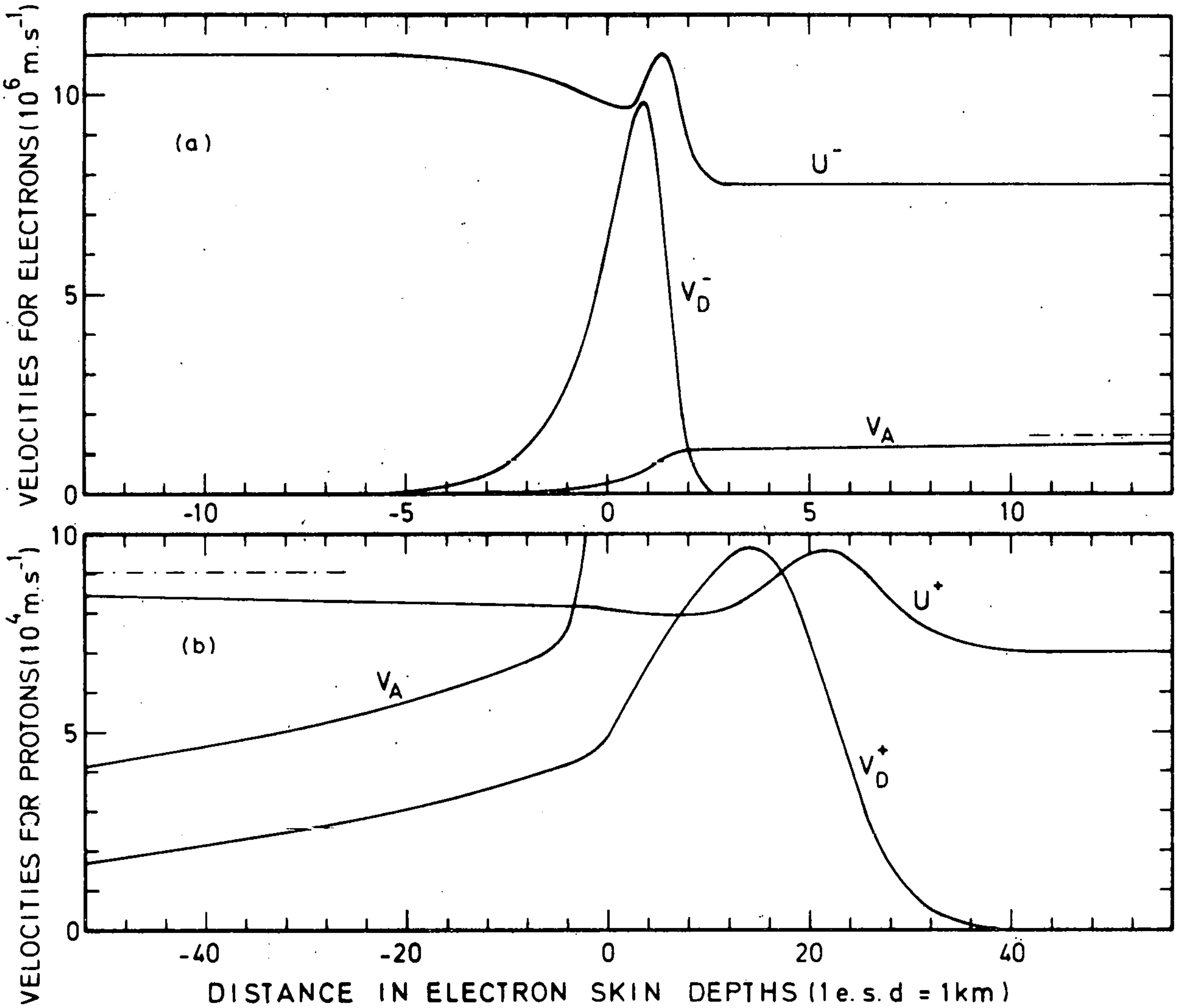

Fig. 4.- Mean drift velocities ($V_D^{\pm}$), thermal velocities ($U^{\pm}$), and Alfvèn wave speed (V_A) for the boundary conditions listed in table 1 with $a_y/a_z = 0.5$ and $\Delta\phi \equiv 0$. (a) for the electrons (superscript -). (b) for the protons (superscript +). Asymptotic values are indicated by dot-dashed lines. Note that the scales are different for the two panels. An instability occurs when the relative mean drift velocity of the ions and electrons ($V_D^- - V_D^+$) exceeds the thermal ions speed (U^+). It is clear that this is actually the case in the center of the sheath where the electron current dominates. This relative velocity exceeds the local Alfvèn wave speed (V_A) in the largest part of the instability region and this instability is therefore electromagnetic in nature.

where the thermal velocities ($U^{\pm}$), the drift velocities ($V_D{}^{\pm}$) and the Alfvèn wave speed (V_A) are displayed as functions of the distance across the current layer. The top panel is for the electrons while the bottom panel is for the H^+ ions. It can be seen that most of the drift is carried by the electrons in a narrow region of thickness at most equal to a few electron skin depths (Note the different scales in the two panels of figure 4). From the curves of thermal velocities, it is seen that the temperatures do not decrease uniformly from their magnetosheath values to their magnetospheric values, but have peaks in between. This results from the particular form of the electric field in the center of the sheath. This example of an electron-dominated layer is certainly unstable. In the center of the sheath, a two-stream instability will occur because the relative electrons-ions mean velocity exceeds the ions thermal speed. Since the relative velocity exceeds the Alfvèn wave speed in a large fraction of the unstable region, this instability is electromagnetic in type (Papadopoulos, 1973).

Other transitions with different characteristic scales for the thickness can be computed by adjusting the electric potential difference between the two edges of the sheath. In particular, one can construct ion-dominated transitions where the electric current is mainly transported by the ions. In this case, the characteristic thickness would be of the order of 100 km, the ion gyroradius (Willis, 1971, 1975).

IV. CONCLUSIONS

In this paper, we have described a possible structure for the magnetopause nose. With no electric potential difference between the two sides of the sheath, the results of computations agree with the classical structure of the Ferraro magnetopause. However, this boundary layer is found unstable. This instability will force the electrons to become more isotropic and this will finally broaden the layer. Such a broaden current layer can be obtained by assuming a full Maxwellian distribution function for the electrons. In such a case, the electrons do not contribute to the current and the layer will be ion-dominated. Consequently, after an electron-dominated layer is formed, it is not necessary, for broadening the layer, to discharge the polarization electric field by means of ionospheric charges coming up along the high latitude field lines; a two-stream instability can be adequate for this broadening. We can construct ion-dominated layers by imposing a suitable electric potential difference between the two ends of the sheath, in order to keep the electrons velocity distribution Maxwellian everywhere. In this way, the electric potential is seen to control the thickness of the layer.

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