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Interpretation of the northward B_z (NBZ) Birkeland current system and polar cap convection patterns in terms of the impulsive penetration model

by

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FOREWORD

The article "Interpretation of the Northward B_z (NBZ) Birkeland current system and polar cap convection patterns in terms of the impulsive penetration model" has been presented at the Chapman Conference "On Magnetotail Physics", held from 28 to 31 October 1985 in Laurel, Md (USA). The text will be published in the Proceedings of this conference : Magnetotail Physics, Ed. A.T.Y. Lui, The Johns Hopkins University Press, Baltimore (Md), p.83-90, 1987.

AVANT-PROPOS

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VOORWOORD

Het artikel "Interpretation of the Northward B_z (NBZ) Birkeland current system and polar cap convection patterns in terms of the impulsive penetration model" werd voorgesteld tijdens de Chapman vergadering "On Magnetotail Physics", gehouden in Laurel, Md (USA) van 28 tot 31 oktober 1985. De tekst zal opgenomen worden in de verslagen van de vergadering : Magnetotail Physics, Ed. A.T.Y. Lui, The Johns Hopkins University Press, Baltimore (Md), p.83-90, 1987.

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INTERPRETATION OF THE NORTHWARD B_z (NBZ) BIRKELAND CURRENT SYSTEM AND POLAR CAP CONVECTION PATTERNS IN TERMS OF THE IMPULSIVE PENETRATION MODEL

by

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Abstract

According to the Impulsive Penetration (IP) theory, solar wind plasmoids penetrate predominently in the two lobes of the magnetotail when the Interplanetary Magnetic Field (IMF) has a northward B_z (Planet. Space Sci., 27, 47-57, 1979). Momentum density of the penetrating solar wind plasma element is transferred to the surrounding plasma and to the central polar cap ionospheric regions, which, as a matter of consequence, is dragged over the poles in the sunward direction. This transient magnetotail plasma convection and the associated non stationary polar cap convection can be added and compared to steady state convection patterns predicted by earlier stationary interaction models.

In the northern hemisphere, the region of preferred penetration is shifted toward dusk for a positive B_y, and toward dawn for $B_y < 0$. The direction of these shifts is reversed in the southern hemisphere. The polar cap convection pattern associated with impulsive penetration of solar wind plasma irregularities is therefore also shifted toward dusk or dawn, according to the value of B_y as mentioned above.

Furthermore, the NBZ Birkeland currents driven at the interfaces between the penetrating plasmoids and the ambiant geomagnetic field are downward (upwards) in the dusk (dawn) side for both hemispheres. The amplitudes of NBZ currents are expected to be larger when B_z is larger (and positive). The region of reversal of the NBZ currents is also shifted toward dawn or dusk depending on the sign of B_y as described above. These transient field aligned currents, driven upwards and downwards, are associated with the non-zero field aligned component of curl $\underline{B}$ (i.e. with magnetic shears) in the vicinity of the penetrating diamagnetic plasmoids.

Résumé

Selon la théorie de Pénétration Impulsive (PI), des plasmoïdes dù vent solaire pénètrent de façon prédominante dans les deux lobes de la queue de la magnétosphère lorsque la direction du champ magnétique interplanétaire a une composante B_z vers le Nord [Northward B_z (NBZ)] (Planet. Space Sci., 27, 47-57, 1979). La densité d'impulsion de l'élément de plasma du vent solaire pénétrant est transféré vers le plasma environnant et vers les régions ionosphériques de la calotte polaire centrale qui, en conséquence, est entraîné par dessus les pôles en direction du soleil. Cette convection transitoire de plasma de la queue de la magnétosphère et la convection associée de la calotte polaire est non stationnaire et devrait être ajoutée aux modèles de convections stationnaires proposés antérieurement.

Dans l'hémisphère nord, la région de pénétration préférentielle est déplacée vers le crépuscule pour B_y positif, et vers l'aube pour $B_y < 0$. La direction de ces déplacements est inversée dans l'hémisphère sud. Pour cette raison, le modèle de convection de la calotte polaire associé à la pénétration impulsive d'irrégularités de plasma du vent solaire est également déplacé vers le crépuscule ou l'aube, suivant la valeur de B_y, comme mentionné ci-dessus.

De plus, les courants Birkeland NBZ existants entre les plasmoïdes et le champ géomagnétique ambiant sont dirigés vers le bas (le haut) du côté du crépuscule (de l'aube) dans les deux hémisphères. On observe que les amplitudes des courants NBZ sont plus élevées lorsque B_z est plus grand (et positif). La région d'inversion des courants NBZ est également déplacée vers l'aube ou le crépuscule, dépendant du signe de B_y, comme décrit ci-dessus. Les courants transitoires alignés sont dirigés vers le haut ou vers le bas suivant l'orientation des tensions magnétiques au voisinage de ces plasmoïdes diamagnétiques.

Samenvatting

Volgens de Impulsieve Penetratietheorie (IP) dringen plasmoïden van de zonnewind op impulsieve wijze in de twee gedeelten ven de staart van de magnetosfeer wanneer de richting van het interplanetair magnetisch veld een noordwaartse B_z Birkeland component heeft (Planet. Space Sci., 27, 47-57, 1979). Het moment van het binnendringend plasma-element van de zonnewind wordt overgedragen naar het omringend plasma en naar de ionosferische gebieden van de centrale poolkap die, bijgevolg, boven de polen gevoerd wordt in de richting van de zon. Deze voorbijgaande plasmaconvectie van de staart van de magnetosfeer en de met de niet-stationaire poolkap geassocieerde convectie zouden moeten bij de stationaire convectiemodellen gevoegd worden die door vroegere stationaire interactiemodellen gesuggereerd werden.

In de noordelijke hemisfeer wordt het gebied van voorkeurspenetratie verplaatst naar de schemering voor een positieve B_y, en naar de dageraad voor $B_y < 0$. De richting van deze verplaatsingen wordt omgekeerd in de zuidelijkee hemisfeer. Om die reden wordt het convectiemodel van de poolkap die geassocieerd is met de impulsieve penetratie van onregelmatigheden van het zonnewind plasma eveneens verplaatst in de richting van de schemering of de dageraad, naargelang de waarde van B_y, zoals hierboven werd vermeld.

Bovendien worden de Birkeland NBZ strome die bestaan van de grenzen tussen de plasmoïden en het omringend geomagnetisch veld naar beneden (naar boven) langs de schemeringszijde (dageraadzijde) geleid in de twee hemisferen. Men merkt op dat de amplitudes van de NBZ stromen hoger liggen wanneer B_z groter is (en positief). Het omkeergebied van de NBZ stromen wordt eveneens naar de dageraad of de schemering verplaatst, afhankelijk van het teken van B_y, zoals hierboven beschreven wordt. Deze gerichte voorbijgaande stromen worden naar boven en naar onder geleid door de magnetische spanningen in de omgeving van de diamagnetische plasmoïden.

Zusammenfassung

Der impulsiven Penetrationtheorie zufolge dringen Plasmoïden des Sonnenwindes auf impulsiven Weise in den zwei Teilen des magnetosphärischen Schweifes ein, wenn die Richtung des interplanetären magnetischen Feldes eine nordwärtse B_z Birkeland Komponente hat (Planet. Space Sci., 27, 47-57, 1979). Der Impuls des eindringende Plasmaelementes des Sonnenwindes wird versetzt nach dem umringenden Plasma und nach den ionosphärischen Gebieten der Zentralpolkappe die, folglich, über die Pole geführt wird in der Richtung der Sonne. Diese vorbeigehende Plasmakonvektion des magnetosphärischen Schweifes und die mit der nicht-stationären Polkappe assoziierte Konvektion würden bei den stationären Konvektionsmodellen gefügt müssen werden den durch früheren stationären Wechselwirkungsmodellen suggeriert werden.

In der nordlichen Hemisphäre wird das Gebiet von Präferenzpenetration versetzt nach der Dämmerung für einen positiven B_y, und nach der Morgenröte für $B_y < 0$. Die Richtung dieser Verlegungen wird umgekehrt in der südlichen Hemisphäre. Um diesen Grund wird das Konvektionsmodell der Polkappe, der assoziiert ist mit der impulsiven Penetration von Umregelmässigkaiten des Sonnenwindplasmas auch versetzt in der Richtung der Dämmerung oder der Morgenröte, dem Wert von B_y zufolge, wie hier oben gemeldet.

Ausserdem werden die Birkeland NBZ Ströme, existierend an den Grenzen zwischen den Plasmoïden und dem umringenden geomagnetischen Feld nach unter (nach oben) längs der Dämmerungseite (Morgenröteseite) geleitet in den zwei Hemisphären. Man bemerkt dass die Amplituden des NBZ Strömes höher liegen wenn B_z grösser ist (und positiv). Das Umkehrgebiet des NBZ Strömes wird auch nach der Morgenröte oder der Dämmerung versetzt, abhängig des Zeichens B_y, wie hier oben gemeldet. Diese gerichteten vorbeigehenden Ströme werden nach oben und nach unten geleitet durch die magnetischen Spannungen in der Umgebung des diamagnetisches Plasmoïdes.

1. Small scale solar wind plasma irregularities

From measurements of the Interplanetary Magnetic Field (IMF) with high time resolution (i.e. ten B-vectors every second of time) it can be seen that the solar wind magnetic field distribution, and, consequently the solar wind plasma distribution itself, are almost never uniform nor stationary. Small amplitude fluctuations in the IMF magnitude or/and direction are observed almost all the time even in the quiet solar wind ; sometimes, it is rare to find high resolution magnetograms with no changes in B_x, B_y or B_z over periods of time larger than 30 seconds. Large amplitude changes in the IMF (e.g. current sheaths, rotational discontinuities, tangential discontinuities, magnetic holes, as illustrated in Fig.1, or shocks) are less frequently observed than small amplitude fluctuations (Burlaga et al., 1977 ; Turner et al., 1977). But, the presence of variations in B in the solar wind even as small as 5% indicates that interplanetary field and plasma are both patchy, non stationary and formed of small scale plasma irregularities : i.e. helicoidal plasmoids, poloidal plasmoids and toroidal plasmoids (Bostik, 1956).

Solar wind plasma measurements are usually sampled with a rather low time resolution (e.g. $\Delta t >> 10$ seconds) and are therefore inappropriate to identify plasma irregularities of small scales. However, these small scale plasma elements have slightly different densities, different temperatures, perhaps different ionic abundances, different magnetizations, different vorticities, and different momentum densities. As a consequence, a steady state and almost uniform radial expansion of the solar atmosphere is a rather oversimplified mathematical representation of the real solar wind. The supersonic nature of this radial expansion and the non-stationarity of phenomena at the Sun's surface as well as in the solar corona lead to the expectation that the interplanetary medium at 1 AU is necessarily non-stationary, highly sheared and non-uniform over a wide range of scales, ranging from 1 AU down to a few ion Larmor gyroradii, i.e. 1 AU > L > 2000 km.

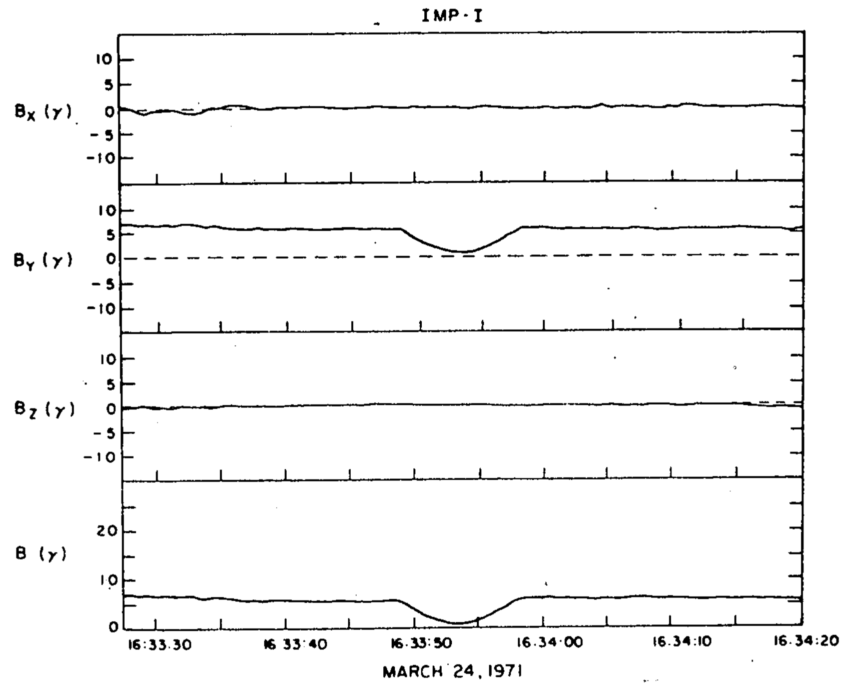

Fig.1 : High resolution magnetograms of the interplanetary magnetic field components (in nT) measured with the IMP I (Explorer 43). The sampling rate of the magnetometer is 12.5/s. The characteristic variation in the B_y component and in the total field B have been identified as "magnetic holes" by Turner <u>et al.</u> (1977). The total duration of this event is less than 10 seconds of time, i.e. less than twenty average ion Larmor radii in extent. The magnetic field variation has been interpreted as a traversal of a field aligned solar wind density irregularity of less than 4000 km in radial extent.

2. Impulsive penetration and adiabatic deceleration

The solar wind plasma irregularities or eddies with largest momentum penetrate deeper into the geomagnetic field (Lemaire, 1977, 1985 ; Lemaire and Roth, 1978). This results from conservation of the total energy : it has been shown in laboratory experiments (Demidenko et al., 1967, 1969) as well as from kinetic plasma theory (Schmidt, 1960) that the kinetic energy ($1/2\ mv_o^2$) of a plasmoid is converted adiabatically into thermal energy ($kT_\perp^+$ and $kT_\perp^-$) when it penetrates into a region of higher magnetic field intensity, $B(r)$. Indeed, as a consequence of adiabatic conservation of the magnetic moment, μ, of ions and electrons, the ratio

$$(kT_\perp^+ + kT_\perp^-)/B(r)$$

is constant when the plasma cloud enters into the geomagnetic field. Since the magnetic field intensity, $B(r)$, increases as r^{-3} when the geocentric distance r decreases, there is always a position r_1 where the incident kinetic energy ($1/2\ mv_o^2$) of the plasmoid particles is fully converted into gyro-motion : i.e. into perpendicular thermal energy. The radial component of the bulk velocity of the plasmoid vanishes at r_1 where the geomagnetic field intensity is equal to

$$B(r_1) = \frac{\frac{1}{2} mv_o^2 + (kT_\perp^+)_o + (kT_\perp^-)_o}{\overline{\mu^+} + \overline{\mu^-}} \tag{1}$$

$\overline{\mu^+}$ and $\overline{\mu^-}$ are the (conserved) average adiabatic moments of the impinging solar wind ions and electrons forming the intruding plasma irregularity (see Lemaire, 1985 for a generalization of Schmidt's theory in the case of a sheared magnetic field).

Eq. (1) indicates that the magnetosheath plasma clouds with larger incident velocities (v_o) are able to penetrate deeper into the geomagnetic field than average solar wind plasma elements with a smaller momentum density. Solar wind plasmoids with the largest momentum densities in the solar wind are therefore stopped or deflected sidewards closer to the Earth i.e. where $B(r_1)$ is larger.

Experimental evidence for solar wind plasma intrusions or plasmoids into the magnetosphere can be identified in a wide range of observations near the magnetopause and more specifically in the measurements reported by Lundin _et al._ (1983), Lundin and Aparicio (1982), Lundin and Dubinin (1984, 1985), Eastman _et al._ (1985). (See also Appendix 2).

3. Non adiabatic deceleration of intruding plasma elements

In addition to the adiabatic deceleration discussed above, a plasma element injected impulsively across geomagnetic field lines is also decelerated _non-adiabatically_. Indeed, geomagnetic field lines are linked into the conducting dayside cusp (cleft) ionosphere. The integrated Pedersen conductivity along these magnetic field lines is not infinitely large nor is it equal to zero. Its value ranges between 1 and 10 Siemens. As a consequence the penetrating eddies are slowed down non-adiabatically as proposed by Lemaire (1977, 1979a), Lundin (1984). The non-adiabatic deceleration of collisionless plasma streams across magnetic field lines anchored in conducting "walls", like the Earth's ionosphere, has clearly been demonstrated in laboratory experiments by Baker and Hamel (1962, 1965).

Part of the incident kinetic energy ($1/2\ mv_o^2$) of the penetrating solar wind plasma cloud is therefore also dissipated by Joule heating in the ionosphere at altitudes of the E-region and above (Lemaire, 1979b). An additional consequence of the finiteness of the integrated Pedersen conductivity is that the ambiant geomagnetic flux diffuses irreversibly into the engulfed solar wind plasma elements. Conversely, the IMF engulfed in the plasmoid gradually diffuses out into the magnetosphere : the B-field inside and at the surface of the plasma intrusion rotates to become parallel to the ambiant geomagnetic field as generally seen in B-field hodograms observed during magnetopause crossings (see also section 8).

4. The influence of IMF B_z on Impulsive Penetration

Plasmoids with an excess momentum which are moving with the background solar wind bulk velocity, have an excess mass density. Assuming nearly equal perpendicular plasma temperatures inside and outside the plasma irregularity, it can be inferred that the perpendicular pressure ($nkT_{\perp}^{+}$ + $nkT_{\perp}^{-}$) is larger inside than outside the element of plasma. As a matter of consequence the magnetic energy density ($B^2/2\mu_o$) must be smaller inside than outside in order to satisfy pressure balance equilibrium. The magnetization and the magnetic dipole moment ($\underline{M}$) of the diamagnetic currents circulating in the plasmoids as well as its surface, are then both pointing in a direction opposite to the ambiant interplanetary magnetic field $\underline{B}$ (Lemaire et al., 1979).

When the IMF has a northward component (i.e. $B_z > 0$), the magnetic dipole moment $\underline{M}$ of a diamagnetic plasmoid with an excess density has a southward component (i.e. $M_z < 0$). It can be shown that the magnetic force, $\underline{\nabla}(\underline{M}.\underline{B}_E)$ exerted on a southward oriented magnetic dipole moment $\underline{M}$ by the geomagnetic field, $\underline{B}_E$, which has a southward oriented dipole component, $\underline{M}_E$, is directed away from the Earth. Indeed, when such a plasmoid is at low latitudes near the front side magnetopause, $\underline{M}$ being there nearly parallel to $\underline{M}_E$, both dipoles repel then each other. In other words, the diamagnetic current loops producing the magnetic field depression inside the plasmoid are then pushed away by the southward oriented Earth's dipole $\underline{M}_E$. The dipole-dipole interaction acts then to reject the intruding small scale plasma current system out of the geomagnetic field distribution.

Above the northern and southern magnetotail lobes the IMF field lines are draped along the magnetopause surface. When IMF $B_z > 0$ in front of the Bow Shock, the directions of magnetic field lines in the magnetosheath are titled in the anti-sunward (sunward) direction above the northern (southern) magnetotail surface. A plasmoid with an excess momentum density and an excess thermal pressure necessarily has a magnetic moment pointing in a direction opposite to $\underline{B}$, the background magnetic field in the magnetosheath, i.e. $M_x > 0$ above the northern magnetopause where $B_x < 0$; $M_x < 0$ above the southern magnetopause surface where $B_x > 0$. The magnetic force, $\underline{\nabla}(\underline{M}.\underline{B}_E)$, acting on the dipole moment $\underline{M}$ is directed toward the interior of the magnetotail over an extended area of the magnetopause beyond the magnetospheric neutral points in the northern and southern hemispheres. In other words, solar wind irregularities with an excess momentum are attracted toward the inside of both magnetotail lobes when the IMF is northward. On the contrary, for a southward IMF, the dipole- dipole interaction between plasmoids and the geomagnetic field favors impulsive penetration in the front side magnetosphere, but not in the northern nor in the southern magnetotail lobes.

The same conclusions had already been reached in a previous article by Lemaire et al. (1979). Unfortunately, the captions of figures 6 and 8 in this article have been mixed up. Moreover, it contains incorrect statements concerning repulsive and attractive current systems on pages 50 and 51. Nevertheless, the conclusions in this article remain valid when the 2D planar current sheaths are replaced by realistic 3D current systems which have a finite magnetic dipole moment $\underline{M}$.

5. The influence of IMF B_y on Impulsive Penetration

The dipole-dipole force acting on a diamagnetic magnetosheath plasmoid is maximum in the vicinity of the polar cusps where the spatial derivatives of $(B_E)_x$, $(B_E)_y$ and $(B_E)_z$ are largest. For any IMF direction and any orientation of $\underline{M}$, there is always a place in the vicinity of the neutral points where the magnetic field directions in the magnetosheath is antiparallel to the magnetospheric field. This is where the magnetic force $\underline{\nabla}(\underline{M}.\underline{B}_E)$ 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 when IMF $B_y = 0$. As a consequence, the region of preferred impulsive penetration of solar wind plasmoids is then shifted toward dusk (dawn) in the northern (southern) hemisphere as illustrated in figs. 2a and c. The directions of these shifts

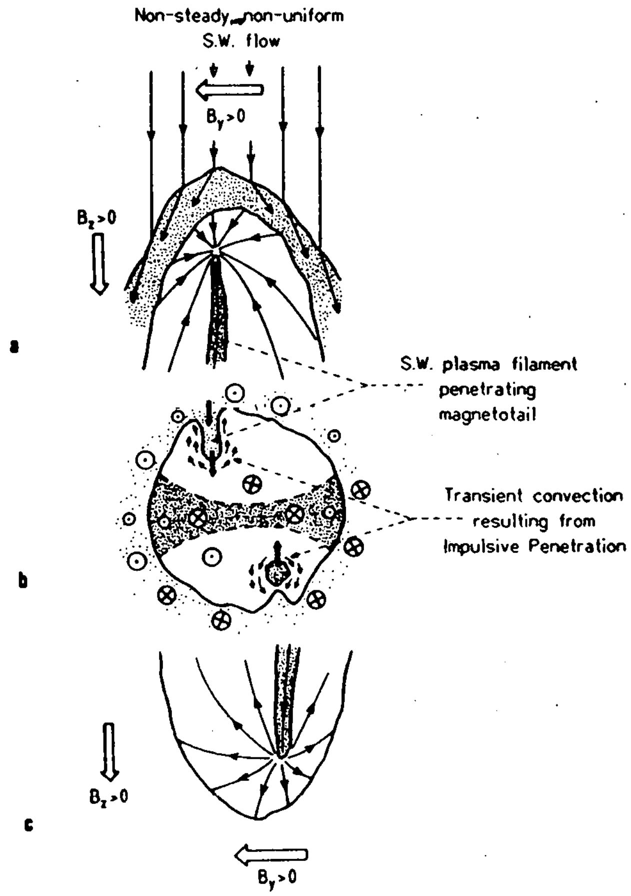

Fig. 2 : Cartoons illustrating the bumpy shape of the magnetosphere in a non-steady and non-uniform solar wind flow. The top panel (a) shows an elongated solar wind plasma filament penetrating across the surface of the northern magnetotail lobe when the IMF has a northward B_z (NBZ). The neutral point of the northern polar cusp is shifted toward dusk when the IMF B_y component is positive. The bottom panel (c) correspond to the penetration of a solar wind plasmoid in the southern tail lobe for the same IMF condition. Note that the southern polar cusp is shifted toward dawn. The central panel (b) represents a cross section of the magnetospheric tail lobes and of the plasmasheet (doted area). The transient flow of magnetospheric plasma around impulsively injected solar wind plasmoids is illustrated by small arrows. The observer is facing the direction of the Sun in the central panel.

is reversed in both hemispheres when IMF $B_y < 0$.

6. Magnetospheric and ionospheric convection patterns resulting from Impulsive Penetration

When a solar wind plasma density irregularity is injected in the magnetotail as illustrated in Figs. 2b and 3a, the ambiant magnetospheric plasma is pushed aside and flows along the flanks of the intruding plasma body. Fig.3a represents a cross section through the northern magnetotail. The reader is looking toward the direction of the Sun.

The directions of the bulk velocity vectors in the surrounding magnetospheric plasma is opposite to the velocity of impact for the solar wind plasma irregularity. This necessarily leads to a transient flow pattern of magnetospheric plasma in the tail lobes. This transient flow pattern is illustrated in Figs. 2b and 3a by small arrows directed toward the surface of the magnetosphere away from the center of the magnetotail.

The convection electric field, $\underline{E}$, associated with this transient flow of magnetospheric plasma across geomagnetic field lines is indicated by open arrows in Fig. 3a. Since the magnetospheric B-field is pointing toward the Sun in the northern tail lobe, the electric field, $\underline{E} = - \underline{V} \times \underline{B}$, outside the plasma element is oriented from dusk to dawn. This convection electric field maps down into the polar cap ionosphere as illustrated in Fig. 3b. Note that the convection electric field inside the intruding plasmoid does not map into the ionosphere since the magnetic field lines traversing this plasma element are not yet connected to the polar cap. The dusk to dawn E-field drags ionospheric plasma over the polar cap in the direction of the Sun as indicated in Fig. 3b by the arrows pointing toward 1200 LT.

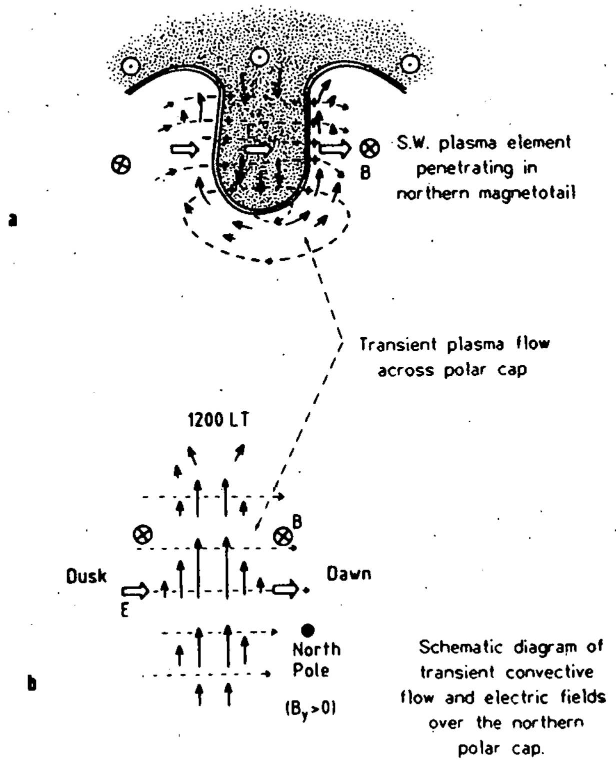

Fig. 3 : Transient flow pattern around a solar wind plasma element penetrating impulsively in the northern magnetotail lobe. The observer is facing the Sun in the top panel (a). The dusk-to-dawn convection electric field is indicated, as well as electric field lines (dashed lines). The bottom panel (b) illustrates the convection electric field and sunward plasma flow pattern at ionospheric heights over the northern polar cap when IMF $B_z > 0$ and IMF $B_y > 0$.

Sunward flow of ionospheric plasma over the northern and southern polar cap has indeed been observed when the IMF has a northern B_z component. Sunward flow in the polar cap ionosphere was first presented by Maezawa (1976) and substantiated by data by Burke et al. (1979) and by 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. The directions of these shifts correspond precisely to those of the preferred region of penetration of solar wind plasma irregularities into the magnetotail lobes, when the direction of IMF B_y changes, and when IMF $B_z > 0$. (see section 5).

Note that the transient flow patterns illustrated in Fig. 3a and b should not necessarily be considered as part of a steady state flow pattern usually illustrated and modeled in terms of closed equipotential contours. Closed equipotential contours are appropriate to represent magnetospheric or ionospheric convection inferred from steady state interaction models. But in the case of transient flow patterns like those expected in the non-steady interaction model discussed here, it is not appropriate to draw closed equipotential contours tangent to the observed velocity sectors. Indeed, like in non-stationary hydrodynamic fluid motion (e.g. eddies or whirls), stream lines are not closed : drawing stationary equipotential patterns is then misleading.

The non-stationary flow patterns shown in Fig. 3a and b can of course be superimposed on the stationary convection flow patterns inferred from steady-state interaction models like those proposed by Crooker (1979), Reiff (1982), Reiff and Burch (1985), Lyons et al. (1985) or Kan and Burke (1985). Note, however, that a large number of small scale solar wind plasma elements penetrating continuously through a wide area of the tail lobes can drive a larger scale quasi-stationary sunward convection flow pattern over the poles, i.e. quite like those described in some of the steady-state anti-parallel merging models mentioned above. Indeed, like for the large number of droplets forming a rain shower and pouring into surface water, the large number of plasma density irregularities forming a disturbed solar wind flow can penetrate in the magnetotail and change the convection in the plasma mantle as well as in the coupled ionosphere over a much wider volume or area than just one single small scale plasmoid. Each individual plasma 'droplet' contributes locally to the overall stream. But the duration of time as well as the extent in latitude of the plasma boundary layer or of the polar cap ionosphere influenced by impulsive penetration of magnetosheath small scale plasma irregularities does not depend so much on the size of these individual irregularities, than on the width and length of the solar wind wolume where the plasma is turbulent and patchy. If the solar wind is non-uniform and patchy over heliocentric radial distances larger than 35,000,000 km, the shower of plasmoids penetrating in the magnetosphere will last longer than one day. In these circumstances a quasi-stationary convection flow pattern can eventually build up in the magnetosphere and in the ionosphere ; but a true stationary regime can be established only when the small scale plasma irregularities are evenly distributed in that solar wind volume.

7. NBZ Birkeland current system

In the laboratory experiments of Demidenko et al. (1967, 1969) and Baker and Hamel (1965) reported above in section 2, the injected plasmoids were characterized by low-Beta values. The solar wind plasmoids are characterized by Beta-values of the order of unity : the kinetic energy density is then of the order of the magnetic energy density. A larger value of Beta, does not impede penetration of plasmoids, when their dipole magnetic moment has the right orientation (see section 4).

The entry of high-Beta diamagnetic solar wind plasma elements in the magnetotail perturbs the geomagnetic field distribution as illustrated in Figs. 4a and 4b.

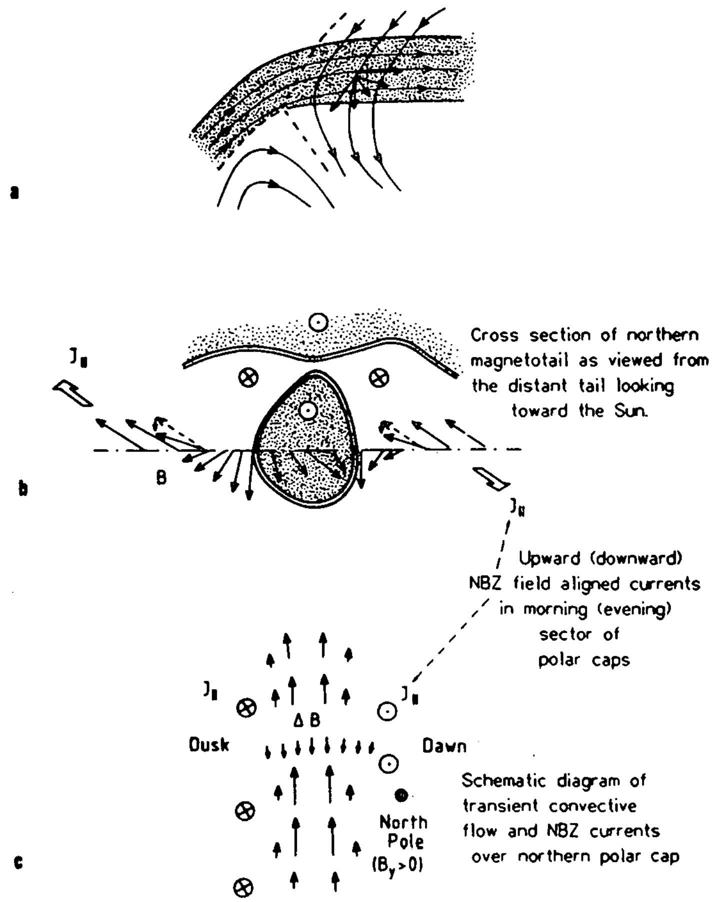

Fig. 4: The top panel (a) shows a meridional cross section of a solar wind plasma element bent into the magnetotail lobe behind the neutral point in the northern polar cusp. The magnetic field lines direction change from sunward direction outside the plasmoid to an anti-sunward direction in the middle of the plasmoid. The central panel (b) shows a cross section of the northern magnetotail lobe perpendicular to the Earth-Sun direction. The observer is facing the Sun. The solid arrows indicate the direction of the magnetic field along a s/c trajectory (dashed-dotted lines) traversing an engulfed plasmoid. The magnetic shears at the surface of the plasma element (where Curl $\underline{B}$ has a component parallel to $\underline{B}$) drive sunward (downward) field aligned currents at the dusk side and anti-sunward (upward) field aligned currents on the dawnside of the plasmoid. When the polar cap ionosphere is a good conductor (i.e. when it is illuminated by UV photons from the Sun) these NBZ Birkeland currents easily close into the ionosphere. In the bottom panel (c) the arrows pointing toward the top represent the sunward plasma convection over the polar cap for NBZ condition (as in Fig.3a). The array of smaller arrows pointing in the 0000 LT direction represent the magnetic field perturbation produced by the NBZ current system ($J_{//}$) flowing down into the ionosphere on the dusk side and out of the ionosphere on the dawn side.

The geomagnetic field and plasmoid magnetic field combine to give a total B-field distribution which is not curlfree. When the direction of the magnetic field inside the plasmoid is not strictly parallel to the ambiant geomagnetic field, Curl $\underline{B}$ has a non-zero component in the direction parallel to $\underline{B}$, i.e. parallel to the magnetic field lines. The parallel component of Curl $\underline{B}$ is non-zero when the magnetic field distribution is sheared, i.e. when magnetic lines are not parallel to each other as in the diamagnetic plasma sheaths studied by Lemaire and Burlaga (1976). These magnetic shears are direct evidence of Birkeland currents whose intensity is equal to

$$J_{/\!/} = \frac{1}{\mu_o} \;(\mathrm{Curl}\; \underline{B})_{/\!/} \tag{2}$$

In Figs. 4a and b we have tried to illustrate how magnetic shears produced by the solar wind diamagnetic elements in the geomagnetic field are associated with Birkeland currents flowing downwards (upwards) in the afternoon (morning) side of the polar cap region. These Birkeland currents can extend down into the conducting ionosphere where they produce small amplitude magnetic field perturbations which indeed have been observed in the polar cap with the satellites MAGSAT. These Birkeland currents are detected in the polar caps only when the IMF has a northward B_z component. This is why they have been called NBZ Birkeland currents by Ijima et al. (1984), Potemra et al. (1984), Zanetti et al. (1984), Baumjohann and Friis-Christensen (1985).

In the northern (southern) polar cap, the location where NBZ currents have been observed shifts toward dusk (dawn) when the IMF B_y becomes positive. These shifts correspond precisely to those expected for the preferred impulsive penetration of solar wind plasmoids into the magnetotail lobes, when IMF B_y is positive.

The observations indicate also that the NBZ field aligned current intensities are generally larger when the IMF is larger. This comes from the fact that the magnetic shears at the surface of a diamagnetic plasma element are enhanced when the IMF intensity is increased. As a consequence (Curl $\underline{B})_{//}$ is enhanced as well as $J_{//}$ according to eq. (2) and the model calculations by Lemaire and Burlaga (1976).

The observations generally indicate also that the NBZ field aligned current intensities are larger when the polar angle of the IMF (measured from the +z axis) is small, i.e. for IMF $B_z > 0$ but $B_y \approx 0$ and $B_x \approx 0$ (Ijima and Potemra, 1982 ; Zanetti and Potemra, 1985). These experimental results can be interpreted in a similar manner : when the polar angle of the IMF is small, the direction of the IMF field lines in the magnetosheath becomes almost anti-parallel to the geomagnetic field lines as shown in Fig. 2a and c. The magnetic shear is then maximum ; consequently (Curl $\underline{B}_{//}$) and the NBZ current densities, $J_{//}$, are also maximum.

It is not yet clear why the IMF B_z must be larger than 5 nT for significant NBZ current and convection flow patterns to occur in the polar cap (Iijima et al., 1984). A quantitative and time dependent simulation of impulsive penetration of high-Beta plasmoids will probably be needed to answer this specific question. To our knowledge, there is no explanation for such a threshold at B_z = 5 nT in the steady state anti-parallel merging theories mentioned in section 6, either.

8. Pedersen currents

In quasi-steady state, when div $\underline{J} = 0$, the field aligned currents generated at the interface between an engulfed diamagnetic solar wind plasma element and the surrounding geomagnetic field must necessarily close somewhere via electric currents transverse to the magnetic field lines (i) either at high altitude in the vicinity of the intruding plasmoid via complex curvature drift currents as discussed in Appendix 1, or (ii) in the ionospheric E-region via Hall and Pedersen currents where the electric conductivity has a finite (non-zero) value.

The amount of field aligned currents which are diverted toward the ionosphere and which close there via horizontal currents depends on the value of the distribution of ionospheric Hall and Pedersen conductivity. The intensity of the transverse currents as well as the density of the associated field aligned currents are therefore larger in the illuminated dayside polar caps than in the nightside region beyond the terminator, where the integrated Pedersen conductivity, Σ_p, is drastically reduced. Observations by Bythrow et al. (1985) confirm that NBZ Birkeland currents are indeed larger in the dayside than over the nightside polar caps where the conductivity of the ionosphere is low because of the lack of photoionization processes.

The most intense Pedersen current should occur at the interface between upward and downward flowing field-aligned current regions. Since the ratio of the Hall to the Pedersen height integrated conductivities is generally larger than unity, the Hall currents are expected to be larger than the Pedersen currents. This is possibly why the magnetic signature of Hall currents is generally prevailing in MAGSAT magnetograms. Furthermore, the intensity of Hall currents should also peak at the limit between Birkeland currents of opposite signs, i.e. also where the dusk-dawn convection electric field ($\underline{E}$) is maximum. This is confirmed by MAGSAT data (Zanetti et al., 1984).

An additional reason for the magnetic signature of transverse Pedersen currents to be small and almost unnoticed in magnetograms is that the length of the Pedersen current sheaths is rather short : 0,3-3 degree in latitude corresponding to the distance between footprints of geomagnetic field lines linked to the volume of magnetospheric plasma regions perturbed by intruding plasmoids. Therefore, the magnetic field perturbations produced by such short currents decrease rapidly with distance : more rapidly than those produced by the wider and more elongated Hall current sheaths.

The Pedersen currents are dissipated because of collisions between ions and neutral atoms at E-region altitudes where the ion Larmor frequency becomes of the order of the ion collision frequency. The rate of dissipation of these transverse Pedersen currents is determined by the electric resistivity of the ionosphere. As a consequence, the field aligned current intensity flowing down in the dusk side and up in the dawn side of the polar cap ionosphere is limited by the value of Σ_p. When Σ_p is small, the NBZ Birkeland currents density is small also, as indeed observed in the nightside polar caps. On the contrary, when Σ_p is large, the NBZ Birkeland currents become large also : they are less impeded to close in the less resistive ionosphere. This is what occurs in the dayside polar cap irradiated by solar UV photons.

Note added to proof

Goertz et al. (1985) and Sandholt et al. (1986) have observed transient poleward motions of small scale structures in the dayside auroral ionosphere during periods of southward IMF (i.e. : SBZ). These events have been associated with impulsive penetration of solar wind plasma density irregularities into the dayside plasma boundary layer when the IMF B_z is negative. But, the former authors argue and conclude that the observed poleward motions of the ionospheric signatures of these intruding blobs conflict with the theory of Impulsive Penetration proposed by Lemaire (1977) and Lemaire et al. (1979). However according to the description given in section 6 of the present paper this conclusion is uncorrect : it appears to be a misinterpretation or misunderstanding of this theory by the former authors. Indeed, when such blobs of plasma intrude into the magnetosphere, the ambiant magnetospheric plasma is pushed aside and flows along the flanks of the penetrating solar wind plasma density enhancement. The directions of bulk velocity vectors for the surrounding magnetospheric plasma is opposite to the velocity of impact of the plasmoid. This leads to a transient flow pattern which maps into the ionosphere on the equatorward side of the polar cusps. The corresponding transient ionospheric convection is indeed poleward as observed by Goertz et al. (1985) and Sandholt et al. (1986). What is shifting equatorward is only the location of the feet of geomagnetic field lines surrounding the intruding blob. Although the location where these ionospheric signatures are observed is shifting equatorwards, the ionospheric plasma is driven polewards. Consequently, the recent observations reported by Goertz _et al._ (1983) and Sandholt _et al._ (1985) fully confirm the theory of Impulsive Penetration and the description given above in section 6.

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APPENDIX 1 : FIELD ALIGNED AND CURVATURE DRIFT CURRENTS

In the 1-D planar plasma sheaths or tangential discontinuities modeled by Lemaire and Burlaga (1976), or Roth (1978, 1980), the parallel (field-aligned) current as well as the perpendicular component of the diamagnetic current layer are both flowing parallel to the plane of the discontinuity. They 'close' at infinity or in non-conducting walls wherein the straight magnetic field lines are supposed to be anchored. Furthermore, in these 1-D tangential discontinuity models there are no currents due to curvature of magnetic field lines.

However, intruding solar wind plasmoids are never really flat slabs extending to infinity in two directions like in Lemaire and Burlaga's 1-D model : they are plasma clouds of finite extent in all directions ; the field aligned currents created at their surfaces are not uniform planar current sheaths, but they are non-uniformly distributed in a volume of finite extent. These field aligned currents are more likely to be filamentary than ideally flat current layers. But, as a result of these localised and patchy parallel currents, the geomagnetic field lines are deformed : they acquire helicity i.e. additional curvature. The additional curvature drifts of the electrons and ions can give raise to complex additional electric currents which are perpendicular to the radius of curvature of the magnetic field lines. In 3-D models these additional curvature drift currents can be closure currents for the field aligned currents $J_{//}$ generated elsewhere.

But 3-D plasma current distributions and magnetic field distributions produced by high-Beta plasma clouds in an external background magnetic field have not yet been worked out in a self consistent manner.

Although simulations of the geomagnetic field perturbations by simple cylindrical current systems have been illustrated by Lemaire (1982), however a 3-D generalization of Lemaire and Burlaga's 1-D plasma slab model for tangential discontinuities, is presently beyond our grasp.

In conclusion, although complete 3-D models of high-Beta plasmoids engulfed in an external magnetic field are not yet available, it can be considered that field aligned currents generated in the vicinity of such plasmoid can possibly be closed by perpendicular drift currents resulting from enhanced curvature (helicity) of the magnetic field lines in the vicinity of the diamagnetic plasma cloud.

APPENDIX 2 : IMPULSIVE PENETRATION OF SOLAR WIND PLASMOIDS IN THE FRONT SIDE MAGNETOSPHERE : FTE, PTE, IPE and Co...!

Plasmoid penetration in the front side magnetosphere is expected when the IMF has a southward B_z. Indeed, the magnetic moment of plasma density enhancements has then a component anti-parallel to the magnetic moment of the Earth.

Plasmoids penetrating in the frontside Plasma Boundary layers produce a wide variety of diamagnetic field signatures among which Flux Transfer Events (FTE) are very special ones (Russell and Elphic, 1979 ; Elphic and Russell, 1979 ; Rijnbeek <u>et al.</u>, 1984 ; Berchem and Russell, 1984 ; Saunders <u>et al.</u>, 1984). Impulsive Penetration Events (IPE) or Plasma Transfer Events (PTE) most likely correspond to less characteristic "events". Plasma Inclusions or Intrusions observed by Sckopke <u>et al.</u> (1981) near the magnetopause belong also to the category of plasmoids penetrating into the magnetosphere. The clouds or blobs of Boundary Layer plasmas considered by Lundin and Evans (1985) to be a source for high-altitude early afternoon auroral arcs are also evidence of impulsive penetration of the same physical plasma-field entities i.e. of plasmoids, as pointed out by Lemaire (1977), Lemaire and Roth (1978) and Heikkila (1982).

The ionospheric signature of plasmoids penetrating in the front side magnetosphere for southward B_z conditions have also been observed in the Troughs or Polar Clefts. Impulsive magnetosheath particles precipitation in the polar cleft was first reported by Carlson and Tobert (1980).