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Two magnetized plasmas at the subsolar low shear magnetopause

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Abstract. A model of a current system generated by two different sorts of plasma at a boundary between nearly parallel magnetic fields is suggested. This system contains two current layers. In the case of a low shear magnetopause, the azimuthal currents in these layers are antiparallel (a current carried by the magnetosheath ions flows from noon to dusk, and a current created by the magnetospheric ions is directed from noon to dawn) and a negative spike in the northward component of the magnetic field arises at the magnetopause. This specific feature allows definition of the magnetopause location in the case of a low magnetic shear when the location of the magnetopause is not obvious. Model estimations allow us to compare the obtained results with observations and existing theoretical models.

1. Introduction

A goal of this paper is to study the current structure at the boundary between nearly parallel magnetic fields, that divides two different sorts of plasma. This situation arises, for example, at the low-shear subsolar magnetopause.

The magnetopause is a complex plasma boundary that consists of both field and plasma transitions. Various characteristics have been used to identify its crossing: The density change, the temperature change, and the current layer [*Le et al.,* 1994; *Russell,* 1995]. On the sunward side of the magnetopause the plasma is dense and cold, on the earthward side it is hot and tenuous. The typical density of the magnetosheath plasma is 5–10 times the magnetospheric density near the magnetopause; the magnetospheric plasma is 6–10 times hotter than the magnetosheath plasma [e.g., *Paschmann et al.,* 1993; *Phan et al.,* 1994; *Phan and Paschmann,* 1996]. For a northward interplanetary magnetic field (IMF), the plasma transition consists of multiple layers with relatively uniform structure inside each layer [*Song et al.,* 1990]. The plasma behavior depends on reconnection, which, in turn, is controlled by the IMF orientation [e.g., *Alexeev and Belenkaya,* 1989; *Belenkaya,* 1998a, 1998b; *Phan et al.,* 1996; *Russell,* 1995; *Sonnerup et al.,* 1981]. When the IMF is northward, reconnection occurs at high latitudes inside the magnetosphere, near the cusps; when the IMF is southward, reconnection takes place at the low-latitude magnetopause.

The magnetopause is nonstationary and it moves with substantial speed of the order of 10 km s^{-1} or more [*Berchem and Russell,* 1982a]. *Paschmann et al.* [1993] found the average magnetopause speed for low magnetic shear conditions to be about 11 km s^{-1}. Due to the magnetopause motion, its observations are rather difficult. Nevertheless, much progress in the study of the magnetosheath–magnetopause low-latitude boundary layer structure is obtained due to ISEE, AMPTE/IRM, AMPTE/CCE, and GEOTAIL missions [*Berchem and Russell,* 1982a, 1982b; *Eastman et al.,* 1996; *Mitchell et al.,* 1987; *Phan and Paschmann,* 1995, 1996; *Phan et al.,* 1994, 1996; *Russell,* 1995].

The change of the magnetic field across the magnetopause is associated with a current layer, or current region. There are a lot of questions about the structure of the magnetopause and in particular about the thin current layer that is sometimes considered to be the magnetopause. *Berchem and Russell* [1982a] found that the thickness of the magnetopause current layer does not depend on the magnetic shear and is approximately equal to 800 km; near the magnetic equator the magnetopause current sheet is thinnest, about 500 km on average. According to *Phan and Paschmann* [1996], the distribution of thicknesses of the current flow region for the high shear has a peak at 250–500 km. *Van Allen and Ad-*

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nan [1992] found that the magnetopause current sheet width varies from 30 km to 850 km with a mean value of 185 km $\approx$0.03 R_E. *Eastman et al.* [1996] noted that the overall magnetopause current layer is one or a few ion gyroradii in thickness. *Berchem and Russell* [1982a] wrote that the parameters typical of experimental particles and magnetic field measurements [*Paschmann et al.,* 1978] give a predicted gyroradius or "magnetopause thickness" of between close to 1 and 100 km for 10^6 K electrons and 10^7 K protons in a 40 nT average magnetic field.

Also well recognized is the important sensitivity of the structure of the magnetopause on the direction of the interplanetary magnetic field. For southward IMF, a magnetopause current layer is identified as the major rotation of the magnetic field. For northward IMF, the magnetosheath and magnetospheric orientations are locally similar, so the magnetopause is hardly identified. This present paper is devoted to study of this structure. As the magnetopause is the interface between the shocked solar wind plasma and the Earth's magnetosphere, the physical processes operating at it can influence both the magnetosheath and magnetospheric global features.

2. Theoretical Approaches to the Problem of the Magnetopause

Since the 1930s, considerable interest has been focused on the structure of the magnetopause *Chapman and Ferraro* [1931a, 1931b, 1932, 1933, 1940] investigated the interaction of an unmagnetized solar wind plasma flow with the Earth's dipole.

Lee and Kan [1979a] have classified models of the magnetopause into three categories: (1) current sheet models separating two vacuum magnetic field regions, (2) current sheet models separating an unmagnetized plasma on one side from a vacuum magnetic field on the other side, and (3) current sheet models separating two magnetized plasmas (see references in [*Lee and Kan*, 1979a]). Measurements have shown that only the models of class 3 are realistic.

To the third class of current sheet models, for example, the works by *Sestero* [1964, 1966], *Lee and Kan* [1979a, 1979b], and *Roth* [1976, 1978, 1979] are related. *Sestero* [1966] noted that the state of the plasma at the end of transition region does not uniquely determine the transition profile. This is a peculiar feature of the nonlinear Vlasov equation, and as a result, that the problem is not uniquely determined. In *Sestero* [1964], the plasma is at rest on either side of the discontinuity; in *Sestero* [1966], two identical plasmas can move parallel to the discontinuity with respect to each other and perpendicular to the magnetic field lines. One set of solutions among the many possible is presented, that satisfies the same conditions at infinity: For equal asymptotic values for the temperature, density, and positive magnetic field, the magnetic field decreases in the transition region and the density increases [*Sestero,* 1966].

In the models considered in *Sestero* [1964, 1966] and *Roth* [1976], every physical quantity depends on one space coordinate, x; the magnetic field $\mathbf{B}$ points along the z axis; the velocity of shear, $\mathbf{V}$, is along the y axis. Any function of the constants of motion is a solution of the Vlasov equation.

Another work following *Sestero* [1964, 1966] is *Lee and Kan* [1979b]. The purpose of their paper was to point out the importance of the temperature ratio T_+/T_- (where T_+ is the temperature of the ions and T_- is the temperature of the electrons) in determining the structure of the transition layer between two magnetized plasmas. The authors found that the thickness of the layer is of the order of the gyroradius of the hotter ion species of the plasmas on the two sides. Plasma measurements show that the plasma temperatures on the two sides of the magnetopause are different and the ions are much hotter than the electrons (by a factor up to 10) [*Eastman and Hones,* 1979]. This explains the observed magnetopause thickness of the order of the ion gyroradius [*Lee and Kan,* 1979b].

Lee and Kan [1979a] noted that microinstabilities are not expected to change the zero-order magnetopause structure that is produced and maintained by the plasmas on either side of the magnetopause. They stated that the trapped particles are required to supplement the necessary current for the magnetic field to rotate more than a critical angle ($\sim$90°) through the magnetopause in the (y, z) plane. To describe the fact that charged particles from one side cannot penetrate arbitrarily deep into the other side, a cut-off factor is required in the distribution function (for example, an error function of momenta, or a step function). *Lee and Kan* [1979a] pointed out that the magnetopause current in their model is carried predominantly by the ions and has a significant field-aligned component.

Whipple et al. [1984] tried to resolve the problem of nonuniqueness of solutions of the Vlasov equation by analyzing the particle accessibility to the magnetopause. *Whipple et al.'s* [1984] cutoff is based on physical arguments about the particle trajectories rather than that being an arbitrary factor as in previous works. *Roth et al.* [1996] review kinetic models based on steady-state solutions of the Vlasov equation. A generalized multispecies Vlasov model of tangential discontinuities is presented in *Roth et al.* [1996].

Lin and Lee [1993] used both a one-dimensional resistive MHD code and a one-dimensional hybrid code to simulate the evolution of the magnetopause current sheet, which separates two plasma regions. In the hybrid simulation, the ions are treated as particles and electrons are treated as a massless fluid. The results obtained from a resistive MHD model and from a hybrid model are found to be different. A similar comparison between the Hall MHD and hybrid models was presented in *Omidi and Winske* [1995]. The Hall MHD differs from the resistive MHD in the Hall term in the equation for $\partial\mathbf{B}/\partial t$. The kinetic solutions are found to be in much better agreement with magnetopause observations.

Hybrid simulations of tangential discontinuities were also performed by *Cargill* [1990]. The final width of the magnetopause was estimated as 2–5 ion Larmor radii. *Berchem and Okuda* [1990] have developed a two-and-a-half-dimensional electromagnetic code to study the formation and stability of the magnetopause current layer. They reexamined the classical problem of equilibrium between solar wind plasma and the vacuum magnetospheric magnetic field.

In the works by *Song et al.* [1990, 1993], the magnetopause structure for northward IMF was studied. *Song et al.* [1993] reported multi-instrument observations of magnetopause parameters for ISEE crossings. *Pudovkin et al.* [1995] complemented this study by examining one of described events in terms of a reconnection model. The magnetopause at the subsolar point for northward IMF is a boundary between two magnetized plasmas with nearly parallel magnetic fields and without significant relative motion [*Song et al.,* 1993]. *Pudovkin et al.* [1995] noted that some fine structure may be obtained only from plasma kinetics, and a more or less complete description of many plasma problems may be most easily secured through a combined MHD and kinetic consideration.

Study of the magnetopause leads to the conclusion that the physics of the magnetopause greatly depend on global interaction and are not governed solely by local properties [*Russell,* 1995]. For example, the occurrence of magnetic reconnection at low or high latitudes and the resulting magnetic field topology is expected to influence the structure of the magnetopause as a whole [*Omidi and Winske,* 1995].

3. Model

Here we will use a simple model of the current region at the subsolar magnetopause [*Belenkaya,* 1998c] to explicitly demonstrate the physical meaning of the processes at the boundary between two different sorts of magnetized plasmas. At the beginning, for fixed external parameters of the plasmas and magnetic fields on both sides of the boundary, we will consider the trajectories of the charged particles and the arising currents. Then we will investigate the case when the given drop of the external magnetic fields is caused by these currents and will find the steady-state scale length of the current region imbedded in the external "background" magnetic field, which also should be defined. Really, the solution will be double scaled, as two current sheets are created by the magnetosheath and magnetospheric ions.

The results obtained will be compared with observations. We will start from a magnetic field boundary with a thickness much less than the ion gyroradii but significantly exceeding the electron gyroradii, and then we will find its final spatial scale as determined by the equilibrium conditions. In this sense, some lack of self-consistency exists.

Under this assumption, electrons are treated as a massless, neutralized fluid. The neutralization of the ion current sheets is allowed to be complete. Electrons do not generate currents of the nature discussed because the magnetic field boundary is assumed to be thicker than the electron giroradii. The electron drift motion is not considered here. This approach ignores the electric field which is a significant restriction of the model.

Although the magnetopause is rarely in a stationary state, we assume that its motion is insignificant over the characteristic period of time this is the gyroperiod. The lifetimes of the magnetopause currents are governed by the time needed to destroy the plasma temperature and density gradients as well as the magnetic field gradient, which define the very existence of a magnetospheric boundary. Observations show that these gradients exist permanently. We also consider the subsolar magnetopause as a plane, as its curvature radius is of the order of a few Earth's radii (R_E) and significantly exceeds the magnetopause thickness [*De Keyser and Roth,* 1997], which is equal to a few ion gyroradii [*Berchem and Russell,* 1982a]. Magnetic fields and plasma properties are different in the magnetosheath and in the magnetosphere. The magnetosheath plasma is dense and cold, and the magnetospheric plasma is hot and tenuous.

We will use a coordinate system (x, y, z), where the x axis is directed along the outer normal to the dayside magnetopause, the z axis coincides with the orientation of the magnetospheric magnetic field near the subsolar magnetopause, and the y axis is directed to dusk. This coordinate system is located at the magnetic field boundary separating the magnetosheath and magnetosphere (magnetopause).

As follows from numerous observations, the shocked solar wind plasma of the magnetosheath cannot penetrate the magnetosphere, but it is mostly deflected around it. Similarly, the magnetospheric plasma cannot penetrate arbitrarily deep into the magnetosheath. As the charged particles do not directly interact with each other, the motion of each individual particle can be treated independently. The typical scale of the magnetopause structure approaches the ion gyroradius in size. On this scale, MHD is unsuitable and kinetic theory steps forth.

The Larmor radius of a particle with charge e and mass m in the magnetic field $\mathbf{B}$ is equal to

$$\rho = \frac{mV_\perp}{\mathrm{e}B} \tag{1}$$

where $V_\perp$ is a component of particle velocity perpendicular to the magnetic field lines. Let us briefly examine what happens at the boundary between two different sorts of plasmas for antiparallel and parallel magnetic fields. We assume in the first approximation that the magnetic field boundary can be treated as a discontinuous jump in the magnetic field at $x = 0$ (at the magnetopause). At this boundary, the density of each sort of ions penetrating the opposite region begins to decrease. It is postulated that the characteristic temperature of the penetrated particles does not change. The penetration is limited by the ion Larmor diameter in the magnetic field of the opposite domain.

3.1. Antiparallel Magnetic Fields

In Figure 1a, the boundary between magnetosheath (msh) and magnetosphere (msph) is shown in the equatorial plane. This boundary separates two antiparallel magnetic fields, and the density of each species of plasma begins to decrease as the ions move across it to the opposite side (as discussed above). The Larmor circular orbits are drawn by solid curves for the magnetospheric ions and by dashed curves for the magnetosheath ions. Near the boundary, the magnetospheric magnetic field ($\mathbf{B}_{\mathrm{msph}}$) and the magnetosheath magnetic field ($\mathbf{B}_{\mathrm{msh}}$) are antiparallel, so, in the magnetosphere, the ions rotate clockwise and in the magnetosheath

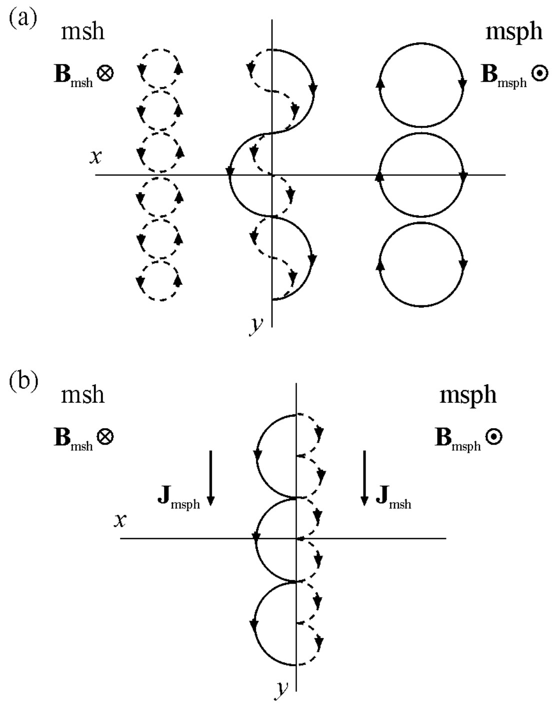

Figure 1. (a) Magnetosheath ion trajectories (dashed curves) and magnetospheric ion orbits (solid curves) at the boundary between two mediums in the equatorial plane for antiparallel magnetic fields; (b) Currents resulting at the boundary between two mediums in the equatorial plane for antiparallel magnetic fields. The parts of orbits of the magnetosheath (magnetospheric) ions that penetrated the outer space are shown by dashed (solid) curves.

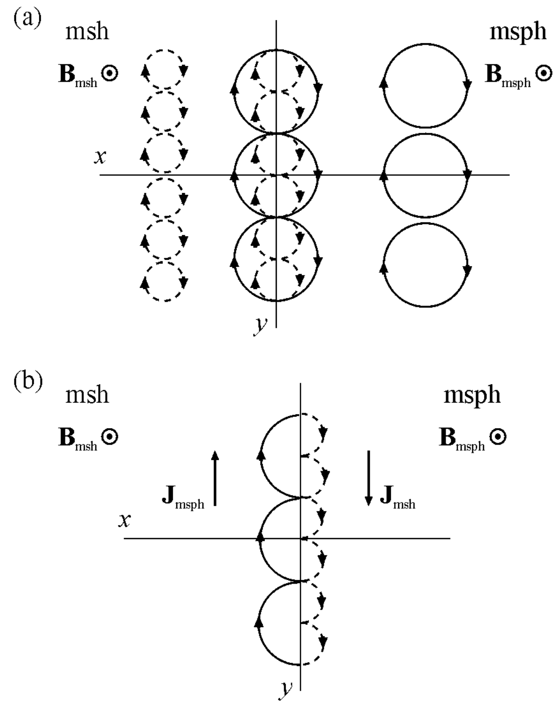

Figure 2. (a) Magnetosheath ion trajectories (dashed curves) and magnetospheric ion orbits (solid curves) at the boundary between two mediums in the equatorial plane for parallel magnetic fields; (b) Currents resulting at the boundary between two mediums in the equatorial plane for parallel magnetic fields. The parts of orbits of the magnetosheath (magnetospheric) ions that penetrated the outer space are shown by dashed (solid) curves.

counterclockwise. Subscripts msph and msh indicate that parameters relate to the magnetosphere and magnetosheath, respectively.

The distributions of gyrocenters of magnetosheath and magnetospheric ions have discontinuous jumps at $x = -\rho_{\mathrm{msh}}$ and $x = \rho_{\mathrm{msph}}$, respectively. So, an interpenetration of both plasma species exists in the region $[-2\rho_{\mathrm{msh}}, +2\rho_{\mathrm{msph}}]$, and $[-\rho_{\mathrm{msh}}, +\rho_{\mathrm{msph}}]$ one finds gyrocenters of both magnetosheath and magnetospheric ions in the region. The current from those segments of the magnetospheric ion Larmor circles that are located earthward of the boundary is compensated by the current of the surrounding magnetospheric ions. The current from the other parts of ion Larmor circular orbits (located sunward from the boundary) is uncompensated. Respectively, for the magnetosheath ions, the current from the parts of gyrocircles located earthward of the boundary is uncompensated. The resulting structure in the equatorial plane is shown in Figure 1b. Uncompensated currents created by the magnetosheath ($\mathbf{J}_{\mathrm{msh}}$) and by the magnetospheric ($\mathbf{J}_{\mathrm{msph}}$) ions are parallel to the y axis.

3.2. Parallel Magnetic Fields

In Figure 2a for parallel magnetic fields on both sides of the boundary, the Larmor circles in the equatorial plane are shown by solid curves for the magnetospheric ions and by dashed curves for the magnetosheath ions. In this case, the sense of ion gyrorotation does not change at the boundary, as magnetic fields are parallel to each other on both sides of it. As before, there is an uncompensated current from those arcs of the magnetospheric ion Larmor orbits that are placed sunward of the boundary, and from those parts of the magnetosheath, gyrocircles are located earthward of the boundary. The resulting currents in the equatorial plane are shown in Figure 2b. The current created by the magnetospheric ions ($\mathbf{J}_{\mathrm{msph}}$) is antiparallel now to the current of the magnetosheath ions ($\mathbf{J}_{\mathrm{msh}}$), which is directed along the y axis, as before. Hereafter, we will concentrate only on the case of parallel magnetic fields, real for the subsolar low shear magnetopause.

3.3. Current Sheets at the Boundary of Two Magnetized Plasmas

At the boundary separating magnetosheath and magnetospheric plasmas, the current region (magnetopause) arises. Its thickness, $D_{\rm mp}$, is approximately $2(\rho_{\rm msh}+\rho_{\rm msph})$ as it is seen from Figures 1b and 2b (in creating the discussed currents, those particles take part that penetrate the outer space at a distance less than their Larmor diameter, or whose gyrocenters penetrate at a distance equal to their Larmor radius). Index "mp" attitudes toward the magnetopause. Currents flowing along the boundary are caused by a space inhomogeneity of the plasma. Plasma inhomogeneity means spatial variations of any plasma main characteristic: Density of the charged particles, temperature, and magnetic field strength. As all these parameters change at the magnetopause, boundary currents arise in each sort of plasma (magnetospheric and magnetosheath). The direction of gyrorotation at the boundary is such that the magnetic field generated by each boundary current is opposite to the external imposed magnetic field. Such behavior creates a diamagnetic effect. These magnetopause currents are essentially the Chapman-Ferraro diamagnetic currents. *Winglee* [1994] mentioned that the magnetopause currents in the y direction are key elements missing from MHD simulations.

The existence of the current along the y direction implies the existence of momentum in this direction. It should be noted that the problem under consideration is substantially unlocal: Boundary conditions at the magnetopause are created by Earth, the Sun, magnetosphere, and the interplanetary medium. So, all these objects should be taken into account as the parts of an entire system. The energy and momentum conservation laws are valid only for the whole (closed) system, which does not undergo any force, but they are not valid not for only part of it. The magnetic field connects these objects, providing the force between them, in particular between the magnetopause and ionosphere and between the magnetopause and the surface of the Sun. So, momentum in the y direction at the magnetopause should be compensated in the ionosphere and in the solar corona.

Thus, we found that diamagnetic, cyclotron, or Larmor currents generated by the ions of the magnetosheath and magnetosphere flow in the current region of the low-latitude dayside magnetopause parallel to each other, from noon to dusk for southward IMF and antiparallel for northward IMF. In the last case, the only one which we will consider in this paper, the current carried by the magnetosheath particles saves its direction, and the current created by the ions of the magnetosphere is reversed.

It is supposed that the ion magnetosheath (magnetospheric) gyrocenters are cut-off at $x=-\rho_{\rm msh}$ ($x=\rho_{\rm msph}$). We assume that all magnetosheath (magnetospheric) ions have velocity equal to the thermal speed $V_{\rm msh\,th}$ ($V_{\rm msph\,th}$) with a constant temperature $T_{\rm msh}$ ($T_{\rm msph}$).

In constructing a one-dimensional model of the magnetopause current region between two collisionless magnetized plasmas, a distribution function $F_\alpha(x)$ of the α-th ion species is used to describe all physical plasma properties. The distribution function is the density of ions at the chosen point, x, having velocity in the interval $[\mathbf{V};\mathbf{V}+d\mathbf{V}]$, where $d\mathbf{V}=\{dV, Vd\tilde\theta, V\sin\tilde\theta d\tilde\Phi\}$. In this notation, the density of ions, $n_\alpha(x)$, inside the volume $d\Omega=V^2\sin\tilde\theta d\tilde\theta d\tilde\Phi dV$ at the point x can be written as

$$dn_\alpha(x)=F_\alpha(x)d\Omega \tag{2}$$

where V is the modulus of the velocity vector; $\tilde\theta$ is a polar angle measured from z axis to the velocity vector; for velocity perpendicular to the magnetic field, $\tilde\theta=\tilde\theta_0=\pi/2$.

The distribution function $F_\alpha(x)$ is chosen to be determined by products of two delta functions, $\delta(V-V_{\alpha\,\rm th})$, $\delta(\tilde\theta-\tilde\theta_0)$, and a function $f_\alpha(x,\tilde\Phi)$ that presents a step cut-off function depending on the x and on the azimuthal angle, $\tilde\Phi$, of the velocity vector

$$F_\alpha(x)=C_\alpha f_\alpha\left(x,\tilde\Phi\right)\delta\left(V-V_{\alpha\ \rm th}\right)\delta\left(\tilde\theta-\tilde\theta_0\right) \tag{3}$$

Here $V_{\alpha\,\rm th}$ is a thermal speed of the α-th ions

$$V_{\alpha\,\rm th}=\sqrt{\frac{2kT_\alpha}{m_\alpha}} \tag{4}$$

$k=1.38\times10^{-23}$ kg m^2 s^{-2} is the Boltzmann constant; C_α is a constant appropriate to the prescribed boundary conditions. The cut-off function, $f_\alpha(x,\tilde\Phi)$, represents the fact that the ions from one side cannot penetrate arbitrarily deep into the other side.

All quantities in the assumed one-dimensional model depend only on the x coordinate. Plasma pressure (in x direction) of the α-th sort of ions can be obtained as the second moment of the distribution function, $F_\alpha(x)$

$$P_{\alpha\,xx}=\int m_\alpha V_{\alpha\,x}^2F_\alpha(x)d\Omega \tag{5}$$

The density of the current carried by the α-th ion species can be obtained using the distribution function and $V_{\alpha\,y}$

$$j_{\alpha\,y}=\mathrm{e}\int V_{\alpha\,y}F_\alpha(x)d\Omega \tag{6}$$

The expressions for the magnetosheath and magnetospheric ion density, $n(x)=n_{\rm msh}(x)+n_{\rm msph}(x)$, pressure, $P_{xx}(x)=P_{\rm msh\,\mathit{xx}}(x)+P_{\rm msph\,\mathit{xx}}(x)$, and current density,

$j_y = j_{\mathrm{msh}\,y}(x) + j_{\mathrm{msph}\,y}(x)$, are:

$$n(x) = \begin{cases} n_{\mathrm{msph0}} & \text{for } x < -2\rho_{\mathrm{msh}} \\ n_{\mathrm{msph0}} + \dfrac{n_{\mathrm{msh0}}}{\pi} \times \arccos\left(-1 - \dfrac{x}{\rho_{\mathrm{msh}}}\right) & \text{for } -2\rho_{\mathrm{msh}} < x < 0 \\ n_{\mathrm{msh0}} + \dfrac{n_{\mathrm{msph0}}}{\pi} \times \left[\pi - \arccos\left(1 - \dfrac{x}{\rho_{\mathrm{msph}}}\right)\right] & \text{for } 0 < x < 2\rho_{\mathrm{msph}} \\ n_{\mathrm{msh0}} & \text{for } x > 2\rho_{\mathrm{msph}} \end{cases} \tag{7}$$

For $x = 0$, $n = n_{\mathrm{msph0}} + n_{\mathrm{msh0}}$, where n_{msh0} and n_{msph0} are the primary parameters of the model, magnetosheath density for $x > 0$, and magnetospheric density for $x < 0$, respectively.

$$P_{xx}(x) = \begin{cases} P_{\mathrm{msph0}} & \text{for } x < -2\rho_{\mathrm{msh}} \\ P_{\mathrm{msph0}} + \dfrac{P_{\mathrm{msh}}0}{\pi}\left[\arccos\left(-1 - \dfrac{x}{\rho_{\mathrm{msh}}}\right) + \sqrt{1 - \left(1 + \dfrac{x}{\rho_{\mathrm{msh}}}\right)^2}\left(1 + \dfrac{x}{\rho_{\mathrm{msh}}}\right)\right] & \text{for } -2\rho_{\mathrm{msh}} < x < 0 \\ P_{\mathrm{msh0}} + \dfrac{P_{\mathrm{msph0}}}{\pi}\left[\pi - \arccos\left(1 - \dfrac{x}{\rho_{\mathrm{msph}}}\right) - \sqrt{1 - \left(1 - \dfrac{x}{\rho_{\mathrm{msph}}}\right)^2}\left(1 - \dfrac{x}{\rho_{\mathrm{msph}}}\right)\right] & \text{for } 0 < x < 2\rho_{\mathrm{msph}} \\ P_{\mathrm{msh0}} & \text{for } x > 2\rho_{\mathrm{msph}} \end{cases} \tag{8}$$

For $x = 0$, $P = P_{\mathrm{msph0}} + P_{\mathrm{msh0}}$, where

$$P_{\mathrm{msh0}} = \frac{1}{2} m_{\mathrm{msh}} n_{\mathrm{msh0}} V^2_{\mathrm{msh\,th}} = n_{\mathrm{msh0}} k T_{\mathrm{msh}} \tag{9}$$

$$P_{\mathrm{msph0}} = \frac{1}{2} m_{\mathrm{msph}} n_{\mathrm{msph0}} V^2_{\mathrm{msph\;th}} = n_{\mathrm{msph0}} k T_{\mathrm{msph}} \tag{10}$$

$$j_y = \begin{cases} 0 & \text{for } x < -2\rho_{\mathrm{msh}} \\ \dfrac{\mathrm{e}}{\pi} n_{\mathrm{msh0}} \sqrt{\dfrac{2kT_{\mathrm{msh}}}{m_{\mathrm{msh}}}} \times \sqrt{1 - \left(1 + \dfrac{x}{\rho_{\mathrm{msh}}}\right)^2} & \text{for } -2\rho_{\mathrm{msh}} < x < 0 \\ -\dfrac{\mathrm{e}}{\pi} n_{\mathrm{msph0}} \sqrt{\dfrac{2kT_{\mathrm{msph}}}{m_{\mathrm{msph}}}} \times \sqrt{1 - \left(1 - \dfrac{x}{\rho_{\mathrm{msph}}}\right)^2} & \text{for } 0 < x < 2\rho_{\mathrm{msph}} \\ 0 & \text{for } x > 2\rho_{\mathrm{msph}} \end{cases} \tag{11}$$

For $x = 0$, $j_y = 0$.

3.4. Magnetic Field at the Subsolar Low-Shear Magnetopause

The magnetic field, $\mathbf{B}$, generated by the current layer with density, j, is determined by Maxwell's equation

$$\mathrm{curl}\left(\frac{1}{\mu_0}\mathbf{B}\right) = \mathbf{j} \tag{12}$$

Because of the assumption of one-dimensionality

$$-\frac{1}{\mu_0}\frac{dB_z}{dx} = j_y \tag{13}$$

Magnetic fields generated by the currents carried by the magnetosheath and magnetospheric ions, $B_z^{\mathrm{sh}}(x)$ and $B_z^{\mathrm{sp}}(x)$, respectively, can be found by integration the equations for $j_{\alpha\ y}$

$$B_z^{\mathrm{sh}}(x) = -B_0^{\mathrm{sh}} - \frac{\mu_0 \mathrm{e}}{2\pi} n_{\mathrm{msh0}} \sqrt{\frac{2kT_{\mathrm{msh}}}{m_{\mathrm{msh}}}} \rho_{\mathrm{msh}} \times \left[\left(1 + \frac{x}{\rho_{\mathrm{msh}}}\right)\sqrt{1 - \left(1 + \frac{x}{\rho_{\mathrm{msh}}}\right)^2} + \arcsin\left(1 + \frac{x}{\rho_{\mathrm{msh}}}\right)\right] \tag{14}$$

$$B_z^{\mathrm{sp}}(x) = -B_0^{\mathrm{sp}} - \frac{\mu_0 \mathrm{e}}{2\pi} n_{\mathrm{msph0}} \sqrt{\frac{2kT_{\mathrm{msph}}}{m_{\mathrm{msph}}}} \rho_{\mathrm{msph}} \left[\left(1 - \frac{x}{\rho_{\mathrm{msph}}}\right)\sqrt{1 - \left(1 - \frac{x}{\rho_{\mathrm{msph}}}\right)^2} + \arcsin\left(1 - \frac{x}{\rho_{\mathrm{msph}}}\right)\right] \tag{15}$$

where B_0^{sh} and B_0^{sp} are the constants of integration, giving the values that the magnetic field $B_z(x) = B_z^{\mathrm{sh}}(x) + B_z^{\mathrm{sp}}(x)$

approaches as x goes to $-\infty$ and to $+\infty$: B_{msph0} and B_{msh0}, respectively (the input parameters of the model). Taking into account that $B_z^{\mathrm{sh}}(x)\big|_{x=-\infty} = B_z^{\mathrm{sh}}(x)\big|_{x=-2\rho_{\mathrm{msh}}}$, $B_z^{\mathrm{sp}}(x)\big|_{x=-\infty} = B_z^{\mathrm{sp}}(x)\big|_{x=0}$, $B_z^{\mathrm{sh}}(x)\big|_{x=\infty} = B_z^{\mathrm{sh}}(x)\big|_{x=0}$, and $B_z^{\mathrm{sp}}(x)\big|_{x=\infty} = B_z^{\mathrm{sp}}(x)\big|_{x=2\rho_{\mathrm{msph}}}$, we obtain

$$B_z(x)\big|_{x=-\infty} = -\left(B_0^{\mathrm{sh}} + B_0^{\mathrm{sp}}\right)$$

$$+\frac{\mathrm{e}\mu_0}{4} n_{\mathrm{msh0}} \sqrt{\frac{2kT_{\mathrm{msh}}}{m_{\mathrm{msh}}}} \rho_{\mathrm{msh}}$$

$$-\frac{\mathrm{e}\mu_0}{4} n_{\mathrm{msph0}} \sqrt{\frac{2kT_{\mathrm{msph}}}{m_{\mathrm{msph}}}} \rho_{\mathrm{msph}} = B_{\mathrm{msph0}} \quad (16)$$

$$B_z(x)\big|_{x=\infty} = -\left(B_0^{\mathrm{sh}} + B_0^{\mathrm{sp}}\right)$$

$$-\frac{\mathrm{e}\mu_0}{4} n_{\mathrm{msh0}} \sqrt{\frac{2kT_{\mathrm{msh}}}{m_{\mathrm{msh}}}} \rho_{\mathrm{msh}}$$

$$+\frac{\mathrm{e}\mu_0}{4} n_{\mathrm{msph0}} \sqrt{\frac{2kT_{\mathrm{msph}}}{m_{\mathrm{msph}}}} \rho_{\mathrm{msph}} = B_{\mathrm{msh0}} \quad (17)$$

and at $x = 0$

$$B_z(x)\big|_{x=0} = -\left(B_0^{\mathrm{sh}} + B_0^{\mathrm{sp}}\right)$$

$$-\frac{\mathrm{e}\mu_0}{4} n_{\mathrm{msh0}} \sqrt{\frac{2kT_{\mathrm{msh}}}{m_{\mathrm{msh}}}} \rho_{\mathrm{msh}}$$

$$-\frac{\mathrm{e}\mu_0}{4} n_{\mathrm{msph0}} \sqrt{\frac{2kT_{\mathrm{msph}}}{m_{\mathrm{msph}}}} \rho_{\mathrm{msph}} \quad (18)$$

If the value $B_z(x)\big|_{x=0}$ is known, the solution of the system of three equations (16)–(18) with three variables — $B_0 \equiv B_0^{\mathrm{sh}} + B_0^{\mathrm{sp}}$, ρ_{msh}, and ρ_{msph} — can be found. Quantity $B_z(x)\big|_{x=0}$ can be defined from the equilibrium condition for each current sheet boundary. For the existence of the described current structure, the pressure balance must be fulfilled at the edges of each current layer:

$$P_{\mathrm{tot}} = P_{xx} + \frac{B^2}{2\mu_0} = \text{ const} \quad (19)$$

where P_{tot} is the total pressure, P_{xx} is the plasma pressure, and B is the total magnetic field strength. So, this condition is valid at the boundary between two current sheets, at $x = 0$, and determines the value $B_z(x)\big|_{x=0}$:

$$\frac{1}{2\mu_0}\, B_z^2(x)\big|_{x=0} + P_{xx}(x)\big|_{x=0} = \frac{B^2_{\mathrm{msph0}}}{2\mu_0} + P_{\mathrm{msph0}}$$

$$= \frac{B^2_{\mathrm{msh0}}}{2\mu_0} + P_{\mathrm{msh0}} \quad (20)$$

From (8), (16)–(18), and (20) we conclude that

$$B_z(x)\big|_{x=0} = \pm\sqrt{B^2_{\mathrm{msph0}} - 2\mu_0 P_{\mathrm{msh0}}}$$

$$= \pm\sqrt{B^2_{\mathrm{msh0}} - 2\mu_0 P_{\mathrm{msph0}}} \quad (21)$$

Here we will consider only the sign "+" in front of the square root (the northward magnetic field inside the magnetopause).

The corresponding solution for the system of equations (16)–(18) is:

$$\begin{aligned} B_0 &= -\frac{B_{\mathrm{msh0}} + B_{\mathrm{msph0}}}{2} \\ \rho_{\mathrm{msh}} &= \frac{2\sqrt{2kT_{\mathrm{msh}} m_{\mathrm{msh}}}}{\mathrm{e}\left(B_{\mathrm{msph0}} + \sqrt{B_{\mathrm{msph0}} - 2\mu_0 P_{\mathrm{msh0}}}\right)} \\ \rho_{\mathrm{msph0}} &= \frac{2\sqrt{2kT_{\mathrm{msph}} m_{\mathrm{msph}}}}{\mathrm{e}\left(B_{\mathrm{msh0}} + \sqrt{B^2_{\mathrm{msh0}} - 2\mu_0 P_{\mathrm{msph0}}}\right)} \end{aligned} \quad (22)$$

This solution gives the constant of integration, B_0, satisfying the magnetic field boundary conditions; $-B_0$ plays the role of the "background" external magnetic field existing in the problem; ρ_{msh} and ρ_{msph} are the half-thickness of the current layers created by the magnetosheath and magnetospheric ions, respectively, in the steady-state case. The values of magnetic fields in which ion gyroradii should be calculated are determined. Equation (21) defines the minimum value of the magnetic field strength inside the magnetopause at the boundary between two current sheets.

The linear integral current density, $J_{\alpha y}$, for the magnetosheath and magnetospheric ion currents are, respectively,

$$J_{\mathrm{msh}\ y} = \int_{-2\rho_{\mathrm{msh}}}^{0} j_{\mathrm{msh}\ y}\, dx$$

$$= \frac{2P_{\mathrm{msh0}}}{B_{\mathrm{msph0}} + \sqrt{B^2_{\mathrm{msph0}} - 2\mu_0 P_{\mathrm{msh0}}}}$$

$$J_{\mathrm{msph}\ y} = \int_{0}^{2\rho_{\mathrm{msph}}} j_{\mathrm{msph}\ y}\, dx$$

$$= -\frac{2P_{\mathrm{msph0}}}{B_{\mathrm{msph0}} + \sqrt{B^2_{\mathrm{msph0}} - 2\mu_0 P_{\mathrm{msh0}}}} \quad (23)$$

The resulting magnetic field corresponding to the two current layers at the subsolar low-shear magnetopause is

$$B_z(x) = B_{\mathrm{msph0}} \qquad \text{for } -\infty < x < -2\rho_{\mathrm{msh}}$$

$$B_z(x) = -B_0 - \frac{\mu_0 \mathrm{e}}{2\pi} n_{\mathrm{msh0}} \sqrt{\frac{2kT_{\mathrm{msh}}}{m_{\mathrm{msh}}}} \rho_{\mathrm{msh}}$$

$$\times \left[\left(1 + \frac{x}{\rho_{\mathrm{msh}}}\right) \sqrt{1 - \left(1 + \frac{x}{\rho_{\mathrm{msh}}}\right)^2}\right.$$

$$+\arcsin\left(1+\frac{x}{\rho_{\mathrm{msh}}}\right)\Bigg]$$

$$-\frac{\mu_0 \mathrm{e}}{4} n_{\mathrm{msph0}} \sqrt{\frac{2kT_{\mathrm{msph}}}{m_{\mathrm{msph}}}} \rho_{\mathrm{msph}} \qquad \text{for } -2\rho_{\mathrm{msh}} < x < 0$$

$$B_z(x) = -B_0 - \frac{\mu_0 \mathrm{e}}{2\pi} n_{\mathrm{msph0}} \sqrt{\frac{2kT_{\mathrm{msph}}}{m_{\mathrm{msph}}}} \rho_{\mathrm{msph}}$$

$$\times \Bigg[\left(1-\frac{x}{\rho_{\mathrm{msph}}}\right)\sqrt{1-\left(1-\frac{x}{\rho_{\mathrm{msph}}}\right)^2}$$

$$+\arcsin\left(1-\frac{x}{\rho_{\mathrm{msph}}}\right)\Bigg]$$

$$-\frac{\mu_0 \mathrm{e}}{4} n_{\mathrm{msh0}} \sqrt{\frac{2kT_{\mathrm{msh}}}{m_{\mathrm{msh}}}} \rho_{\mathrm{msh}} \qquad \text{for } 0 < x < 2\rho_{\mathrm{msph0}}$$

$$B_z(x) = B_{\mathrm{msh}} \qquad \text{for } 2\rho_{\mathrm{msph0}} < x < +\infty \tag{24}$$

A peculiarity of the obtained solution is due to our particular choice of the distribution function.

It should be noted that in figures demonstrating calculations performed by *Lee and Kan* [1979a], for northward IMF, one can see at the magnetopause two pairs of antiparallel currents carried by the magnetospheric and magnetosheath ions and electrons. However, in the text by *Lee and Kan* [1979a], the existence of antiparallel magnetopause currents is not even mentioned. Moreover, the authors considered that the magnitude of the magnetic field intensity inside the magnetopause current sheet should be greater than that on the two sides. This situation opposes that presented here.

3.5. Comparison With Observations

For comparison with observations we use 4.35-s data from the AMPTE/IRM satellite [*Phan et al.,* 1994], which provide dayside plasma and magnetic field observations obtained on 13 and 24 October 1985 (see Figure 4 and Figure 3 from *Phan et al.* [1994]). On 13 October 1985, the magnetopause crossing was at 1132:07 UT for the low magnetic shear which was less than 30°. The magnetosheath magnetic field direction in this case remained rather steady for at least 30 min prior to the magnetopause encounter. In this time, a decrease in the magnetic field B (from ~67 nT to ~57 nT) and an increase of the plasma pressure, p_{pla} (from ~0.4 nPa to ~0.8 nPa), were observed, followed by a reverse increase of B to ~65 nT and decrease of p_{pla} to ~0.5 nPa.

Taking the observed data for this event as the input values, we can calculate the model "background" external magnetic field, the minimum magnetic field strength in the magnetopause double-layer current structure, and the character length scale of each current layer.

According to *Phan et al.* [1994], the magnetosheath parameters were: $n_{\mathrm{msh}} \approx 8$ cm^{-3}, $T_{\mathrm{msh}} \approx 4 \times 10^6$ K, $B_{\mathrm{msh}} \approx 67$ nT, and the magnetospheric parameters near the magnetopause were: $n_{\mathrm{msph}} \approx 2$ cm^{-3}, $T_{\mathrm{msph}} \approx 20 \times 10^6$ K, and $B_{\mathrm{msph}} \approx 65$ nT. For these values, we obtain for the magnetosheath protons: $V_{\mathrm{msh}\perp} \approx 180$ km s^{-1}, $\rho_{\mathrm{msh}} \approx 44$ km, $j_{y\,\mathrm{msh}}$ max $\approx 1 \times 10^{-7}$ A m^{-2}, and $J_{\mathrm{msh}} \approx 1.3 \times 10^{-2}$ A m^{-1}.

Similarly, for the magnetospheric protons: The thermal velocity $V_{\mathrm{msph}\perp} \approx 400$ km s^{-1}, $\rho_{\mathrm{msph}} \approx 94$ km, $j_{\mathrm{msph}\ y} \approx -0.6 \times 10^{-7}$ A m^{-2}, and $J_{\mathrm{msph}} \approx -1.6 \times 10^{-2}$ A m^{-1}. The "background" magnetic field $-B_0 = 66$ nT, and the minimum magnetic field at the magnetopause, between two current layers, is $B_{z\ \min} = 57$ nT, which agrees well with observations (~57 nT).

The observation data show that the duration of the magnetopause structure connected with the negative spike in magnetic field and the positive spike in plasma pressure is approximately 1.5 min. If we use, after *Phan et al.* [1994], the average low-shear magnetopause normal velocity of 11 km s^{-1}, this duration translates into a thickness of 0.15 R_E ($R_E = 6.4 \times 10^6$ m). This value may be considered only as an upper limit. As *Phan et al.* [1994] mention, this is due to the fact that the magnetopause is unlikely to move unidirectionally at the same speed. If we assume the magnetopause to be stationary for 1.5 min if the typical satellite velocity of 2 km s^{-1} is used, the 1.5-min duration translates into a thickness of 180 km, which may be considered as a lower limit [*Phan et al.,* 1994]. According to our model of the magnetopause structure, the distance between two current magnetopause layers is of the order of $\rho_{\mathrm{msh}} + \rho_{\mathrm{msph}} \approx 138$ km (consequently, the thickness of the magnetopause is ≈276 km).

Another example of low-shear (<15°) dayside magnetopause crossing is also published in *Phan et al.* [1994] and presented in their Figures 2 and 3. On 24 October 1985 at 1302:47 UT, AMTE/IRM reached magnetopause. For the magnetosheath parameters, $n_{\mathrm{msh}} \approx 10$ cm^{-3}, $T_{\mathrm{msh}} \approx 3 \times 10^6$ K, $B_{\mathrm{msh}} \approx 67$ nT, we obtain: $V_{\mathrm{msh}\perp} \approx 160$ km s^{-1}, $\rho_{\mathrm{msh}} \approx 36$ km, $j_{\mathrm{msh}\ y} \approx 1.1 \times 10^{-7}$ A m^{-2}, and $J_{\mathrm{msh}} \approx 1.3 \times 10^{-2}$ A m^{-1}.

Respectively, for the magnetospheric parameters, $n_{\mathrm{msph}} \approx 1$ cm^{-3}, $T_{\mathrm{msph}} \approx 20 \times 10^6$ K, $B_{\mathrm{msph}} \approx 69$ nT, we calculate: $V_{\mathrm{msph}\perp} \approx 400$ km s^{-1}, $\rho_{\mathrm{msph}} \approx 93$ km, $j_{\mathrm{msph}\ y} \approx -0.3 \times 10^{-7}$ A m^{-2}, $J_{\mathrm{msph}} \approx -0.9 \times 10^{-2}$ A m^{-1}. The "background" magnetic field $-B_0 = 68$ nT, and the minimum magnetic field at the magnetopause, between two current layers, is $B_{z\ \min} = 61$ nT. The observed minimum magnetic field strength is of the order of 60 nT. The duration of examined structure is 2 min. So, its thickness is ≥ 240 km, and the model thickness of the magnetopause is ≈258 km.

For comparison, characteristic values of the y component of the magnetosheath and magnetospheric ion current densities calculated by *Lee and Kan* [1979a] and presented in their Figures 2–4, are, respectively: ~0.28×10^{-7} A m^{-2} and ~ 0.09×10^{-7} A m^{-2} for $B_{z\ \mathrm{msh}}$ ~18 nT, $B_{z\ \mathrm{msph}}$ ~35 nT, n_{msh} ~18 cm^{-3}, n_{msph} ~4.5 cm^{-3}, T_{msh} ~0.3 keV, $T_{+\ \mathrm{msph}}$ ~ 0.4 keV. On average, electron current densities are less than the ion densities.

Our estimation of the magnetopause current layer thickness $2(\rho_{\mathrm{msh}} + \rho_{\mathrm{msph}})$ is in good agreement with the *Eastman* *et al.* [1996] result that the inferred magnetopause thickness in units of plasma ion gyroradii ranges from 1.4 to 3.4, and with the *Le and Russell* [1994] conclusion that magnetopause current thickness is 2–4 ion gyroradii.

The results of our model and observations [e.g., *Eastman et al.,* 1996; *Le and Russell,* 1994] show that the magnetic field rotation is connected with the ion currents. The scale length of the magnetopause current layer is determined by the distribution of protons (and positive ions) of the magnetosheath and magnetospheric plasmas at the boundary between them. As mentioned above (see *Sestero* [1966]), the solution obtained satisfying the same conditions at infinity, is not unique. Such solutions depend on an assigned distribution function. However, all integral characteristics of the constructed double-layer current structure are determined unambiguously from the equilibrium conditions.

In the model presented, by gyroradius we mean the Larmor radius of an ion of energy equal to the mean thermal energy, in the magnetic field, equal to the arithmetic mean between the magnetic fields at the two ends of corresponding current sheet at the outer space.

We constructed a model describing the interaction between the magnetosheath and magnetospheric plasmas at the subsolar magnetopause for northward IMF. This model is physically realistic, gives a good representation of observations, and at the same time is rather simple mathematically.

9. Conclusions

The investigation of an interpenetration at the subsolar magnetospheric boundary of the two sorts of collisionless plasmas in a strong magnetic field allows us to construct a model of the magnetopause current structure and to obtain the following results:

1. The subsolar magnetopause consists of the two current sheets created by the magnetosheath and magnetospheric ions. Ion double-current layer is connected with the magnetic field rotation. For southward IMF, both ion currents flow from noon to dusk. This is a metastable configuration in which reconnection may occur. For northward IMF, the current created by the magnetosheath ions is directed to dusk, and the current generated by the magnetospheric ions flows to dawn.

2. At the magnetopause, an interpenetration of both plasma species exists in the range $(-2\rho_{\rm msh},\ 2\rho_{\rm msph})$. A mechanism of generation of two double-current layers at the subsolar magnetopause is connected with the difference of plasma parameters and magnetic fields in the magnetosheath and magnetosphere. In the steady-state case, the distance between the two ion current sheets responsible for the magnetic field rotation is of the order of $D_{\rm mp}/2 \approx (\rho_{\rm msh}+\rho_{\rm msph})$. Here, $\rho_{\rm msh}$ ($\rho_{\rm msph}$) is the gyroradius of the thermal magnetosheath (magnetospheric) ion, penetrating into the outer space, in the magnetic field equal to the arithmetic mean of the fields at the edges of the magnetosheath (magnetospheric) current layer.

3. The direction of charged particle gyration at the magnetopause is such that the magnetic field generated by each boundary current creates a diamagnetic effect.

4. At the subsolar magnetopause, between two ion current sheet the strengths of the magnetic field (B) and its z component (B_z) decrease and the plasma pressure increases. For this reason, the magnetopause current region may be identified even for northward IMF, when the magnitudes and directions of the magnetospheric and magnetosheath magnetic fields are rather similar.

The main restrictions of the model presented are the lack of electrostatic field effects and self-consistency; the initial assumption of the zero-width boundary between two external magnetic fields is not in agreement with the thickness of the double current sheet structure that is obtained.

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