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INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE
3 - Avenue Circulaire
B - 1180 BRUXELLES

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Impulsive Transport of Solar Wind into the Magnetosphere

by

M. Roth

BELGISCH INSTITUUT VOOR RUIMTE-AERONOMIE
3 - Ringlaan
B - 1180 BRUSSEL

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 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 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 in Physics of the Magnetopause, een volume van de serie *Geophysical Monograph*. Het is gebaseerd op een voordracht op uitnodiging gegeven tijdens de Chapman Conferentie over de Fysica van de Magnetopause, San Diego (USA), 14-18 maart, 1994.

VORWORT

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

Impulsive Transport of Solar Wind into the Magnetosphere

M. Roth [*]

Abstract

According to the theory of "impulsive penetration" proposed by Lemaire and Roth, magnetosheath plasma irregularities with an excess momentum density enter the geomagnetic field by means of an **E** × **B** drift resulting from their self electric polarization. Collective polarization, thermo-electric charge separation, and non-adiabatic braking are important non-ideal MHD processes. The dipole-dipole interaction force between the Earth's dipole field and the current system of a penetrating 3-dimensional diamagnetic plasmoid can increase or decrease the entry velocity, depending on the orientation of the IMF. A large number of laboratory experiments as well as significant geophysical observations are consistent with this impulsive penetration model.

Résumé

D'après le modèle de "pénétration impulsive" proposé par Lemaire et Roth, des irrégularités de plasma de la magnétogaine, avec un excès de densité d'impulsion, pénètrent dans le champ géomagnétique au moyen d'une dérive **E** × **B** provenant de leur propre polarisation électrique. La polarisation électrique, la séparation de charges thermoélectriques et le freinage non-adiabatique sont des processus importants de MHD non idéale. La force d'interaction dipôle-dipôle, entre le champ dipolaire de la Terre et le système de courants d'un plasmoïde diamagnétique tridimensionnel en train de pénétrer, peut augmenter ou diminuer la vitesse d'entrée, suivant l'orientation du champ magnétique interplanétaire (CMI). Un grand nombre d'expériences de laboratoire, ainsi que des observations géophysiques importantes sont compatibles avec ce modèle de pénétration impulsive.

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[*] *Institut d'Aéronomie Spatiale de Belgique*
Avenue Circulaire 3, B–1180 Brussels, Belgium.

Samenvatting

Volgens de theorie van de “impulsieve penetratie” voorgesteld door Lemaire en Roth, dringen onregelmatigheden in het plasma van de magnetische gordel die een overmaat aan impulsdichtheid hebben binnen in het geomagnetisch veld via een ExB drift die een gevolg is van hun eigen elektrische polarisatie. De elektrische polarisatie, thermo-elektrische ladingsscheiding en niet- adiabatische remming zijn belangrijke niet-ideale MHD processen. The dipool-dipool interactie tussen het dipolair veld van de Aarde en het systeem ladingsstromen geassocieerd aan een 3- dimensionaal diamagnetisch plasmoïde dat binnendringt kan de indringsnelheid vergroten of verkleinen alnaargelang de oriëntatie van het interplanetair magnetisch veld (IMV) Een groot aantal laboratoriumexperimenten evenals bijlangrijke geofysische waarnemingen zijn consistent met dit model van impulsieve penetratie.

Zusammenfassung

Nach dem von Lemaire und Roth vorgeschlagenen Modell der “impulsive Penetration” dringen Plasmaunregelmässigkeiten der Magnetohülle mit überhöhter Impulsionsdichte, durch einen aus ihrer eigenen elektrischen Polarisation herrührenden Drift $\mathbf{E} \times \mathbf{B}$, in das geomagnetische Feld ein. Elektrische Polarisation, Trennung thermoelektrischer Ladungen und nicht-adiabatische Bremsung sind wichtige Prozesse nicht-idealer MHD. Die wechselseitig wirkende Dipol-Dipol-Kraft zwischen dem dipolaren Feld der Erde und dem Strömungssystem eines eindringenden dreidimensionalen diamagnetischen Plasmoiden kann die Eintrittsgeschwindigkeit je nach Orientierung des interplanetaren Magnetfeldes (IMF) erhöhen oder vermindern. Eine grosse Reihe Labortests sowie wichtige geophysische Beobachtungen sind mit diesem Modell der impulsiven Penetration vereinbar.

1 Introduction

The idea that magnetosheath plasma elements with an excess momentum density can penetrate impulsively through the magnetopause was proposed by *Lemaire and Roth* [1978]. It was observations of the irregular nature of the interplanetary magnetic field (IMF) [*Burlaga et al.*, 1977] that led to the conclusion that small-scale plasma density irregularities are present almost all the time in the solar wind, associated with the frequent small changes of the three components of the IMF. Later, such small-scall irregularities were indisputably identified by the ISEE wave propagation experiment [*Harvey et al.*, 1979; *Celnikier et al.*, 1987]. Their presence in the solar wind indicates that the solar wind momentum density is nonuniform over distances much smaller than the diameter of the magnetosphere. These solar wind plasma elements are "plasmoids", i.e., they are plasma-magnetic entities [*Bostick*, 1956].

If one of these many plasma density enhancements ($dn > 0$) moves towards the magnetopause with the background solar wind speed (V_{sw}), its momentum density, $(n + dn)mV_{sw}$, is then necessarily larger than the average (nmV_{sw}). This plasma element will conserve its excess momentum (or at least a part of it) after it has passed through the magnetospheric bow shock. Therefore it will reach the position of the mean magnetopause with an excess momentum and an excess kinetic energy.

2 Schmidt's theory revisited

Schmidt [1960] has described how a self polarization electric field builds up in a weakly diamagnetic plasma element injected into different magnetic field configurations of interest for laboratory experiments. When we consider the penetration of solar wind plasma elements into the magnetosphere the magnetic field configuration should simulate the magnetopause interface where the magnetic field changes from a fixed direction in the magnetosphere to arbitrary orientations and intensities in the magnetosheath. We can also consider that the unperturbed magnetosphere is closed so that its surface is a tangential discontinuity in a first approximation. Schmidt's theory assumes that the motion of a solar wind plasma element can be described using the guiding center approximation, according to which the guiding center of a gyrating particle drifts perpendicular to the magnetic field with the velocity

$$\mathbf{W}_{\perp} = \mathbf{W}_{0\perp} + \frac{\mu}{qB^2}\mathbf{B} \times \nabla B + \frac{m}{qB^2}\mathbf{B}\times\frac{d\mathbf{W}_{0\perp}}{dt} \tag{1}$$

where q, m and μ are the charge, mass and the magnetic moment of the gyrating particle. In (1) the first right-hand term is the electric drift ($\mathbf{W}_{0\perp} = \mathbf{E} \times \mathbf{B}/B^2$) resulting from the charge separation electric field arising from the opposite $q\mathbf{V} \times \mathbf{B}$ force of the ions and electrons ($\mathbf{V}$ is the bulk velocity of the plasmoid). This first right-hand term is of zeroeth order, the others of first order, in the usual guiding center expansion. The second term is the gradient-B drift and the last one is the polarization drift. The first order drifts are not necessarily small compared to the perpendicular component of the zero-order drift velocity ($\mathbf{W}_{0\perp} \approx \mathbf{V}_{\perp}$) and are opposite for ions and electrons.

Because the curvature of the magnetopause is negligible the centrifugal drift, studied by *Lemaire* [1985], has been neglected in (1). Centrifugal and gradient-B drifts contribute to an eastward deflection of plasmoids penetrating impulsively into the dawn and dusk flanks of the magnetosphere. The gradient-B and curvature drifts depend on the mass to charge ratio. Therefore the bulk velocity of different ion species in plasmoids will be different. This is precisely what has been observed by *Lundin and Dubinin* [1985] from Prognoz-7 observations: within plasma density enhancements observed in the magnetopause region, the He^{++} ions (of solar wind origin) do not drift in the same direction, nor with the same speed, as the He^{+} and O^{+} ions (of magnetospheric origin). Furthermore, the drifts of the ions species were observed to be significantly different from the $\mathbf{E} \times \mathbf{B}/B^2$ convection velocity which is the only drift considered in the "frozen-in field" approximation of ideal MHD.

The rate of change of the electric field inside the moving element can be calculated from the simple "capacitor" model introduced by *Schmidt* [1960]. It is given by

$$\frac{\partial \mathbf{E}}{\partial t} = -\frac{q^+ n^+ \overline{\mathbf{W}_{\perp}^{+}} + q^- n^- \overline{\mathbf{W}_{\perp}^{-}}}{\epsilon_0} \tag{2}$$

where the bars over quantities indicate variables averaged over the velocity distribution of the ions and electrons [*Lemaire*, 1985]. It should be pointed out that magnetization currents do not contribute to a net transport of electric charges. Therefore these magnetization currents are not included in the right-hand side of (2). The acceleration of the plasmoid ($d\mathbf{V}_{\perp}/dt$) is obtained from (1) and (2) as

$$\frac{d\mathbf{V}_{\perp}}{dt} = -\frac{\overline{\mu^+} + \overline{\mu^-}}{m} \nabla B \tag{3}$$

To obtain (3) we have taken into account that the plasma dielectric constant is large, that the electron mass (m^-) is negligible compared to the ion mass ($m^+ = m$), and that the zero-order drift velocity ($\mathbf{E} \times \mathbf{B}/B^2$) is close to the perpendicular bulk velocity of the penetrating solar wind plasmoid ($\mathbf{V}_{\perp}$).

The acceleration $d\mathbf{V}_{\perp}/dt$ in (3) is a vector parallel to $-\nabla B$, that is, a vector parallel to the normal component of the magnetopause tangential discontinuity. If the x axis is directed along the normal to the magnetopause, the forward velocity of the plasmoid, ($V_{\perp}(x) = V_x(x)$) is obtained by integrating (3) from x_0 (the point of impact at the magnetopause where the magnetic field strength is B_0) to x (a place inside the magnetosphere where the magnetic field strength is $B(x)$)

$$V_x(x) = \left\{ V_{ex}^2 + 2\frac{\overline{\mu^+} + \overline{\mu^-}}{m}[B_0 - B(x)] \right\}^{1/2} \tag{4}$$

where V_{ex} is the normal component of the plasmoid residual velocity at the point of impact on the magnetopause [*Lemaire*, 1985]. When the direction of the magnetic field rotates by an arbitrary angle across the magnetopause tangential discontinuity, the tangential polarization electric field inside the plasmoid ($\mathbf{E}_t = (0, E_y, E_z)$) rotates by the same angle. Both vectors $\mathbf{E}_t$ and $\mathbf{B}$ remain orthogonal to each other. At a zero-order approximation $E_t(x)$ varies with x as $V_x(x)/B(x)$ where $V_x(x)$ is given by (4). Therefore in the guiding center approximation the velocity of weakly diamagnetic plasmoids penetrating into the magnetosphere does not depend on the angle of rotation of the magnetic field across the magnetopause.

A normal polarization electric field E_x appears in a penetrating plasmoid, that is connected with the inhomogeneity of the surface charge density responsible for the tangential polarization field $\mathbf{E}_t$. In the experiments by *Demidenko et al.* [1969, equation 12], $E_x = ydE_y/dx$ near the symmetry plane ($y = 0$) of plasma streams penetrating across inhomogeneous, but unidirectional magnetic fields (B_z). In these experiments the latter analytical expression for E_x was shown to be in excellent agreement with experimental measurements of the normal electric field. Extrapolation to rotating magnetic field configurations should lead to: $E_x = ydE_y/dx + zdE_z/dx$. It then follows that, sufficiently far from the front of the plasmoid (where $\partial\mathbf{B}/\partial t \approx 0$), the Faraday law ($\nabla \times \mathbf{E} \approx 0$) is satisfied in the general case when $\mathbf{B}$ rotates. Because the charges experience a drift in opposite directions in the crossed fields E_x and $\mathbf{B}$, changes take place in the y and z dimensions of the plasmoid (see *Demidenko et al.* [1969]).

3 Adiabatic and non-adiabatic braking

From (4) it can be seen that a plasmoid penetrating into the magnetosphere is decelerated adiabatically when the magnetic field intensity inside the magnetosphere is larger than in the magnetosheath. Conversely it is accelerated adiabatically when the magnetic field intensity is smaller in the region where it penetrates. A plasmoid cannot penetrate further than x_1, a position in the magnetosphere where the magnetic field intensity is

$$B(x_1) = B_0 \left\{ 1 + \frac{mV_{ex}^2}{2k(T_{\perp 0}^+ + T_{\perp 0}^-)} \right\} \tag{5}$$

The quantity between braces is equal to $M_s^2 + 1$, where M_s is the sonic Mach number in the magnetosheath. Note that a plasmoid penetrates a larger distance inside the magnetosphere ($B(x_1)$ increases) when B_0 or/and M_s increase. To our knowledge, it is *Schmidt* [1960] who first gave the theoretical demonstration of this adiabatic slowing down mechanism which was later confirmed by laboratory experiments like those of *Demidenko et al.* [1969, 1972]. In these experiments the magnetic field intensity was nonuniform: B increased along the x axis, like the geomagnetic field.

In addition to the adiabatic slowing down mechanism the plasmoid is also decelerated non-adiabatically by dissipation of its kinetic energy by Joule heating in the resistive cusp ionosphere. Indeed, like the walls of the vacuum chamber in the laboratory plasma experiments of *Baker and Hammel* [1962, 1965], the Earth's ionosphere is an electric load coupled to the moving plasmoid via magnetic field lines whose parallel conductivity is extremely large but whose transverse (integrated) Pedersen conductivity (Σ_p) always has a finite value at low altitudes [*Lemaire*, 1977; *Lemaire and Roth*, 1978]. When the ionospheric Σ_p is large the polarization electric field inside the moving plasma element (which keeps it moving) as well as the electric field in its surrounding (which deflects the magnetospheric plasma around the intruding plasmoid) are quickly short-circuited, and consequently, the penetration velocity also quickly slows down to zero.

4 Influence of the IMF

It is worth noting that (1), (2) and (3) are valid for a diamagnetic plasmoid (in general, the effects of the curvature drifts could also be included). But in the case of high β plasmoids, the magnetic field **B** in these equations, is the sum of the externally imposed field and the diamagnetic fields associated with all local and distant currents. The fact that a diamagnetic plasmoid can penetrate across a nonuniform magnetic field was illustrated in *Demidenko et al.* [1969], since for some of their experiments, $\beta \approx$ 2–3 ($n \approx 5\times10^{14}$ cm^{-3}, $V_0 \approx 5\times10^6$ cm/s, B = 500 G).

A three-dimensional diamagnetic plasma cloud in the solar wind satisfies Bostick's definition of a plasmoid, since it has a measurable magnetic moment, a measurable translation speed, a transverse electric field, and a measurable size [*Bostick,* 1956]. The magnetization currents circulating around (and possibly inside) the body of this plasma cloud have a finite net magnetic moment, **M**, which produces a dipole-like magnetic field. It is important to note that when magnetic field lines cross the surface of the plasmoid electrostatic double layers appear. The distribution of charges inside these double layers can be quite complex. The resulting parallel electric fields, localized at the surface of the plasmoid, are assumed to be able to prevent both electrons and ions from escaping outwards.

Because of the magnetic force $\nabla(\mathbf{M}.\mathbf{B}_E)$ between the geomagnetic field $\mathbf{B}_E$ and the magnetic moment **M** of a diamagnetic plasmoid, the impulsive penetration can be accelerated or decelerated depending on the orientation of the interplanetary magnetic field (IMF). Indeed, drifts ($\nabla(\mathbf{M}.\mathbf{B}_E)\times\mathbf{B}/qB^2$), which arise due to this magnetic force, will act to increase or decrease the polarization electric field, depending on the orientation of the force. These drifts correspond to the second term in the right-hand side of (1). The resulting acceleration or deceleration of the plasmoid is always in the direction of $\nabla(\mathbf{M}.\mathbf{B}_E)$. This effect is summarized in figure 1 (see *Lemaire* [1987], and *Lemaire and Roth* [1991, p 83–88] for a recent review). As the magnetic moment of a diamagnetic plasmoid is always pointing in a direction opposite to the external magnetic field, it is easy to deduce the direction of the magnetic interaction force $\nabla(\mathbf{M}.\mathbf{B}_E)$ acting on an intruding plasmoid at different places on the magnetopause surface and for different orientations of the IMF. For instance, when the IMF has a northward component (figure 1a), the magnetic interaction force between plasmoids and the geomagnetic field favours the impulsive penetration in the magnetotail lobes, but tends to reject the intruding plasmoid at low latitudes, near the frontside magnetopause. This conclusion is reversed when the IMF has a southward component (figure 1b).

The change in the polarization electric field inside a penetrating diamagnetic plasmoid, due to the $\nabla(\mathbf{M}.\mathbf{B}_E)\times\mathbf{B}/qB^2$ drifts, is maximum near the polar cusps where $\nabla B_E/B$ is the largest. Furthermore, for any orientation of the IMF (and any orientation of the plasmoid magnetic moment) there is always a place near the neutral points where the magnetospheric field is anti-parallel to the magnetic field in the magnetosheath. This is where the magnetic force acting on the plasmoid is maximum and directed toward the interior of the magnetosphere. When IMF $B_y > 0$ this place is shifted toward dusk (dawn) with respect to the location of the northern (southern) polar cusp. As a consequence, the region of preferred impulsive penetration of solar wind plasmoids is shifted toward dusk (dawn) in the northern (southern) hemisphere. The direction of these shifts is reversed in both hemispheres when IMF $B_y < 0$. Note that similar conclusions have been obtained in theories of “antiparallel merging”.

The magnetospheric and ionospheric convection patterns resulting from impulsive penetration have been studied by *Lemaire* [1987]. Sporadic sunward flows of ionospheric plasma over the northern and southern polar caps have been observed when the IMF has a northward B_z component (see for instance, *Zanetti et al.* [1984]). The locations where sunward flows were observed are shifted toward the dawn or dusk side of the polar caps depending on the sign of IMF B_y. By mapping the flow patterns surrounding penetrating plasmoids under different IMF conditions, these observations have been explained in the framework of the impulsive penetration model [*Lemaire*, 1987; *Lemaire and Roth*, 1991].

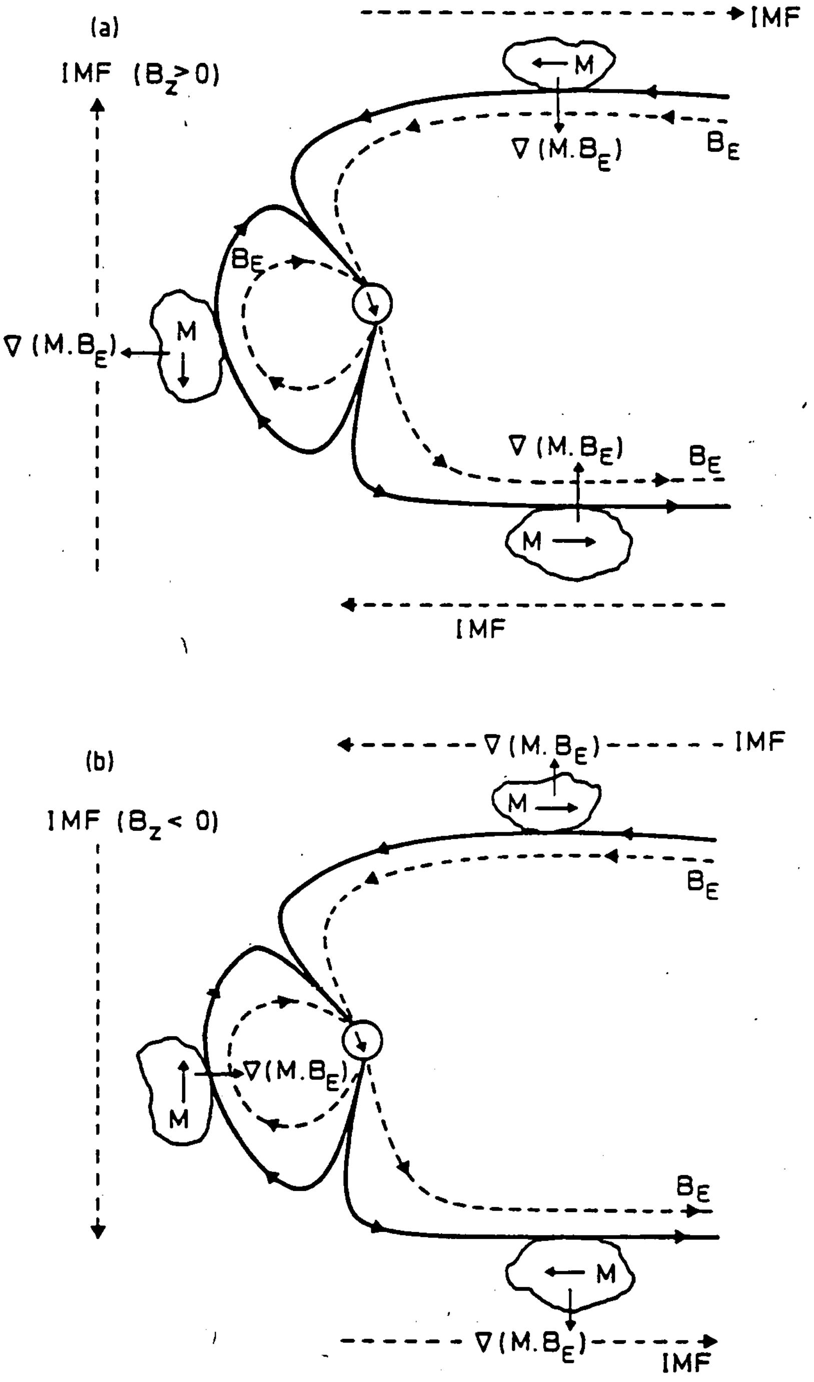

Figure 1: Meridional sections illustrating the dipole-dipole interaction force $\nabla(\mathbf{M} \cdot \mathbf{B}_E)$ acting on a penetrating diamagnetic plasmoid at different locations on the magnetopause surface: (a) for IMF $B_z > 0$; (b) for IMF $B_z < 0$.

5 Discussion

Impulsive penetration of solar wind plasma across the magnetopause is a potentially important and highly debated topic in magnetospheric research, which challenges the reconnection or merging theories. Lemaire and Roth's mechanism has often been quoted in relation to magnetosheath plasma injection events observed at the dayside magnetopause and in the low latitude boundary layer (see *Lundin* [1988] for a review, and *Woch and Lundin* [1991] for recent Viking observations) and their ionospheric or auroral signatures [*Lundin and Evans,* 1985; *Heikkila et al.,* 1989; *Lui and Sibeck,* 1991; *Roth et al.,* 1993; *Newell and Meng,* 1994; *Moen et al.,* 1994].

It is important to point out that the frozen-in-field condition ($\mathbf{E} \cdot \mathbf{B} = 0$) is not satisfied everywhere along magnetic field lines connected to penetrating solar wind plasmoids because of the existence of electrostatic double layers located at the surface of these plasma structures. Non ideal MHD effects such as resistive dissipation or particle inertia have been discussed qualitatively by *Schindler* [1979] in an attempt to evaluate the role of solar wind irregularities in plasma entry into the magnetosphere. These non-MHD effects are strongest in regions where solar wind irregularities locally compress the magnetopause. Following Schindler, merging or diffusion processes had to be postulated in these dissipation regions for impulsive entry to occur. Spontaneous reconnection may also occur behind the intruding "filament" in cases of high relative momentum [*Schindler*, 1979, figure 7] or at two remote non-ideal dissipation regions located along the magnetic field lines connected to the filament [*Schindler*, personal communication, 1994]. However in Lemaire and Roth's mechanism thermo-electric charge separation is the primary "non-dissipative mechanism" which violates the ideal MHD condition $\mathbf{E} \cdot \mathbf{B} = 0$. Note that, due to the inhomogeneity of the polarization electric field the potential differences between two adjacent magnetic field lines are not identical on both sides of the plasmoid boundary. This is why the charge distribution within the plasmoid boundary is able to decouple the plasmoid from neighboring plasma located on the same field lines. A quantitative study of this effect is required to analyze the decoupling more accurately.

Entry of filaments within ideal MHD theory in a two-dimensional model has been shown to occur only if the magnetic fields in the magnetosheath and magnetosphere are nearly aligned [*Schindler,* 1979; *Ma et al.,* 1991]. Note that within these 2-D infinitely long filaments, there is no magnetic coupling between the inside and the outside [*Lemaire and Roth,* 1981], in contrast with a real 3-D plasmoid.

Heikkila [1982] has proposed a theory for impulsive penetration of solar wind plasma clouds that is quite different from that introduced by Lemaire and Roth. In Heikkila's mechanism a magnetosheath plasma cloud with some excess momentum is assumed to distort the surface of the magnetopause, and its associated currents, inducing an electric field that can be of the order of 1–2 mV/m. Following Heikkila, the induction electric field and the cloud polarization electric field are just what is needed so that the plasma can follow the moving magnetopause, assuming that there is no normal component of the magnetic field B_n. When B_n is introduced into the problem, a normal component of the inductive electric field causes the plasma to polarize along B_n. This polarization enhances the transverse component of the inductive electric field. That enhancement allows the cloud to move through the moving magnetopause. Heikkila's mechanism has been subsequently criticized by *Owen and Cowley* [1991] who claimed that the electromagnetic field distribution in this model violates Faraday's law. This subject remains controversial (see *Heikkila* [1992], *Owen and Cowley* [1992]).

Heikkila's mechanism for impulsive penetration, although different from that introduced by Lemaire and Roth, is based on the same premises, that is, that the penetrating plasma elements are of solar wind origin and do not necessarily result from local instabilities at the magnetopause. Differences between the two mechanisms have been pointed out by *Roth* [1992, p. 199–200]. In Heikkila's model, Schmidt's mechanism is effective once the plasmoid is inside the magnetosphere. In his scenario, Heikkila considers singular magnetic field configurations with X-line topologies, like those postulated in reconnection or merging theories, while in Lemaire and Roth a B_n component is not a necessary ingredient of the theory.

The merit of Heikkila's approach to the problem of impulsive penetration is to have outlined the role of induced electric fields. Lemaire and Roth did not consider this aspect in their model, neglecting induced electric fields in a first approximation on the basis that polarization electric fields have a larger intensity ($\approx$ 5 mV/m) than induced electric fields ($\approx$ 1–2 mV/m). It is clear however that induced electric fields should not be ignored in a self-consistent theory. Indeed, as a consequence of the penetration of diamagnetic plasmoids, the outer geomagnetic field distribution becomes distorted and variable in time. By vector superposition of the variable diamagnetic field carried by moving plasmoids, and the earth's magnetic field, one obtains patchy and time-dependent interconnections of magnetic field lines as illustrated in a video film (*J. Lemaire and M. Roth*, A simulation of the interconnection between interplanetary magnetic field lines and geomagnetic field lines, IASB, Brussels). Bundles of geomagnetic field lines interconnected to those of interplanetary space in a dynamical way indicate that the impulsive penetration theory, when properly understood, does predict the existence of interconnected magnetic field lines inherent in early steady state "open" magnetospheric models.

Like many effects described in the space plasma literature, some aspects of the impulsive model need a more quantitative description than is now available. Indeed, this model depends on a number of plasma and field parameters (value of excess momentum, intensity of dipole-dipole interaction force, value of height-integrated Pedersen conductivity, etc.). *Lemaire* [1977, 1985] has given quantitative estimates of the maximum penetration depth based on adiabatic and non-adiabatic braking of the plasmoid, as a function of the height-integrated Pedersen conductivity or as a function of magnetic field and solar wind parameters. The influence of other physical parameters needs to be simulated and worked out on a quantitative basis.

However, the basic kinetic description of the physical mechanism setting up the polarization electric field within a plasmoid, and permitting it to penetrate in a higher magnetic field, is well established. It should be pointed out that this description remains valid in the high β limit since the particle drifts caused by the external dipole-dipole interaction force contribute to increase or decrease the polarization electric field, depending on the relative orientation of the magnetic moment of the plasmoid with the geomagnetic field. Furthermore, some of the laboratory experiments carried out by *Demindenko et al.* [1969] demonstrate that plasmoids with β of the order of 2–3 are able to penetrate through an inhomogeneous magnetic field.

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