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Kinetic Structure of the Magnetopause : Equilibrium and Percolation

by

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FOREWORD

This paper has been accepted for publication in a volume of Geophysical Monograph Series entitled *Physics of the Magnetopause*. It is based on the invited talk presented by M. M. Kuznetsova during the Chapman Conference on Physics of the Magnetopause, San Diego (USA), March 14 –18, 1994.

AVANT–PROPOS

Cet article a été accepté comme publication dans un volume de la Série des "Geophysical Monograph", intitulé *Physics of the Magnetopause*. Il est basé sur l'exposé invité présenté par M. M. Kuznetsova au cours de la Conférence Chapman sur la Physique de la Magnétopause, qui s'est déroulée à San Diego (USA) du 14 au 18 mars 1994.

VOORWOORD

Dit artikel is aanvaard voor publikatie als een boekdeel in de reeks "Geophysical Monograph", getiteld *Physics of the Magnetopause*. Het is gebaseerd op een voordracht, die door M. Kuznetsova op uitnodiging werd gehouden tijdens de "Chapman Conferentie over de Fysica van de Magnetopause" te San Diego (USA) van 14 tot 18 maart 1994.

VORWORT

Dieser Artikel wurde zur Veröffentlichung in einem Band der "Geophysical Monograph"-Reihe *Physics of the Magnetopause* zugelassen. Er gründet sich auf die Gastrede von M. M. Kuznetsova bei der vom 14. bis 18. März 1994 in San Diego (USA) abgehaltenen Chapman-Konferenz über die Physik der Magnetopause.

Kinetic Structure of the Magnetopause: Equilibrium and Percolation

M.M. Kuznetsova * M. Roth § and L. M. Zelenyi¶

Abstract

This paper addresses theoretical studies of the magnetopause kinetic fine structure. A considerable amount of effort was made beginning in the early sixties to construct Vlasov equilibrium models of one dimensional tangential discontinuities which were assumed to provide a reasonable approximation for the structure of the magnetopause current layer (MCL). Simple models of MCLs of finite thickness (with a minimum number of free parameters) can be used to illustrate the effects of asymmetrical boundary conditions on the internal structure of the current layer. One dimensional current layers are thermodynamical nonequilibrium systems which have an excess of free energy that allows excitation of drift tearing modes which result in destruction of magnetic surfaces. The stochastic wandering of magnetic field lines between the destroyed surfaces can result in formation of percolated magnetic filaments topologically connecting magnetosheath and magnetospheric field lines. The stochastic percolation model by *Galeev et al.* [1986], based on the symmetrical charge-neutral Harris equilibrium, is generalized for asymmetrical MCLs. Asymmetry in the **B** field profile strongly modifies the dependence of the marginal MCL thickness (below which the MCL is subjected to percolation) on the angle of magnetic field rotation θ_0. The maximum thickness of MCLs which still could be subjected to percolation is achieved for $\theta_0 > 90°$, that is, for southward IMF. Realistic asymmetrical MCLs are likely to be thinner for a northward IMF than for a southward IMF. For northward IMF the MCLs are likely to be thinner for larger values of plasma β in the magnetosheath.

Résumé

Cet article contient une étude théorique de la structure fine et cinétique de la magnétopause. Une quantité considérable d'efforts a été fournie, au début des années soixante, pour construire des modèles d'équilibre de Vlasov de discontinuités tangentielles à une

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dimension. Ces modèles étaient supposés fournir une approximation raisonnable de la structure de la couche de courant de la magnétopause (CCM). Des modèles simples de CCM d'épaisseur non nulle (avec un nombre minimal de paramètres libres) peuvent être utilisés pour illustrer les effets de conditions frontières asymétriques sur la structure interne de la couche de courant. Les couches de courant à une dimension ne sont pas des systèmes en equilibre thermodynamique. Elles possèdent un excès d'énergie libre permettant l'excitation de modes "drift tearing", qui aboutit à la destruction de surfaces magnétiques. L'errance stochastique de lignes de champ magnétique entre les surfaces détruites peut donner lieu à la formation de filaments magnétiques infiltrés, reliant entre elles, de façon topologique, des lignes de champ magnétique issues de la magnétogaine à d'autres, issues de la magnétosphère. Le modèle de "percolation" stochastique de *Galeev et al.* [1986], basé sur l'équilibre symétrique, électriquement neutre de Harris, est généralisé pour des CCM asymétriques. L'asymétrie du profil du champ **B** modifie fortement la dépendance de l'épaisseur marginale de la CCM (en deçà de laquelle la CCM est soumise à "percolation") par rapport à l'angle de rotation du champ magnétique θ_0. L'épaisseur maximale des CCM qui pourraient encore être l'objet d'une "percolation" est réalisée lorsque $\theta_0 > 90°$, c'est-à-dire, pour un champ magnétique interplanétaire (CMI) d'orientation sud. Des CCM d'asymétrie réaliste sont vraisemblablement plus minces lorsque le CMI est orienté au nord, plutôt qu'au sud. Pour un CMI d'orientation nord, les CCM sont probablement plus minces pour des valeurs plus élevées du β de la magnétogaine.

Samenvatting

Dit artikel handelt over de theoretische studie van de kinetische fijnstructuur van de magnetopause. In het begin van de zestiger jaren werd een aanzienlijke inspanning gedaan om Vlasov evenwichtsmodellen van één-dimensionale tangentiële discontinuïteiten op te stellen. Deze werden verondersteld een redelijke benadering te geven van de structuur van de stroomvoerende plasma-laag in de magnetopause ("magnetopause current layer" of MCL). Eenvoudige modellen van MCL's met een beperkte dikte kunnen gebruikt worden om het effect van asymmetrische randvoorwaarden op de inwendige structuur van de magnetopause aan te tonen. Eén-dimensionale stroomvoerende plasma-lagen zijn thermodynamisch gezien niet in evenwicht : ze hebben een teveel aan vrije energie. Daarom laten ze het ontstaan van drift-verbrekingsinstabiliteiten ("drift-tearing mode instabilities") toe, hetgeen een vernietiging van magnetische oppervlakken tot gevolg heeft. Het stochastische gedrag van magnetische veldlijnen tussen de vernietigde magnetische oppervlakken kan leiden tot de vorming van percolerende magnetische filamenten, die de magnetoschede en de magnetosfeer met elkaar verbinden. Het stochastische percolatiemodel van Galeev et. al. [1986], dat gebaseerd is op het symmetrische neutrale Harris-evenwicht, wordt veralgemeend voor asymmetrische MCL's. Asymmetrie in het magnetisch veld-profiel wijzigt de invloed van de rotatiehoek θ_0 van het magnetisch veld op de marginale MCL dikte (de dikte beneden dewelke percolatie mogelijk is) aanzienlijk. De maximale dikte van MCL's waardoor percolatie nog mogelijk is, wordt bereikt bij $\theta_0 > 90°$, dus voor een interplanetair magnetisch veld met zuid-polariteit. Realistische asymmetrische MCL's zijn waarschijnlijk dunner voor het geval van een noord-polariteit; in dat geval zijn de MCL's wellicht dunner voor grote waarden van plasma β in de magnetoschede.

Zusammenfassung

In dieser Arbeit ist die Rede von der kinetichen Feinstruktur der Magnetopause. Im Anfang der 60er Jahre wurden mit beträchtlichem Aufwand Vlasov'sche Gleischgewichtsmodelle mit eindimensionalen tangentialen Diskontinuitäten erstellt, mit dem Ziel, über eine vernünftige Annäherung für die Stromschichtstruktur (SSM) der Magnetopause zu verfügen. Einfache SSM-Modelle endlicher Dicke (mit einer Mindestzahl freier Parameter) ermöglichen die Darstellung von Auswirkungen asymmetrischer Grenzbedingungen auf die innere Struktur der Stromschicht. Eindimensionale Stromschichten sind Systeme in thermodynamischem Nicht-Gleichgewicht, deren Übermass an freier Energie die Erregung von "drift tearing" Schwingbereichen, die eine Zerstörung von magnetischen Oberflächen bewirken, ermöglichen. Die regellose Wanderung magnetischer Feldlinien zwischen den zerstörten Oberflächen kann zur Bildung infiltrierter Magnetfilamente führen, die ein topologisches Bindeglied bilden zwischen Magnetfeldlinien aus der Magnetohülle und solchen aus der Magnetosphäre. Das auf dem Harris'schen symetrischen elektrisch neutralen Gleichgewicht beruhende stohastische Perkolationsmodell von *Galeev et al.* [1986] wird für asymmetrische SSM Verallgemeinert. Die Asymmetrie des **B**-Feldprofils verursacht eine starke Veränderung in der Abhängigkeit der SSM-Grenzdicke (unterhalb derer die SSM einer "Perkolation" unterliegt) von dem Drehwinkel des magnetischen Feldes θ_0. Die höchste SSM-Dicke, bei der eine Perkolation möglich wäre, liegt bei $\theta_0 > 90°$, d.h. bei einem südlich orientierten interplanetaren Magnetfeld (IMF). Realistische asymmetrische SSMs sind wahrscheinlich dünner bei nördlich als bei südlich orientierten IMF. Für ein nördlich orientiertes IMF sind die SSM voraussichtlich dünner bei höheren β-Werten der Magnetohülle.

1 Introduction

Study of the fine structure and dynamics of the magnetopause current layer (MCL) separating magnetosheath and magnetospheric plasmas is of fundamental importance in understanding mechanisms of transport of solar wind energy, momentum and particles through the magnetopause boundary. The simplest model of the MCL is roughly described by a one-dimensional tangential discontinuity (TD) of finite thickness within which the magnetic field rotates from an arbitrary interplanetary direction to the magnetospheric direction. In a global sense it means that the MCL represents a smooth transition between open magnetosheath field lines and closed magnetospheric field lines. Equilibrium Vlasov models of steady state TDs received a great deal of attention beginning in the early sixties, see, e.g., *Grad* [1961], *Harris* [1962], *Nicholson* [1963], *Sestero* [1964, 1966], *Alpers* [1969], *Kan* [1972], *Roth* [1976-1983], *Lemaire and Burlaga* [1976], *Channell* [1976], *Lee and Kan* [1979], *Roth et al.* [1990].

A single plasma particle of species ν (having electric charge e_ν and mass m_ν) in a one dimensional TD parallel to the y-z plane is characterized by three constants of motion: the Hamiltonian ($H_\nu = m_\nu v^2/2 + e_\nu \phi$) and the y and z components of the canonical momentum ($P_{\nu y} = m_\nu v_y + e_\nu a_y/c$ and $P_{\nu z} = m_\nu v_z + e_\nu a_z/c$). The most generally used way to solve the time independent Vlasov equation is to introduce single-valued velocity distribution functions F_ν in the $(H_\nu, P_{\nu y}, P_{\nu z})$ space. The partial number densities n_ν and the y and z components of the partial current densities $J_{\nu y}$ and $J_{\nu z}$ can then be obtained after integrating the distribution functions $f_\nu(v_x, v_y, v_z, a_y, a_z, \phi) = F_\nu(H_\nu, P_{\nu y}, P_{\nu z})$ over velocity space (v_x, v_y, v_z) as functions of the electrostatic potential $\phi(x)$ and the y and z components of the vector potential $a_y(x)$ and $a_z(x)$. The charge density $\sigma = \sum e_\nu n_\nu$ and the y and z components of the total current density $J_y = \sum J_{\nu y}$, $J_z = \sum J_{\nu z}$ are then substituted into Maxwell's equations, leading to a set of coupled second order differential equations for $\phi(x)$, $a_y(x)$ and $a_z(x)$

$$\frac{d^2\phi}{dx^2} = -4\pi\sigma(\phi, a_y, a_z) \tag{1}$$

$$\frac{d^2 a_{y,z}}{dx^2} = -\frac{4\pi}{c} J_{y,z}(\phi, a_y, a_z) \tag{2}$$

The differential equation for $\phi(x)$ is usually replaced by the quasi-neutrality condition

$$n(x) = \sum_{\nu=\nu_+} Z_\nu n_\nu = \sum_{\nu=\nu_-} n_\nu' \tag{3}$$

where ν_+ correspond to ion populations and ν_- to electron populations, $Z_\nu e_\nu$ is the ion charge ($Z_\nu = 1$ for protons). In the general case, the number of ion and electron populations can be arbitrarily large. All particle populations can be subdivided into three groups associated with each of the two sides of the transition, called the "outer" regions, and its "inner" region. For magnetopause modeling it is reasonable to introduce magnetosheath, magnetospheric, and trapped (i.e. inner MCL) populations.

The density of magnetosheath particles tends to zero on the magnetospheric side ($x \to +\infty$), while the density of magnetospheric particles tends to zero on the magnetosheath side ($x \to -\infty$). The inner (or trapped) populations are confined inside the current layer, their density having a maximum inside the MCL and tending to zero on both sides ($x \to \pm\infty$). The inner population is especially important in MCLs with large magnetic shear.

The dependence of the velocity distribution function on H_ν is usually introduced in a Maxwellian form

$$F_\nu = s_\nu (m_\nu/2\pi T_\nu)^{3/2} \exp(-H_\nu/T_\nu) \mathcal{G}_\nu(P_{\nu y}, P_{\nu z}) \tag{4}$$

that corresponds to Poisson distributions of the partial number densities in the electrostatic potential

$$n_\nu(\phi, a_y, a_z) = s_\nu \exp(-e_\nu \phi/T_\nu) g_\nu(a_y, a_z) \tag{5}$$

$g(a_y,a_z) = \pi^{-1} \int \exp\{-(v_{\nu y}^2 + v_{\nu z}^2)\} \mathcal{G}_\nu(P_{\nu y}, P_{\nu z}) dv_{\nu y} dv_{\nu z}$, $v_{\nu y,\nu z}^2 = (m_\nu/2T_\nu) v_{y,z}^2$. The functions $\mathcal{G}_\nu(P_{\nu y}, P_{\nu z})$ represent cutoff factors in phase space to describe the fact that charged particles from one side cannot penetrate arbitrarily deeply into the other side of the current layer and that trapped particles are confined inside it. The form of $\mathcal{G}(P_{\nu y}, P_{\nu z})$ determines the gradient scale D_ν of the partial current density of the ν'th species

$$J_{\nu y,\nu z}(\phi, a_y, a_z) = cT_\nu(\partial n_\nu/\partial a_{y,z})$$

An isotropic Maxwellian distribution (with zero current velocity) corresponds to $\mathcal{G}_\nu = 1$. The spatial variation of the density of such a population can only be controlled by the nonuniform electrostatic potential profile (that is, by the equilibrium electric field, E_x, inside the layer).

The well known analytical Harris distribution, modified by a superposed constant $B_y = B_{0y}$ magnetic field component, is

$$\mathbf{B} = B_0 \tanh \frac{x}{L} \mathbf{e}_z + B_{0y} \mathbf{e}_y \tag{6}$$

$$a_z = -B_{0y} x, \quad a_y = LB_0 \ln(\cosh(x/L))$$

It is described by trapped populations of protons and electrons with $\mathcal{G}(P_{\nu y}, P_{\nu z}) = \exp(-m_\nu u_\nu^2/2T_\nu + u_\nu P_{\nu y}/T_\nu)$ corresponding to Maxwellian distribution functions shifted by the diamagnetic drift velocity in the y direction ($u_\nu = -2cT_\nu/e_\nu B_0 L$): $F_\nu = n(x)$ $(m_\nu/2\pi T_\nu)^{(3/2)} \exp\{-m_\nu[v_x^2 + (v_y - u_\nu)^2 + v_z^2]/2T_\nu\}$ ($n(x) = n_0 \cosh^{-2}(x/L)$). Other forms of trapped distributions were introduced in the papers by *Nicholson* [1963] and *Roth* [1978, 1980].

The cutoff factors $\mathcal{G}_\nu(P_{\nu y}, P_{\nu z})$ for magnetosheath and magnetospheric populations are usually chosen in the form of step functions (e.g., *Sestero* [1964, 1966], *Roth* [1976, 1980]) or error functions (e.g., *Alpers* [1966], *Lee and Kan* [1979]) because they lead to relatively simple analytical expressions for the moments n_ν, $J_{\nu y}$, and $J_{\nu z}$ of the distribution functions. The choice of error functions allows one to introduce arbitrary gradient scales $D_\nu \geq \rho_\nu$ (ρ_ν is the gyroradius of the ν'th species). Even for step-like cutoffs the characteristic thickness of the TD can not be less than one electron gyroradius $\rho_{\nu-} = \rho_e$ (in electron-dominated layers, where ions are isotropic, i.e. $\mathcal{G}_{\nu+} = 1$, and the electric current is only carried by electrons), or one ion gyroradius $\rho_{\nu+} = \rho_i$ (in ion-dominated layers, where the electric current is carried by ions). However, in symmetrical transitions of the

Harris type (6), the minimum thickness can approach the Debye length. In the general case the characteristic thickness of the transition is determined by the gradient scales D_ν of all populations collectively. Thin electron layers appear to be extremely unstable (see, e.g., *Drake et al.* [1994]; *Drake*, this volume), so below we will only consider layers with characteristic thickness of a few ion gyroradii. The choice of functions $\mathcal{G}_\nu(P_{\nu y}, P_{\nu z})$ is of course not unique.

In summary, the existing one-dimensional Vlasov models can be characterized by the following set of attributes:

• The number of different particle populations (magnetosheath, magnetospheric, and inner). For instance, the models by *Harris* [1962] and *Nicholson* [1963] include only inner (i.e., trapped) populations of electrons and protons, while *Sestero* [1964, 1966] and *Alpers* [1969] introduced only magnetosheath and magnetospheric particles without trapped populations. Both "inner" and "outer" populations were incorporated by *Lee and Kan* [1979]. Multi-species plasma with different densities, ion charges and temperatures (including asymptotic temperature anisotropies) were considered by *Lemaire and Burlaga* [1976] and *Roth* [1978, 1980].

• Assumptions about the charge neutrality and the electric field within the layer.

• The form of the cutoff functions $\mathcal{G}_\nu(P_{\nu y}, P_{\nu z})$ and corresponding gradient scales D_ν that control the thickness of the MCL.

• The degree of asymmetry in boundary conditions that can be described by the model (e.g., the velocity shear; the angle of magnetic field rotation, θ_0; density and temperature asymmetries). For instance, models by *Sestero* [1966] and *Roth* [1976], where velocity shear was taken into account imply unidirectional magnetic fields ($\theta_0 = 0$). The model by *Alpers* [1969] without inner populations can only describe MCLs with zero velocity shear and small magnetic shear ($\theta_0 < 90°$). The unified model by *Lee and Kan* [1979] can describe asymmetric MCLs with zero velocity shear and arbitrary magnetic shear (including $\theta_0 > 90°$) as well as MCLs with finite velocity shear and small magnetic shear ($\theta_0 < 90°$), but due to different formalisms for inner and outer populations their model is unable to describe MCLs with both velocity shear and large magnetic shear ($\theta_0 > 90°$).

A generalized one-dimensional kinetic multi-species model of MCLs was developed recently by *Roth, De Keyser and Kuznetsova* [Belgian Institute for Space Aeronomy, preprint, 1994]. In this model all particle populations (from both outer regions and from inside the layer) are described using a unique formalism for the velocity distribution functions. Most of the previous models can be retrieved as special cases. The model also describes current layers with velocity shear and large angles of magnetic field rotation.

Such multi-species models with a large number of free parameters and different gradient scales could in principle illustrate many observable features of the MCL, including its multiscale fine structure. However a number of problems associated with the one-dimensional, time-independent Vlasov approach should be kept in mind:

• Vlasov theories of plane tangential discontinuities yield nonunique solutions because particle distribution functions are assigned arbitrarily in different regions of phase space.

• Time-independent plane TD models do not provide a complete solution to the problem of particle accessibility, both to the current layer itself, and, more specifically, to different phase space regions [*Whipple et al.*, 1984]. Stationary plane Vlasov configurations are supposed to be formed from remote plasma source regions by suitable transport across magnetic field lines. A possible way to solve the particle accessibility problem is to consider the temporal behavior of the sheath and introduce two (or three) dimensional "degrees of freedom".

- The large number of free parameters obscures the relation between boundary conditions and the internal structure of the layer.
- One-dimensional current layers with magnetic shear are thermodynamical nonequilibrium systems that have an excess of free energy and are potentially unstable with respect to the excitation of large scale electromagnetic perturbations, resulting in the destruction of magnetic surfaces. Therefore, MCLs most likely are in a state of turbulence rather than in a state of one-dimensional Vlasov equilibrium.

Therefore, a reasonable application of these one-dimensional Vlasov models is to adopt them as an initial unperturbed state and then consider the temporal and spatial evolution of the system caused by superposed perturbations.

In section 2, we consider several simple models of MCLs of finite thickness (with a minimum number of free parameters) to illustrate the effects of asymmetrical boundary conditions (velocity shear, density gradient) on the internal structure of the current layer. In section 3, the free energy and the "energy level" of large-scale, adiabatic electromagnetic perturbations is evaluated and a way is discussed to reduce the number of free parameters of the initial configuration. In section 4, the stochastic percolation model by *Galeev et al.* [1986] is reviewed and the thresholds for the formation of percolated magnetic filaments are generalized to the case of asymmetrical MCLs. Qualitative conclusions concerning the probable fine structure and thickness of the MCL are presented in section 5.

2 Harris Equilibrium Modified by Asymmetrical Boundary Conditions

Let us assume that, in a first approximation, the MCL can be modeled as a one dimensional TD which separates two plasmas with number densities N_1 and N_2, temperatures T_{i1}, T_{e1} and T_{i2}, T_{e2}, bulk flow velocities $\mathbf{V}_1(0, 0, V_{1z})$ and $\mathbf{V}_2(0, 0, V_{2z})$ and magnetic fields $\mathbf{B}_1(0, B_{1y}, B_{1z})$ and $\mathbf{B}_2(0, B_{2y}, B_{2z})$ (subscript "1" corresponds to the magnetosheath side $x \to -\infty$, subscript "2" to the magnetospheric side $x \to +\infty$, subscript "i" corresponds to ions and subscript "e" to electrons). The TD is assumed to be parallel to the (y, z) plane so that all plasma and field variables depend only on the x coordinate normal to the layer. We also choose the coordinate system in such a way that B_z is equal to zero in the center of the MCL ($x = 0$), but has opposite signs on its outer edges ($B_z < 0$ for $x < 0$, $B_z > 0$ for $x > 0$), while B_y remains everywhere positive. In this configuration, the total angle of the magnetic field rotation $\theta_0 \leq 180°$ is then given by

$$\theta_0 = \mathrm{arctg}(|B_{1z}|/B_{1y}) + \mathrm{arctg}(|B_{2z}|/B_{2y})$$

This approach is not able to described magnetic field rotations greater than 180° which according to *Berchem and Russell* [1982b] are seldom observed.

2.1 2.1 Effect of Relative Flow Velocity

To illustrate the modifications of the Harris neutral sheet (configuration (6) with $B_{y0} \ll B_0$) separating magnetosheath and magnetospheric plasma with nearly antiparallel magnetic fields (θ_0 close to 180°) by the flow asymmetry *Kuznetsova et al.* [1994] suggested to consider a simple equilibrium which is a combination of the models of *Harris* [1962] and *Sestero* [1966]. To illustrate effects of the relative flow velocity an isothermal plasma is considered (T_{i1}=T_{i2}=T_i=T_e=T_{e1}=T_{e2}=1 keV) and the absolute value of the magnetic fields is assumed to be equal on both sides of the transition ($|B_{1z}|$=$|B_{2z}|$=B_0 = 60nT, B_{1y}=B_{2y}=B_{0y}=0.08B_0). We also choose the coordinate system in which the bulk flow velocity, directed along the z axis, has an antisymmetric profile, that is, V_{1z}=U=$-V_{2z}$. The structure of the configuration is only determined by the flow asymmetry factor $u = U/u_i$, where u_i is the ion diamagnetic drift velocity. The configuration reduces to the Harris plane neutral sheet (with B_{0y}=0.08B_0, i.e., $\theta_0 \approx 170°$) when the factor u tends to zero.

Fig. 1 illustrates the structure of the MCL for two different positive u values. It is seen that the relative flow velocity results in the generation of a strong B_y component in the center of the layer ($B_y(0) \gg B_{0y}$). For u = 2 $B_y(0)$ becomes comparable with B_0. Therefore, in the presence of a shear flow in the MCL with $\theta_0 \rightarrow 180°$, the magnetic field is expected to rotate from one direction to another, rather than to change its sign only. For negative u the bulk flow velocity has a nonrealistic oscillating profile inside the current layer. However simultaneous change of the sign of B_{0y} and u (which is equivalent to change of the coordinate system, $y \rightarrow -y$, $z \rightarrow -z$) corresponds to configurations similar to those shown in Fig. 1.

Therefore for $\theta_0 \rightarrow 180°$ the sense of magnetic field rotation is likely to be related with the direction of the flow in the magnetosheath, i.e., it should be opposite in the northern and southern hemispheres. Experimental data, discussed by *Sonnerup and Cahill* [1968] and *Su and Sonnerup* [1968], appear consistent with this prediction.

2.2 Effect of Asymmetrical Magnetic Fields

The modification of the Harris equilibrium by an asymmetrical magnetic field is considered in detail in the paper by *Kuznetsova and Roth* [1994], where the velocity shear is neglected and the plasma is assumed to be isothermal (i.e., the temperature T_i = $4T_e$ = 1 keV is assumed to be independent of x). In this study, three proton and two electron populations are introduced and two groups of Vlasov equilibria are illustrated. The first group (referred to as case I) corresponds to situations where an increase of the thermal pressure in the magnetosheath (B_1 = 40nT is fixed) causes an earthward displacement of the MCL (B_2 is increasing, N_2 = 0.1cm^{-3} is fixed). Magnetic field hodograms and number density profiles for fixed B_1 =40 nT and different values of B_2 and θ_0 are shown in the left columns of Figs. 2 and 3. The second group (referred to as case II) corresponds to situations where the positions of the MCLs are fixed (B_2 = 80nT and N_2 = 0.1cm^{-3} are fixed), while any increase of the thermal pressure in the adjacent magnetosheath results in a corresponding reduction of the magnetic pressure (B_1 is decreasing). Magnetic field hodograms and number density profiles for fixed B_2 = 80 nT and different values of B_1 and θ_0 are

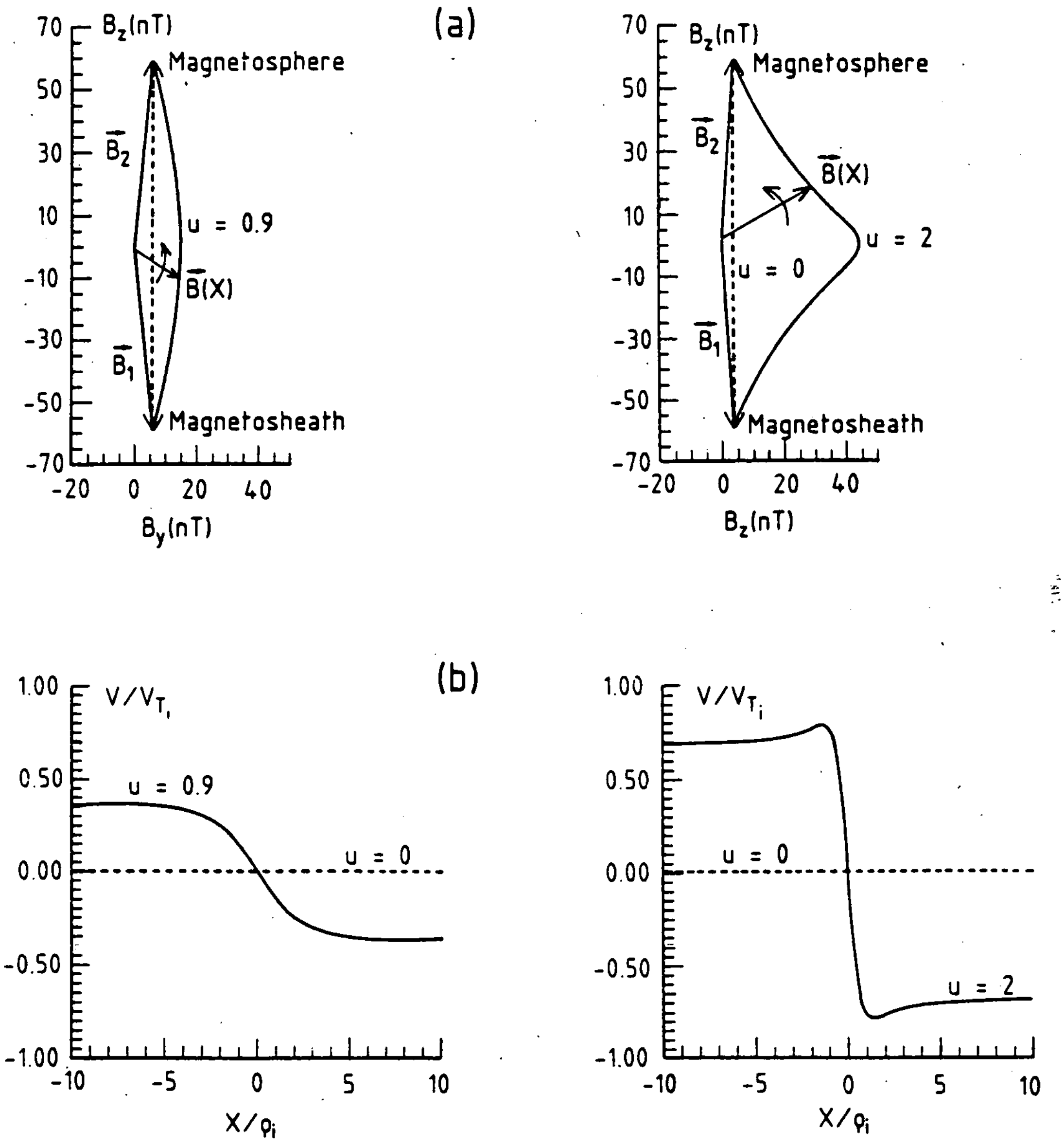

Figure 1: Structure of the magnetopause current layer for different flow asymmetry factors $u = U/u_i$ ($u = 0.9$ in the left column, $u = 2$ in the right column), $|B_1| = |B_2| = 60$nT, $T_i = T_e = 1$keV, $\theta_0 = 170°$. Harris profiles, corresponding to $u = 0$, are shown by the dashed lines. (a): Hodogram of the magnetic field; (b): Bulk flow velocity normalized by the ion thermal velocity as a function of the distance x/ρ_i from the center of the layer, where $\rho_i = 54$km is the ion Larmor radius in the asymptotic magnetic field.

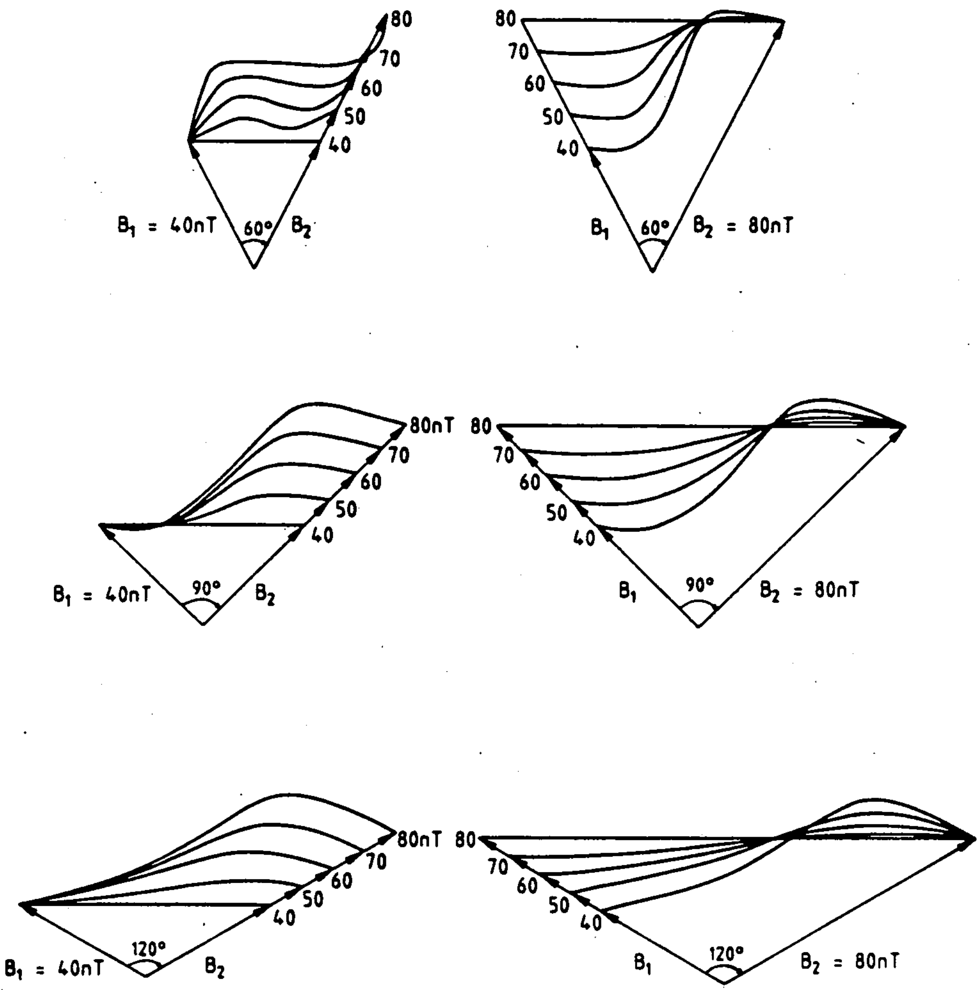

Figure 2: Hodograms of **B** through the MCL for different values of B_1, B_2 and θ_0.

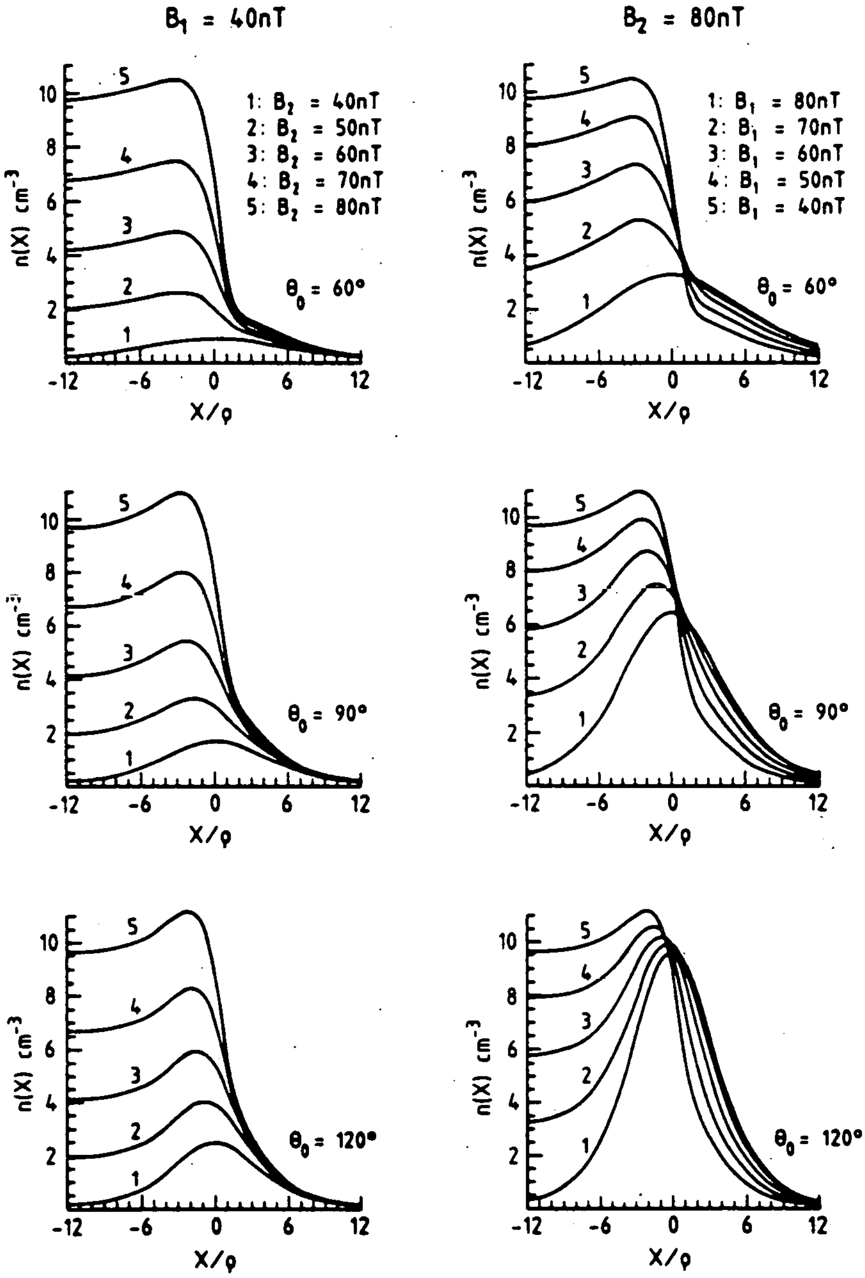

Figure 3: Number density profiles $n(x)$ (cm^{-3}) corresponding to the magnetic field hodograms shown on Fig. 2.

shown in the right columns of Figs. 2 and 3. The number density profiles in Fig. 3 are illustrated as a function of the distance x/ρ from the center of the layer $x = 0$, where $\rho = c(2T_i m_i)^{1/2}/eB^*$ is a typical ion Larmor radius (T_i = 1keV, B^* = 40 nT).

In both groups, the internal structure of the MCL depends on two parameters characterizing the magnetic field asymmetry, that is, the asymmetry factor $\kappa_B = (B_2 - B_1)/B_2$ and the angle of the magnetic field rotation θ_0. These parameters determine in particular the plasma density and the magnetic field in the center of the layer. When the asymmetry factor κ_B tends to zero the configuration reduces to the symmetrical Harris equilibrium (6) with a rarefied uniform background. The peak in density in the center of the layer is associated with the trapped populations (the relative contribution of which to the total number density increases with increasing angle θ_0) and is likely to be a general feature of an isothermal current sheet with large magnetic shear. It is seen that the introduction of asymmetry in case I (the left column) significantly modifies the number density in the center of the layer, while in case II (the right column) the number densities at $x = 0$ are only slightly different for various asymmetry factors.

3 "Energy Level" of Adiabatic Perturbations

Generalized models of TDs usually introduce a large number of free parameters which are not determined by the boundary conditions. One such parameter is the electrostatic potential drop across the layer. We now discuss a procedure that could help to reduce this uncertainty.

Let us introduce a three-dimensional "degree of freedom" into the configuration in the form of periodic perturbations of vector and scalar potentials. Such perturbations can be described by small variations $\tilde{A}_y$,$\tilde{A}_z$, $\tilde{\varphi} \sim \exp(ik_z z + ik_y y)$ superposed on the equilibrium vector and scalar potentials a_y, a_z and ϕ: $A_y = a_y + \tilde{A}_y$, $A_z = a_z + \tilde{A}_z$, $\varphi = \phi + \tilde{\varphi}$. Taking into account the approximate gauge condition $\mathbf{k} \cdot \mathbf{A} = 0$ it is convenient to introduce the scalar quantity $A = A_\parallel = (k_z \tilde{A}_y - k_y \tilde{A}_z)/k$, which corresponds to the component of the vector potential parallel to the local direction of the magnetic field near the so-called singular magnetic surface x_s, where $\mathbf{k} \cdot \mathbf{B}(x_s) = 0$ (i.e., $B_z(x_s)/B_y(x_s) = -k_y/k_z$).

We assume that adiabatically perturbed electric current and number densities can be expressed as functions of φ, A_y, and A_z and expanded in Taylor series for $\tilde{A}_y \ll a_y$, $\tilde{A}_z \ll a_z$, $\tilde{\varphi} \ll \phi$. The linearized Maxwell equations and quasi-neutrality condition can then be reduced to an eigenmode equation of Schrödinger's type

$$(d^2A/dx^2) - (k^2 + V_0)A = 0 \tag{7}$$

where

$$V_0 = -\frac{4\pi}{k^2}\left[\hat{a}^2 G + \frac{1}{\alpha}\left(\hat{a}\frac{\partial G}{\partial \phi}\right)^2\right], \quad \hat{a} = k_z\frac{\partial}{\partial a_y} - k_y\frac{\partial}{\partial a_z}$$

and

$$G(a_y, a_z, \phi) = \sum_\nu n_\nu T_\nu, \quad \alpha(a_y, a_z, \phi) = e^2 \sum_\nu \frac{n_\nu}{T_\nu}$$

The solution of equation (7), satisfying the natural boundary conditions $A(x \rightarrow \pm\infty) \rightarrow \exp(\mp kx) \rightarrow 0$, has a jump of the logarithmic derivative $R(x) = (d\ln A/dx)$ at $x = x_S$

$$\Delta'(x_S, k) = R^+(x \rightarrow x_S + 0) - R^-(x \rightarrow x_S - 0) \tag{8}$$

which is proportional to the excess free energy that could be released by current filamentation in the vicinity of the singular surface. This term depends on the form of the equilibrium distribution functions and contains information about the global distribution of plasma and magnetic field in the layer.

For the symmetrical Harris configuration (6) the "potential well" V_0 takes the simple form [*Furth et al.*, 1963]

$$V_0 = B_z''/B_z = -2(k_z/kL)^2 \cosh^{-2}(x/L)$$

and equation (7) can be solved analytically. The analytical expression for $\Delta'(x_s, k)$, at an arbitrary magnetic surface x_s within the symmetrical configuration (6), in terms of associated Legendre functions is presented in the paper by *Kuznetsova and Zelenyi* [1985]. For $x_s = 0$ this expression reduces to the well-known formula $\Delta' = (1 - k^2L^2)/kL$ [*Laval et al.*, 1966].

In a general asymmetrical case, the solution of the eigenmode equation (7) and the corresponding jump of the logarithmic derivative (8) can be obtained numerically (see *Kuznetsova and Roth* [1994]).

When $\Delta'(x_s, k = k_*) = 0$ the solution of equation (7) is smooth at $x = x_S$. The corresponding eigenvalue ${k_*}^2$ of the Schrödinger-type equation (7) may be thought of as an "energy level", $\mathcal{E}_k = {k_*}^2$, of adiabatic perturbations at $x = x_S$. For instance, at the plane of symmetry, $x_S = 0$, of the Harris configuration (6) we have $\mathcal{E}_k = 1/L^2$.

The integral value

$$\bar{\mathcal{E}}_k = \int \mathcal{E}_k(x_S)\, dx_S \tag{9}$$

depends on the form of equilibrium distribution functions F_ν (that is, on free parameters of the model controlling the internal structure of the layer). It is reasonable to assume that the most favorable free parameters of the model, related to the most stable configuration (among those with the same thickness and boundary conditions), correspond to the minimum value of $\bar{\mathcal{E}}_k$. This gives us a method to reduce arbitrariness and to determine some properties of the internal structure of the MCL (e.g., the electrostatic potential drop across the layer).

4 Percolated Magnetic Filaments. Marginal Thickness of Asymmetrical MCLs

When $\Delta'(x_s, k) > 0$ (for $k < k_*$) the magnetic surface x_S has an excess of free energy with respect to the excitation of the drift tearing perturbations $A_\parallel, \tilde{\varphi} \sim \exp(-i\omega t + ik_y y + ik_z z)$ with wavelength $2\pi/k$ and wave vector perpendicular to the local direction of the equilibrium magnetic field ($\mathbf{k} \cdot \mathbf{B} = 0$). Whether this tendency will be realized depends on other contributions to the energy-balance condition associated with the temporal evolution of the layer ($\partial/\partial t \sim -i\omega$) and with irreversible nonadiabatic interaction of resonant particles with perturbations in some small vicinity of the x_s plane, where $k_{\parallel} = (\mathbf{k} \cdot \mathbf{B}/B)$ is small and the inductive and potential part of the parallel electric field $E_{\parallel} = (i\omega/c)A_{\parallel} - ik_{\parallel}\tilde{\varphi}$ cannot compensate each other.

The linear and nonlinear dynamics of the collisionless drift tearing mode has been thoroughly investigated by a number of authors (e.g., *Galeev and Zelenyi* [1977], *Drake and Lee* [1977], *Coppi et al.* [1979], *Quest and Coroniti* [1981], *Kuznetsova and Zelenyi* [1985, 1990*a,b*], *Gladd* [1990]). The linear stability analysis shows that the drift tearing mode can be stabilized due to its coupling with ion sound waves. The analysis of the nonlinear dynamics of the drift tearing mode (in the single mode approach) shows that the growth of the magnetic islands saturates when their half width approaches the ion Larmor radius [*Kuznetsova and Zelenyi*, 1990b] which, according to *Berchem and Russell* [1982a], is much less than the thickness of the MCL. The principal conclusion from this result is that the destruction of a single magnetic surface cannot lead to macroscopic reconnection of magnetosheath and magnetospheric magnetic fields.

A stochastic percolation model based on these studies has been suggested by Galeev, Kuznetsova and Zelenyi, hereafter referred to as the GKZ model [*Galeev et al.*, 1986]. In this model, reconnection was considered as an irregular multiscale process associated with the magnetic field diffusion caused by the self-consistently generated magnetic turbulence. If the distance between the singular magnetic surfaces corresponding to unstable modes is less than the ion Larmor radius, the overlap of magnetic islands growing on neighboring magnetic surfaces results in stochastic wandering of magnetic field lines from one magnetic surface to another [*Rosenbluth et al.*, 1966]. This stochastic process leads to the formation of percolated magnetic filaments which connect the two sides of the current layer via an irregular path [*Galeev et al.*, 1986, Figure 1*a*]. Results of particle simulations of magnetic field line stochasticity due to the growth and overlapping of multiple tearing mode islands within a symmetrical current layer, reported recently by *Wang and Ashour-Abdalla* [1994], support the GKZ percolation model.

If regions of stable magnetic surfaces wider than the ion gyroradius exist within the MCL, the stochastic wandering of magnetic field lines does not result in percolation, i.e., the topological connection of magnetosheath and magnetospheric field lines is absent [*Galeev et al.*, 1986, Figure 1*b*]. Therefore the necessary condition for magnetic percolation through the MCL appears to be the destruction of all magnetic surfaces within it. This condition imposes a bound on the thickness of the MCL, required for the formation of reconnection "patches" with characteristic spatial scales along the magnetopause $\lambda_z \times \lambda_y \sim \lambda_{ext}^2$.

The energy balance equation for the tearing mode development can be represented in the following form

$$\Delta' = U_e + U_i \tag{10}$$

The right-hand side of equation (10) is a total non-adiabatic response which is proportional to the perturbed electric field work upon the singular current ($J_{\parallel} = \sigma_{\parallel} E_{\parallel}$). The values of these terms are controlled by the local values of the magnetic field and electron density in the vicinity of the singular surface $x = x_s$. The term U_e describes the irreversible increase of resonant electron energy. The term U_i is the energy expenditure for the excitation of field-aligned ion oscillations, which carry the wave energy away from the interaction region (where $k_{\parallel} \sim 0$) and slow down the growth of the electron drift tearing mode. At the stability threshold, the energy of ion-sound oscillations is exactly equal to the free energy of the instability, i.e., $U_i = \Delta'$.

The integral expressions for nonadiabatic contributions U_e and U_i for the general case and the numerical solution of the marginal condition $\Delta' = U_i$ for the sets of equilibria illustrated in section 2.2 are presented in the paper by *Kuznetsova and Roth* [1994]. It is shown that the "most unstable" magnetic surfaces (i.e., those with the widest wavelength range of unstable modes) are located close to the maxima of the number density profiles where the stabilizing influence of the coupling with ion field-aligned oscillations appears to be inefficient. On the contrary, the "most stable" magnetic surfaces (where the marginal wavelength for the instability is maximal) are located in regions with the strongest density gradients, where drift effects are the most prominent and where perturbations are strongly coupled with ion sound oscillations.

One can assume that the characteristic spatial scale along the magnetopause, λ_{ext}, is determined by external conditions (the size of the magnetopause, the convection pattern in the magnetosheath). The dependence of the dimensionless marginal magnetopause characteristic thickness L_0^{cr}/ρ on θ_0 for $\lambda_{ext} = 90\rho \approx$ 10,000 km and different κ_B is shown in Fig. 4. A MCL of thickness less than the marginal one (L_0^{cr}) will be subject to percolation of magnetic field lines. The results shown on Fig. 4 represent the generalization of the GKZ model to the asymmetrical case. Note that for the symmetrical case ($\kappa_B = 0$, i.e., $B_1 = B_2$) the characteristic thickness L_0^{cr} shown in Fig. 4 is linked to the characteristic thickness L_0^{GKZ} used in the GKZ model ($L_0^{GKZ} = 2L$, where L is the half thickness of the Harris current sheet (6)) by the relation $L_0^{cr}/L_0^{GKZ} = \sin(\theta_0/2)$.

In the GKZ model, northward orientation of the IMF was found to be optimum for the percolation, that is, the maximum thickness of Harris-type layers subjected to percolation is achieved for $\theta_0 < 90°$. The introduction of asymmetry $\kappa_B \neq 0$ in the magnetic field helps overcome this seeming contradiction with experimental data [*Berchem and Russell*, 1984; *Southwood et al.*, 1986]. When $\theta_0 < 90°$, it can be seen that even for small values of the asymmetry factor ($\kappa_B \geq 0.15$) the marginal thickness L_0^{cr} is significantly decreased, that is, only thin MCLs can be subject to percolation. Therefore the most favorable angle for percolation (θ_0^*) is shifted to larger values: $\theta_0^* > 90°$ (southward IMF). The larger the asymmetry factor κ_B, the larger the angle θ_0^*. For very asymmetrical MCLs ($\kappa_B \geq 0.4$), $\theta_0^* \geq 120°$.

5 Discussion and Conclusions

The kinetic analysis discussed above enables us to draw a number of qualitative conclusions about the magnetopause thickness and structure.

If the MCL thickness is much larger than the marginal one, a large domain of stable magnetic surfaces should exist within it, which should prevent particles diffusion across the layer. Note that microscopic plasma turbulence (e.g., lower hybrid drift instability [*Gary and Eastman*, 1979; *Winske et al.*, this volume; *Treumann et al.*, this volume] that

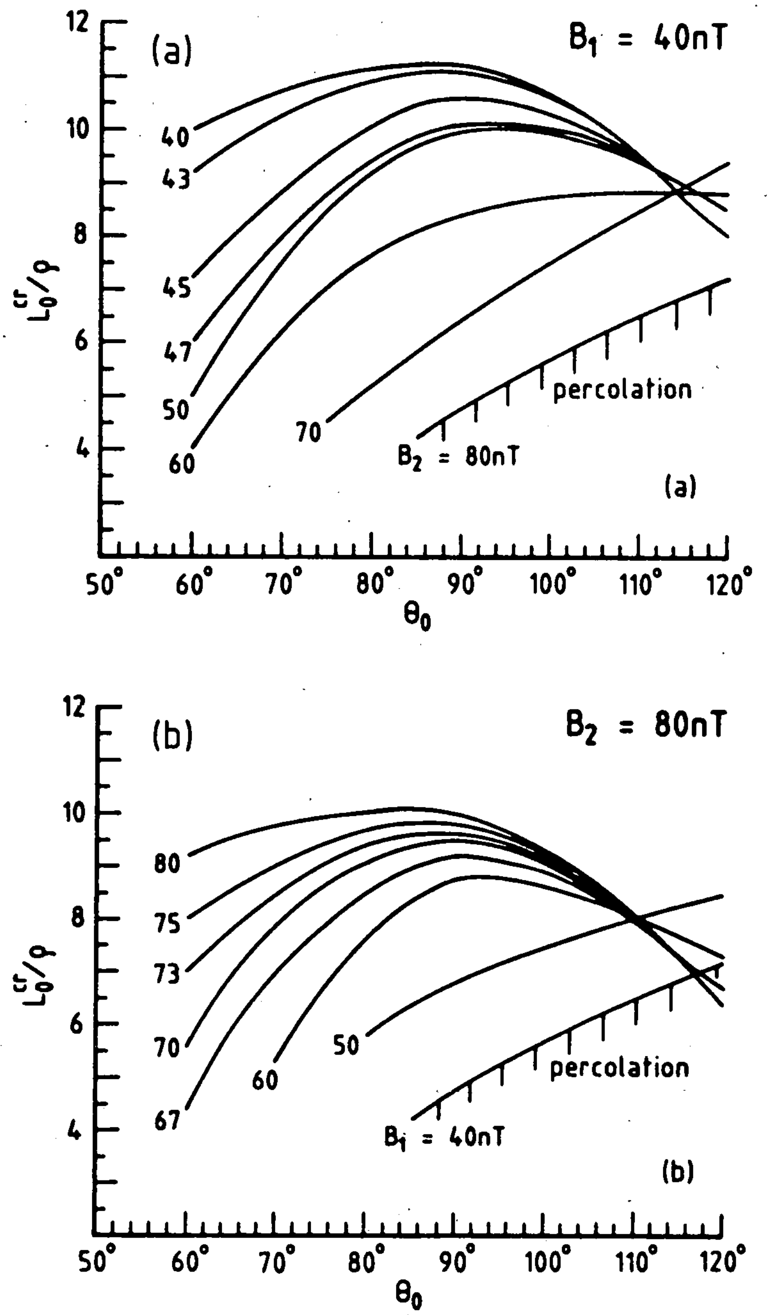

Figure 4: Dimensionless marginal magnetopause thickness L_0^{cr}/ρ, for typical spatial scale of the reconnection patch of $\lambda_{ext} = 90\rho \approx 10{,}000$ km, as a function of θ_0 for different values of B_1 and B_2. Here $\rho = c(2T_i m_i)^{1/2}/eB^* \sim 115$ km is a typical ion Larmor radius (T_i = 1keV, $B^* = 40$ nT). (a) case I (B_1=40nT and N_2=0.1cm^{-3} are fixed, B_2 is increasing from 40nT to 80nT); (b) case II (B_2=80nT and N_2=0.1cm^{-3} are fixed, B_1 is decreasing from 80nT to 40nT).

could provide diffusion when the magnetosheath and magnetospheric fields are parallel) is strongly stabilized by the magnetic shear when θ_0 is substantial. In this case a one-dimensional slab TD could be considered as a good model for the MCL, if one disregards the question of particle accessibility discussed by *Whipple et al.* [1984]. In other words, the process of formation of such a thick smooth slab configuration in the absence of transport mechanisms across the magnetic field, which could bring the plasma inside the transition, is still unknown.

When the thickness is close to the marginal value, the MCL can be modeled as a tangential discontinuity "spoiled" (in the first approximation) by embedded percolated magnetic filaments. In this case the MCL is likely to have a pore-like fractal structure, where percolated magnetic filaments (common for both sides of the MCL) are surrounded by closed magnetospheric and open magnetosheath field lines. The process of aggregation (self-organization) of these filaments into large-scale clusters (like FTEs) due to the attraction of field aligned currents is a challenging subject for future studies.

When the MCL thickness is much less than the marginal one, strong, large-scale magnetic turbulence develops within the layer. This turbulence creates a perfect "kinetic background" for turbulent magnetic reconnection models (e.g., *Galeev* [1991], *Tetreault* [1992]). The diffusive broadening of the symmetrical current layer when a large number of tearing modes are allowed to grow together was illustrated by *Wang and Ashour-Abdalla* [1994], using a three-dimensional particle simulation. It was shown that after the field lines become stochastic, the tearing modes which cause the stochasticity grow 2-3 times faster than in the linear stage. The diffusion coefficient was found to reach 10^9 m^2/s for typical magnetopause parameters which is in good agreement with quasi-linear analytical estimates $D_F = \sum(\tilde{B}_k^2/B^2)\pi\delta(k_{\parallel}(x)) \sim (\rho^3/L\lambda_{ext})\tan(\theta_0/2)$ [*Rosenbluth et al.*, 1966; *Galeev et al.*, 1986] as well as observationally based estimates [*Sckopke et al.*, 1981]. Recently it was shown [*Milovanov and Zelenyi*, this volume] that the taking into account of finite ion Larmor radius effects could appreciably enhance the stochastic diffusion rate across the magnetopause.

It is reasonable to assume that the curves shown in Fig. 4 qualitatively reflect the dependence of the characteristic magnetopause thickness (normalized on a typical ion Larmor radius $\rho = c(2T_i m_i)^{1/2}/eB^* \sim 115$ km for T_i = 1keV, B^* = 40 nT) on the angle θ_0 and the plasma beta in the magnetosheath (which for $N_2 \approx 0$ can be expressed through the asymmetry factor κ_B: $\beta = \kappa_B(2-\kappa_B)/(1-\kappa_B)^2$). One can see, that in realistic asymmetrical cases ($\kappa_B > 0.3$), the magnetopause should be thinner for $\theta_0 < 90°$ (northward IMF) than for $\theta_0 > 90°$ (southward IMF). For southward IMF ($\theta_0 > 90°$) the magnetopause thickness depends only slightly on κ_B and β. For northward IMF the magnetopause should be thinner for larger values of β in the magnetosheath.

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