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ON IMPULSIVE PENETRATION OF SOLAR WIND PLASMOIDS INTO THE GEOMAGNETIC FIELD

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Abstract—The idea that solar wind plasma-field irregularities, i.e. plasmoids with an excess momentum density penetrate deeper into the geomagnetic field was introduced in 1976 by Lemaire and Roth at an EGS meeting. It was based on the observation that the solar wind is most of the time patchy over distances smaller than the diameter of the magnetosphere. In this early paper about "impulsive penetration", the authors did not attend to give a detailed physical description of the underlying mechanism. When Lemaire was more informed about some relevant laboratory plasma experiments carried out by Bostick, Baker and Hammel or Demidenko *et al.*, he published in 1985 [Lemaire, J. (1985) *Plasma Phys.* **33**, 425] a physical description of the mechanism, based on a theory first proposed by Schmidt in 1960 [Schmidt, G. (1960) *Phys. Fluids* **3**, 961].

Transient and impulsive interaction processes between the solar wind and the magnetosphere have now become an important and highly debated topic. In particular, Heikkila's argument claiming that the effects of induced electric fields are the primary cause for impulsive penetration has been shown by Owen and Cowley to be erroneous. Although the conclusions reached by Owen and Cowley [Owen, C. J. and Cowley, S. W. H. (1991) *J. geophys. Res.* **96**, 5565] are correct, at least within the framework contrived by Heikkila (i.e. that of ideal MHD) [Heikkila, W. J. (1982) *Geophys. Res. Lett.* **9**, 159], they do not demonstrate that real plasmoids can not penetrate impulsively onto closed geomagnetic field lines. Indeed, non-ideal MHD processes, like collective polarization effects, formation of electrostatic potential barriers, adiabatic and non-adiabatic brakings or collective diamagnetic effects, have to be taken into account in the "real world".

Account of the theory of "impulsive penetration" both for weakly and strongly diamagnetic plasmoids is given, emphasizing in which respect the entry mechanism differs from ideal entry mechanisms like those proposed by Schindler in 1979 [Schindler, G. (1979) *J. geophys. Res.* **84**, 7257] and by Heikkila in 1982.

1. INTRODUCTION

Transient and impulsive interaction processes between the solar wind and the magnetosphere have now become an important and highly debated topic in magnetospheric research (see for instance the recent paper by Owen and Cowley, 1991). In particular, the mechanism for an impulsive transport of magnetosheath plasma elements through the magnetopause, first proposed by Lemaire and Roth in 1976 at an EGS meeting on "the magnetopause regions" (Lemaire and Roth, 1978), has been often quoted in recent years in relation to magnetosheath plasma injection events observed at the dayside magnetopause and in the low latitude boundary layer region (Lundin, 1984; Lundin and Aparicio, 1982; Lundin and Dubinin, 1984, 1985; Lundin and Evans, 1985; Lundin *et al.*, 1987) and their ionospheric signatures near the polar cusp boundary (Sandholt and Egeland, 1988; Sandholt *et al.*, 1986; Lui and Sibeck, 1991; Wei and Lee, 1990; Lanzerotti, 1989; Lanzerotti *et al.*, 1990; Heikkila *et al.*, 1989; Woch and Lundin, 1991).

In retrospect, the mechanism proposed by Lemaire and Roth in 1976 was a "rediscovery" since the physical theory of the motion of plasma-magnetic entities across non-uniform magnetic field distributions was first described by Schmidt (1960). The validity of Schmidt's kinetic theory has been confirmed by relevant laboratory plasma experiments carried out by Bostick (1956, 1957), Baker and Hammel (1962, 1965), Wessel *et al.* (1988), as well as by Demidenko *et al.* (1966, 1967, 1969, 1972). These experiments have indeed demonstrated that slightly diamagnetic plasma streams injected impulsively across uniform or non-uniform magnetic fields are able to penetrate the magnetic field by electrically polarizing and producing an $\mathbf{E} \wedge \mathbf{B}$ drift. The relevance of these experimental results to the problem of the solar wind magnetosphere interaction has been subsequently discussed in some detail by Lemaire (1989).

But in 1976 other sets of observations had led Lemaire and Roth to the idea of "impulsive penetration" of solar wind plasma elements through the magnetopause: namely the high-time resolution magnetic field observations in the solar wind. These observations indicate that almost all the time there are small directional changes in IMF components similar to those observed by Burlaga *et al.* (1977). It is indeed unusual to find in high resolution magnetograms periods of more than 30 s of time when all three IMF components do not change at least by a few percent.

There are also, but less frequently, field variations with much larger amplitudes (Burlaga *et al.*, 1977; Turner *et al.*, 1977). The frequent small changes of the IMF intensity and direction over time scale of seconds (i.e. scale lengths of 1000–3000 km) are evidence that small-scale electric currents are flowing nearly everywhere within the solar wind plasma. This system of small-scale currents is the manifestation of small-scale plasma elements, i.e. plasma density and/or temperature gradients in the solar wind. These small-scale plasma density irregularities have been indisputably identified in Harvey's observations obtained from the wave propagation experiment (Harvey *et al.*, 1979; Celnikier *et al.*, 1983, 1987). The presence of these plasma irregularities indicate that the solar wind momentum density is not uniform over distances much smaller than the diameter of the magnetosphere, and that the dynamic pressure the solar wind inflicts upon the magnetosphere must be patchy, non-uniform and rapidly changing in time as emphasized by Sibeck *et al.* (1989a, b).

These solar wind plasma elements are "plasmoids", a word which means plasma-magnetic field entities (according to the definition of Bostick, 1956). Such a generic name has the advantage of including not just the special kind of magnetic field signatures now singled out as *flux transfer events* (FTE), but also the whole of many other **B**-field signatures (and plasma density structures) which are usually seen in the vicinity of the magnetopause region. These plasmoids, which are almost always present in the solar wind, can penetrate inside the geomagnetic field beyond what is considered to be the mean position of the magnetopause. These plasma elements penetrate deeper when they have an excess momentum density with respect to the background solar wind plasma. Collisionless solar wind plasmoids are thrown into the geomagnetic field, just like rain droplets penetrate impulsively through the surface of a lake (Lemaire and Roth, 1978; Lemaire, 1979a). This idea is illustrated in Fig. 1b showing a series of plasmoids at different depths inside the magnetosphere.

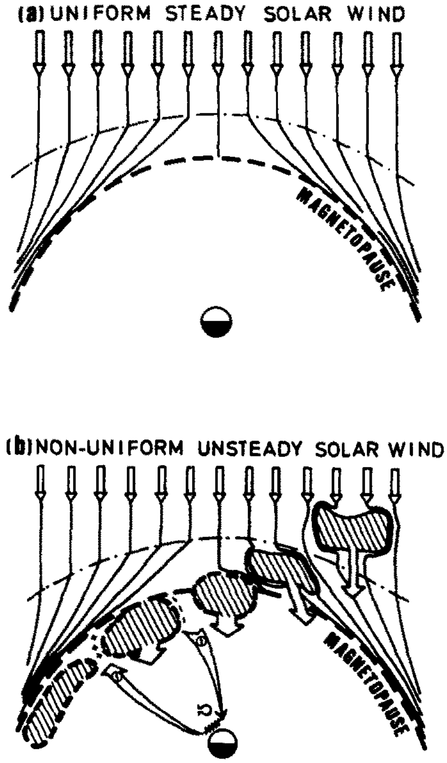

Fig. 1. Equatorial sections of the magnetosphere.
(a) When the solar wind is steady and uniform, the magnetopause is a smooth surface along which the solar wind slips without penetration. (b) When the solar wind is non-uniform and unsteady, plasma density irregularities (plasmoids) carried in the solar wind will be able to penetrate deeper in the geomagnetic field provided they have an excess momentum density (after Lemaire and Roth, 1978).

It is also interesting to quote a suggestion made by Gold in 1959 in order to interpret the magnetic variations on the ground (both in time and position) during a magnetic storm. Following Gold, these variations are likely to have their sources in a magnetopause "containing many fine corrugations or tongues with scale lengths not greater than a few hundred km" (Gold, 1959). "When the electric currents flowing at the surface of these small-scale features dissipate, the penetrating tongues of solar field can then shed its particles into the terrestrial field." The essential difference between Gold's interpretation and ours resides in the origin of these tongues: according to Gold, the small-scale patchiness at the magnetopause is a phenomenon set up by an instability of the solar wind flow, while we argue that this patchiness originates from plasmoids brought in from the solar wind through the bow shock and magnetosheath. In this respect, Gold's interpretation is thus closer to that of Miura (1987) who considers that Kelvin–Helmholtz instabilities at the magnetopause surface can push plasma tongues through the magnetopause.

In this paper, the *impulsive penetration theory* is reviewed emphasizing in which respects the entry mechanism differs both, from the ideal MHD entry mechanism proposed by Schindler (1979), and from that developed by Heikkila (1882) and recently criticized by Owen and Cowley (1991).

2. IMPULSIVE PENETRATION OF A PLASMOID INTO THE MAGNETOSPHERE

The theory of impulsive penetration has been explained in a series of papers (Lemaire and Roth, 1978, 1991; Lemaire, 1977, 1979a, b, 1985, 1987, 1989; Lemaire *et al.*, 1979). In this section, we outline the mean features of this theory, i.e. we examine what happens when the solar wind is not uniform and not stationary, but formed of small-scale plasma density irregularities, like those illustrated in Fig. 1b.

Let us consider one of these many plasma density enhancements ($dn > 0$) moving towards the magnetopause with the background speed (V_{sw}). If this plasmoid corresponds to an excess density but has the same bulk velocity as the surrounding solar wind background, its momentum density, $(n+dn)mV_{sw}$, is then necessarily larger than the average (nmV_{sw}).

This plasma element will conserve its excess momentum after it has passed through the magnetospheric bow shock. Therefore, it can plough its way through the magnetosheath with a larger speed than the decelerated average solar wind plasma. Unlike the other plasmoids which have a lower momentum density than average, the former one will reach the position of the mean magnetopause with an excess momentum and an excess kinetic energy. At the mean magnetopause position, where the normal component of background magnetosheath plasma velocity becomes equal to zero, the plasmoid has a residual velocity (V_e) given by

$$V_e = V_{sw}\, dn/(n+dn). \tag{1}$$

The penetration mechanism of the plasmoid into the region of the magnetospheric field lines lies between the following two extreme cases: weakly diamagnetic, low-β plasmoids on one hand, and strongly diamagnetic, high-β plasmoids on the other hand.

2.1. *The plasma is weakly diamagnetic* ($\beta \ll 1$)

In this case, the plasmoid enters the geomagnetic field by means of an electric polarization and its associated $\mathbf{E} \wedge \mathbf{B}$ drift. Indeed, when the density of ions and electrons is large enough for the plasma dielectric constant ε to be much larger than unity (this is always the case in space plasmas), collective plasma effects lead to the accumulation of polarization charges which generates a local (internal) electric field inside the moving plasma element such that its initial momentum can be preserved. For weakly diamagnetic plasmoids the penetration and crossing of the magnetic field by this mechanism has been demonstrated by the laboratory experiments already quoted in the introduction. It has also been discussed theoretically by Schmidt (1960). We will now concentrate on this mechanism for solar wind plasmoids entering into the non-uniform geomagnetic field.

Since we assume in this section that the plasma is weakly diamagnetic, diamagnetic currents or other plasma currents generate additional magnetic fields which are small compared with the applied external magnetic field strength. This implies that the total energy density of the particles is much smaller than the magnetic energy density, i.e. plasma-$\beta \ll 1$.

Under these low-β conditions the total **B**-field inside and outside the plasmoid is close to the externally imposed field. When the variation of the magnetic field is small over a few Larmor gyroradii, the guiding centre of a gyrating particle drifts perpendicular to the magnetic field with the velocity

$$\mathbf{w}_\perp = \frac{\mathbf{E} \wedge \mathbf{B}}{B^2} + \frac{\mu}{qB^2}\mathbf{B} \wedge \operatorname{grad}(B) + \frac{m}{qB^2}\mathbf{B} \wedge \frac{d}{dt}\left(\frac{\mathbf{E} \wedge \mathbf{B}}{B^2}\right), \tag{2}$$

where q, m and μ are the charge, mass and the magnetic moment ($\mu = mv_\perp^2/2B$ is an adiabatic invariant) of the gyrating particle, respectively (Schmidt, 1960; Lemaire, 1985). In equation (2), the curvature (centrifugal) drift has been neglected [this drift contributes to an additional eastward deflection of a solar wind plasmoid entering into the dayside magnetopause, as shown by Lemaire (1985)]. The first term on the right-hand side of equation (2) is of zero order; the others are first-order corrections, in the usual guiding centre approximation. The last term is the inertial drift caused by the inertial forces arising in the coordinate system moving with the zero-order drift velocity. Since the centrifugal drift is not taken into account here, the only inertial drift is the polarization drift, coming from the inertial forces due to changes in the electric drift, i.e.

$$\mathbf{w}_p = \frac{m}{qB^2}\mathbf{B} \wedge \frac{d}{dt}\left(\frac{\mathbf{E} \wedge \mathbf{B}}{B^2}\right). \tag{3}$$

The last two terms of equation (2) corresponds thus to the grad B and polarization drifts, respectively. Their directions are opposite for electrons and ions. These drifts are not necessarily small compared to the perpendicular component of the zero-order guiding centre velocity

$$\mathbf{w}_\perp^0 = \frac{\mathbf{E} \wedge \mathbf{B}}{B^2} \approx \mathbf{V}_\perp, \tag{4}$$

where $\mathbf{V}_\perp$ is the perpendicular bulk velocity of the plasmoid.

As a consequence of the oppositely directed drifts for ions and electrons, the ions tend to form a positive space charge along one of the lateral surfaces of the moving plasmoid, while the electrons build up a negative surface charge on the opposite side as described by Schmidt (1960). These drifts generate polarization currents which do not however modify significantly the external geomagnetic field. Therefore

$$\mathrm{curl}\,(\mathbf{B}) \approx 0. \tag{5}$$

Neglecting stray fields and magnetization currents because of the low-β conditions, the rate of change of the electric field inside the moving plasmoid is then given by

$$\frac{\partial \mathbf{E}}{\partial t} = -\frac{q^+n^+\langle \mathbf{w}_\perp^+\rangle + q^-n^-\langle \mathbf{w}_\perp^-\rangle}{\varepsilon_0}. \tag{6}$$

After averaging the drift velocity [equation (2)] over the velocity distribution of the ions and electrons ($\langle \mathbf{w}_\perp^+\rangle$ and $\langle \mathbf{w}_\perp^-\rangle$), taking into account that $q^+n^+ = -q^-n^- = qn$ and neglecting the electron mass (m^-) as compared with the ion mass ($m^+ = m$), equation (6) becomes

$$\frac{\partial \mathbf{E}}{\partial t} = -\frac{nm}{\varepsilon_0 B^2}\mathbf{B} \wedge \left[\frac{\langle \mu^+\rangle + \langle \mu^-\rangle}{m}\,\mathrm{grad}\,(B) + \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathbf{E}\wedge\mathbf{B}}{B^2}\right)\right]. \tag{7}$$

It can be seen from equation (7) that the polarization electric field building up with time is normal to $\mathbf{B}$. Since the plasma dielectric constant ($\varepsilon = 1 + nm/\varepsilon_0 B^2 = 10^3$–$10^5$ in thermal space plasmas) is very large, the value of the expression within the brackets in equation (7) must be very small in order to avoid unreasonably high values for the rate of change of the electric field intensity.

Therefore, taking into account of equation (4), it can be deduced that $\mathrm{d}\mathbf{V}_\perp/\mathrm{d}t$ is a vector parallel to $-\mathrm{grad}\,(B)$, i.e. parallel to Ox, the normal component of the magnetopause (assumed to be locally a tangential discontinuity)

$$\frac{\mathrm{d}V_\perp}{\mathrm{d}t} = V_\perp \frac{\mathrm{d}V_\perp}{\mathrm{d}x} = -\frac{\langle \mu^+\rangle + \langle \mu^-\rangle}{m}\frac{\mathrm{d}B}{\mathrm{d}x}. \tag{8}$$

Taking into account of the adiabatic invariance of the magnetic moments μ^+ and μ^-, and integrating equation (8) from x_0 (the point of impact on the magnetopause of the penetrating plasmoid) to x [a point inside the magnetosphere where the magnetic field strength is $B(x)$], Lemaire (1985) has deduced the forward velocity in the Ox-direction, i.e.

$$V_x(x) = \left\{V_{\mathrm{ex}}^2 + 2\frac{\langle \mu^+\rangle + \langle \mu^-\rangle}{m}[B_0 - B(x)]\right\}^{1/2}. \tag{9}$$

Replacing $\langle \mu\rangle$, the average magnetic moments of the electrons and ions, by $kT_\perp/B$, equation (9) becomes

$$mV_x^2/2 + kT_\perp^+ + kT_\perp^- = \mathrm{const.} \tag{10}$$

This implies that the sum of the translation and thermal energy densities of the ions and electrons is a constant of motion. Note from equation (9) that when the magnetic field intensity $B(x)$ is independent of x, as it is the case in Baker and Hammel's first series of experiments (Baker and Hammel, 1962), the velocity $V_x(x)$ is also independent of x.

From equation (9), it can also be seen that the 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 wherein it penetrates. Equation (9) has been used by Lemaire (1985) to determine x_1 the maximum penetration depth of the plasmoid where $V_x(x_1) = 0$. This depth is function of the injection speed V_{ex}, of the magnetosheath field (B_0), and of the mean magnetic moments $\langle \mu\rangle$ of the particles (which are determined by the perpendicular temperatures of the ions and electrons in the magnetosheath).

In addition to this adiabatic slowing down mechanism, the plasmoid is also decelerated non-adiabatically by dissipation of its kinetic energy by Joule heating in the resistive dayside 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. When 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 magnetosheath or magnetospheric plasma around the intruding plasmoid) are quickly short-circuited. This means that all electric potential gradients inside and in the vicinity of the plasmoid quickly decrease to zero. The convection electric field becomes thus vanishingly small and the bulk speed ($\mathbf{E} \wedge \mathbf{B}/B^2$) of the plasma inside as well as outside the moving plasmoid quickly slows down to zero. This non-adiabatic braking is illustrated in Fig. 2.

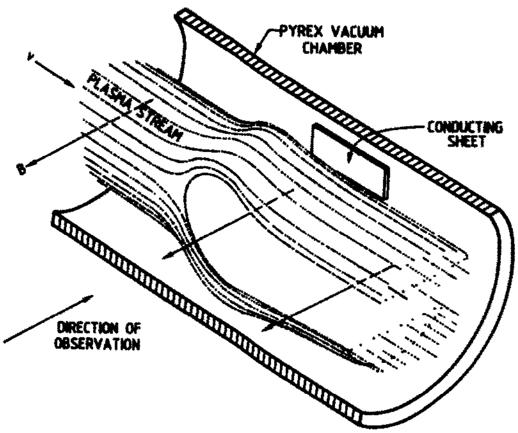

FIG. 2. SCHEMATIC DIAGRAM OF A PLASMA FLOW AROUND THE CYLINDRICAL REGION OF ZERO ELECTRIC FIELD CREATED BY A CONDUCTING STRIP LOCATED ADJACENT TO THE INSIDE WALL OF THE VACUUM CHAMBER IN THE EXPERIMENT OF BAKER AND HAMMEL.

In front of the "forbidden" region of zero electric field, the forward motion of the plasma stops and portions of the plasma drift upward and downward across the magnetic field lines connected to the insulated wall (after Baker and Hammel, 1962).

2.2. *The plasma is strongly diamagnetic* ($\beta \gtrsim 1$)

In this case, the diamagnetic currents flowing at the surface of the plasmoid produce additional magnetic fields which are comparable or larger than the background magnetic field. This also means that the total kinetic energy of the particles is at least of the order of the magnetic energy, i.e. $\beta \gtrsim 1$. From the point of view of *ideal MHD*, the plasmoid excludes the geomagnetic field from its interior as it penetrates the magnetosphere. Figuratively speaking, the plasmoid "pushes" the field lines aside and "passes" between them. Such a mechanism of field penetration has been discussed by Tuck (1959).

Note that when the plasmoid is an *infinitely* long solenoidal filament, this ideal MHD entry is only possible if the magnetic fields inside the filament and in the magnetosphere are aligned, while for oblique orientation of these fields there is a repelling force due to the piling up of magnetic flux in front of the filament (Schindler, 1979). However, this plasma structure is only of academic interest, since infinitely long solenoidal filaments necessarily have an infinite self-induction coefficient. Indeed, when this model filament, which can be compared to an infinitely long and superconducting solenoid (Lemaire and Roth, 1981), is introduced into an external magnetic field, the total magnetic energy of the system does not depend on its orientation with respect to the external field. This results of course from the absence of magnetic coupling between the inside and the outside of this ideal MHD filament. On the contrary, a real diamagnetic plasmoid is magnetically coupled to the exterior field. It produces a dipole-like magnetic field outside its surface and can be accelerated or decelerated in an external dipole magnetic field, depending on the relative orientation of their respective magnetic moments (see Lemaire and Roth, 1991, p. 84 for a discussion of the dipole–dipole interaction force between an external dipole field and the current system of a 3-D diamagnetic plasmoid).

Real solar wind plasmoids differ also from ideal MHD objects. Unlike the latter, the interface between a plasmoid and its background is not everywhere a tangential discontinuity. At the locations where field lines dip across this interface, parallel electric potential barriers inside electrostatic double layers prevent electrons from escaping outwards. These parallel potential differences imply parallel charge separation electric fields, and non-equipotential magnetic field lines (perpendicular charge separation electric fields also exist at locations where the interface is a tangential discontinuity). Obviously, the existence of finite parallel electric fields invalidates the MHD approximation near the surface of real plasmoids.

As illustrated in a video-film produced by Lemaire and Roth in 1982 and available at the Institut d'Aéronomie Spatiale (Brussels), the magnetic field line distribution in the wake of a penetrating diamagnetic filament is continuously reforming. This demonstrates that in the case of a real plasmoid, *magnetically coupled with its background*, the penetrating plasma element can become trapped inside the geomagnetic field while the magnetopause is restoring behind. Lemaire and Roth (1991) have argued that the different kinds of magnetic field signatures observed near the magnetopause (including FTE) are due to stable diamagnetic solar wind plasmoids injected from outside into the magnetopause region. According to the present mechanism of penetration there is no need to postulate neither Kelvin–Helmholtz instabilities, nor local anomalous effects in "small diffusion regions" (as postulated in reconnection or merging theories) to explain most magnetic field observations near the magnetopause.

When diamagnetic plasmoids approach the Earth's magnetosphere they produce time dependent field variations in the geomagnetic field. If the value of β is large, large induced electric fields ($\mathbf{E}_i$) are generated by these B-field variations. A simple order of magnitude calculation shows that magnetic field intensity variations of 2 nT measured over a period of 2 s (for instance across the surface of plasmoids moving past a stationary observer with a velocity of 400 km s^{-1}) will induce an electric field of 0.8 mV m^{-1}. Although the convection electric field [deduced from the zero-order guiding centre velocity of equation (4)] has a larger intensity (4 mV m^{-1}), it is clear that induced electric fields cannot be ignored when β is large.

3. COMMENTS ABOUT OWEN AND COWLEY'S CRITICISM OF HEIKKILA'S PENETRATION MECHANISM

In the previous section, we have mentioned that high-β plasmoids generate induced electric fields ($\mathbf{E}_i$) whose intensities cannot be ignored in a self-consistent theory of the solar wind–magnetosphere interaction.

The effect of these induced electric fields has been emphasized by Heikkila (1982) in the context of a magnetically "open" magnetopause (i.e. when the magnetopause has a small normal component $B_x = B_n$) with antiparallel tangential fields. In fact, the tangential magnetic field is assumed by Heikkila to be uniform on either side of the magnetopause but of opposite polarity. It has no B_y-component along the magnetopause screening current and is thus parallel to the Oz-axis. This B_z component is discontinuous at $x = 0$ (the magnetopause), i.e. $B_z = 0$ at $x = 0$; $B_z = +B_0$ for $x < 0$ (the magnetosphere); $B_z = -B_0$ for $x > 0$ (the magnetosheath, where B_z has thus a southward orientation).

Although Heikkila's mechanism for impulsive penetration is quite different from that introduced by Lemaire and Roth, it is based on the same premises, i.e. that the plasmoids have their origin in the solar wind and do not necessarily result from local instabilities at the magnetopause.

3.1. *The re-examination of Heikkila's work by Owen and Cowley*

In a recent paper, Owen and Cowley (1991) have criticized Heikkila's mechanism for the impulsive transport of magnetosheath plasma through the magnetopause configuration described above, and have shown that the argument sustaining that mechanism contains an error. This criticism has not only clarified Heikkila's mechanism but has also placed it in its true context: that of ideal MHD. As shown by Owen and Cowley, Heikkila's mechanism can be more clearly understood as a sequence of cause and effect relationships:

1. The effect of the "impact" on the magnetosphere of a solar wind plasmoid having excess momentum is to cause the magnetopause to "move in" toward the Earth in the same direction as the plasma cloud. The changing magnetic field configuration which results from the deformation of the magnetopause current layer is associated with an induction electric field. The latter has a tangential component ($\mathbf{E}_{it}$) reversing sense across the magnetopause.

2. When transforming to the rest frame of the moving magnetopause, in the centre of the perturbed region, the induction electric field is zero, since (following Heikkila) the magnetic field is steady in this frame. Accordingly, when the flow is considered in this frame, the plasma has no normal component of velocity on either side of the magnetopause. This also means that $\mathbf{E}_{it}$ is just the field required to keep the plasma cloud moving with the magnetopause.

3. The induction electric field has also a normal component (E_{in}), produced by the changing current in the normal direction at the edges of the perturbed magnetopause region. This normal electric field can, however, be discharged by a field-aligned current since the magnetic field is assumed to have a small normal component B_n. Since, during this process, the rate of change of the magnetic flux (through any closed contour) associated with the moving magnetopause remains unchanged, the reduction of E_{in} must necessarily be associated with an increase of the tangential electric field component. In Heikkila's mechanism it is an electrostatic (zero curl) electric field which acts to increase this component. It is the addition of this electrostatic tangential electric field which then causes the plasma to move faster than the magnetopause, since as argued in (2) above, $\mathbf{E}_{it}$ alone is just sufficient to keep the plasma moving with that boundary.

In their paper, Owen and Cowley have shown where Heikkila's argument is wrong: the error is contained in (2) above. It is indeed incorrect to postulate the existence of a frame of reference in which the induction electric field may be transformed everywhere to zero. In fact, a locally curl-free induction electric field is present in the rest frame of the perturbed magnetopause, produced by the changing current distribution elsewhere on the boundary. Following Owen and Cowley, the flow normal to the current layer produced by the induction electric field alone is then in general lower than "the boundary speed" and may just match this "speed" when the normal induction electric field is cancelled to zero by a curl-free charge separation electric field. Therefore, Heikkila's argument, when correctly applied as in Owen and Cowley's paper, does not lead to impulsive transport of plasma through the magnetopause (in this context, the hypothetical surface $B_z = 0$).

3.2. Differences between Heikkila's scenario and that proposed by Lemaire and Roth

The conclusions reached by Owen and Cowley are correct, at least within the framework contrived by Heikkila to "explain" the mechanism by which solar wind plasma density irregularities should penetrate impulsively into the magnetosphere. We note however that this framework is based on a set of "*a priori* (and simplifying) assumptions": assumption of equipotential magnetic field lines, assumption that the $\mathbf{E} \wedge \mathbf{B}$ drift alone contributes to the normal plasma motion, and assumption of a peculiar reconnection type 2-D magnetic field configuration. It is also clear that the first two assumptions require a strict adherence to the "frozen-in" condition of ideal MHD. The plasma flow is then analyzed with respect to a hypothetical magnetopause surface where $B_z = 0$, moving earthward as a consequence of the "impact" of the plasmoid on the magnetopause. This premise is of course based on the unconditional acceptance of the "frozen-in field" theorem.

However, we wish to point out that the impulsive penetration mechanism described in Section 2, and originally introduced by Lemaire and Roth in 1976, is quite different from that proposed by Heikkila. Therefore, the conclusions reached by Owen and Cowley do not infer that it is impossible for solar wind plasma elements to penetrate impulsively onto closed geomagnetic field lines (genuinely, at the end of their article, Owen and Cowley concede that they "do not dispute the experimental evidence that boundary layers are sometimes formed on closed flux tubes..."; but they only "wish to point out that Heikkila's argument does not provide a valid mechanism which leads to their formation").

It is important to recall that the mechanism suggested by Lemaire and Roth does not rely on ideal MHD. Unlike most MHD methodologists (including Heikkila when he wrote in 1982 his paper on "impulsive plasma transport through the magnetopause"), we do not consider that a plasmoid reaching the magnetopause with an excess momentum would only deform it as if that boundary would be an impermeable rubber membrane. On the contrary, for a real plasmoid, the magnetopause is just a continuous transition region separating the magnetosheath from the magnetosphere. There are for instance cases when neither the magnetic field intensity nor its direction change significantly across the magnetopause (Eastman, 1979). This occurs at the frontside magnetopause when the IMF is northward and when the magnetosheath plasma has a low β-value. Under these circumstances, a plasmoid approaching the Earth with an excess momentum will proceed (as in the experiments of Baker and Hammel) and will not really care whether it is on "closed" geomagnetic field lines or still on "open" or interconnected interplanetary ones. If not too much decelerated adiabatically by the magnetic field gradient, it will eventually penetrate in a region where the magnetic field lines are connected to a resistive ionosphere. The polarization electric field which builds up inside the plasma element to keep it moving is then quickly short-circuited and the plasmoid is slowed down non-adiabatically as described by Schmidt (1960).

What is surprising is that the theory of Schmidt was known by Walter Heikkila when he presented in 1982 his alternative scenario. Schmidt's textbook (Schmidt, 1966) is indeed quoted in his paper. But for Heikkila, who tried to generalize Schmidt's theory for the peculiar magnetic field geometry appropriate to reconnection, Schmidt's mechanism is effective once the plasmoid is inside the magnetosphere where it can continue in its earthward motion by means of an electric polarization across magnetic field lines and its associated $\mathbf{E} \wedge \mathbf{B}$ drift.

Furthermore, any mechanism for the impulsive transport of plasma through the magnetopause, based on ideal MHD, ignores the formation of electrostatic double layers at the locations where field lines dip across the surface of plasmoids, and consequently the existence of finite parallel E-fields. Magnetic field lines are therefore not everywhere equipotential field lines, nor are plasmoids ideal superconducting elements magnetically uncoupled with the external background.

That the ideal MHD approximation breaks down for real plasmoids is also illustrated by PROGNOZ-7 observations of ion composition near the magnetopause (Lundin and Dubinin, 1985): within plasma density enhancements observed in the magnetospheric boundary layer, the perpendicular flow vectors of the H^+ and He^{2+} ions (of solar wind origin) can differ by up to 200 km s^{-1} in magnitude and 90° in direction from the flow vectors of the He^+ and O^+ ions (of magnetospheric origin). In such multi-ion species plasmoids whose electron and ion temperatures are not vanishingly small, the bulk velocity of the ion species can be significantly different from the $\mathbf{E} \wedge \mathbf{B}/B^2$ convection velocity which is the only one considered in the "ideal MHD" approximation. In this case, the concept of magnetic field lines "moving" with the $\mathbf{E} \wedge \mathbf{B}/B^2$ velocity is obsolete. Indeed, "the motion of field lines" does not determine any more (as it could do for zero temperature plasma) where the electrons and all the different ion species drift as a whole. Each ion species has its own drift path which is a consequence of different grad B, curvature and polarization drifts. A multi-component plasmoid with a finite temperature does not follow the same drift path than an ideal MHD plasma irregularity.

One more difference between our theory of impulsive penetration and that of Heikkila resides in the model for the magnetic field configuration. In his scenario, Heikkila considers singular magnetic field configurations with X-line topologies, like those postulated in reconnection or merging theories (where the main magnetic field reverses direction and becomes equal to zero along an hypothetical X-line). Contradictory enough is the fact that none of the magnetic field hodograms published so far in the abundant literature hardly shows that this peculiar magnetic field configuration has ever been observed during any magnetopause crossing. If this happens that such a magnetic field configuration has ever existed at the magnetopause (and has been observed) it must have been a very uncommon case. Actually, cases where the magnetic field rotates from a northward direction inside the magnetosphere to any orientation beyond the magnetopause are the rules, not the exceptions. In retrospect, one may wonder why so many theoretical articles have been published after that of Dungey (1961), based on this special but uncommon and singular field distribution introduced by the latter.

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