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

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According to the impulsive penetration (IP) theory, solar-wind plasmoids penetrate predominantly 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 nonstationary polar-cap convection can be added and compared to steady-state convection patterns considered in 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 ambient geomagnetic field are downward (upward) 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 upward and downward, are associated with the nonzero field-aligned component of curl $\boldsymbol{B}$ (i.e., with magnetic shears) in the vicinity of the penetrating diamagnetic plasmoids.

SMALL-SCALE SOLAR-WIND PLASMA IREGULARITIES

From measurements of the interplanetary magnetic field (IMF) with high time resolution (i.e., 10 $\boldsymbol{B}$-vectors every second of time), it can be observed that the solar-wind magnetic field distribution and, consequently, the solar-wind plasma distribution itself are almost never uniform or stationary. Small-amplitude fluctuations in the IMF magnitude or/and direction are observed almost all the time. It is sometimes 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, of course, less frequently observed than small-amplitude and small-scale fluctuations.[1,2] But the presence even of only 5% variation of $\boldsymbol{B}$ in the solar wind indicates that the interplanetary field and plasma are both patchy, nonstationary, and formed out of small-scale "plasma magnetic field entities" – i.e., helicoidal plasmoids, poloidal plasmoids, and toroidal plasmoids.[3]

Solar-wind plasma measurements are usually sampled with a rather low time resolution (e.g., $t \gg 10$ seconds) and are therefore inappropriate to identify plasma small-scale irregularities. 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 physical reality. The supersonic nature of this radial expansion and the strong nonstationarity of phenomena at the sun's surface and in the solar corona lead to the expectation that the interplanetary medium at 1 AU cannot be anything else but nonstationary, high-

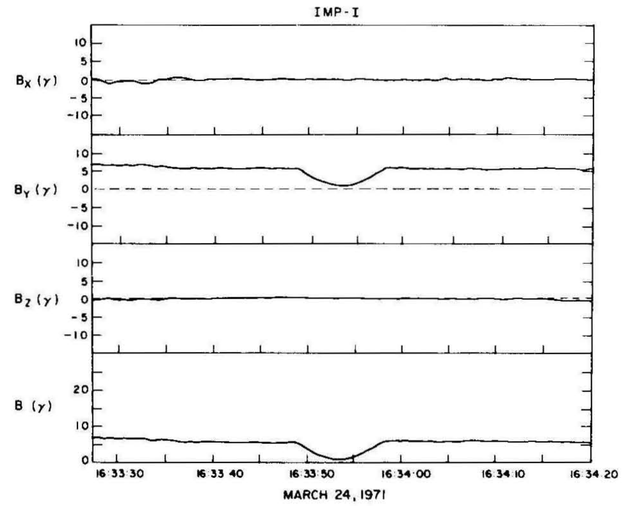

Figure 1—High-resolution magnetogram of the interplanetary magnetic field components (in nT) measured with the IMP I (Explorer 43). The sampling rate of the magnetometer is 12.5/s. The characteristic variation in the B_y component and in the total field B have been identified as "magnetic holes" by Turner et al.[2] The total duration of this event is less than 10 seconds, i.e., less than 20 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.

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ly sheared, and nonuniform over a wide range of scales, ranging from 1 AU down to a few ion Larmor gyroradii (i.e., 1 AU $> L >$ 2000 km).

IMPULSIVE PENETRATION AND ADIABATIC DECELERATION

The solar-wind plasma irregularities or eddies with largest momentum penetrate deeper into the geomagnetic field.[4,5] This results from conservation of the total energy. It has been shown in laboratory experiments[6,7] as well as from kinetic plasma theory[8] that the kinetic energy ($\frac{1}{2}\, mv^2$) 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 μ, the magnetic moment 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 ($\frac{1}{2}\, mv_0{}^2$) 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

$$B(r_1) = \frac{\frac{1}{2}\, mv_0{}^2 + (kT_\perp{}^+)_0 + (kT_\perp{}^-)_0}{\bar{\mu}^+ + \bar{\mu}^-} \qquad (1)$$

where $\bar{\mu}^+$ and $\bar{\mu}^-$ are the (conserved) average adiabatic moments of the impinging solar-wind ions and electrons forming the intruding plasma irregularity (see Ref. 9 for generalization and application of Schmidt's theory in the case of a sheared magnetic field distribution).

Equation 1 indicates that magnetosheath plasma clouds with larger incident velocities (v_0) 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 sideward 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.*,[10] Lundin and Aparicio,[11] Lundin and Dubinin,[12,13] and Eastman et al.[14] (See also Appendix 2.)

NONADIABATIC 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 nonadiabatically. 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 result of the large transverse conductivity in the ionospheric *E*-region. As a consequence, the penetrating eddies are slowed down nonadiabatically as emphasized by Lemaire.[4,15] The nonadiabatic 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.[16,17] Part of the incident kinetic energy ($\frac{1}{2}\, mv_0^2$) 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.[18]

An additional consequence of the finiteness of the integrated Pedersen conductivity is that the ambient geomagnetic flux "diffuses" irreversibly into the engulfed solar-wind plasma elements. The *B*-field inside and at the surface of the plasma intrusion rotates to become gradually parallel to the ambient geomagnetic field.[19] *B*-field hodograms observed during magnetopause crossings support rotation of $\boldsymbol{B}$ better than a reversal of the magnetic field direction along hypothetical neutral lines.[20,21]

THE INFLUENCE OF IMF B_z ON IMPULSIVE PENETRATION

Plasmoids with an excess momentum that 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 ($B^2/2\mu_0$) must be smaller inside than outside in order to satisfy pressure-balance equilibrium. The magnetization and the magnetic dipole moment ($\boldsymbol{M}$) of the diamagnetic currents circulating in the plasmoid as well as its surface are then both pointing in a direction opposite to the ambient interplanetary magnetic field $\boldsymbol{B}$.[22]

When the IMF has a northward component (i.e., $B_z > 0$), the magnetic dipole moment $\boldsymbol{M}$ 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, $\nabla(\boldsymbol{M}\cdot\boldsymbol{B}_E)$ exerted on a southward oriented magnetic dipole moment $\boldsymbol{M}$ by the geomagnetic field, $\boldsymbol{B}_E$, which has a southward oriented dipole component, $\boldsymbol{M}_E$, is directed away from the earth. Indeed, when such a plasmoid is at low latitudes near the front side magnetopause, $\boldsymbol{M}$ being there nearly parallel to $\boldsymbol{M}_E$, both dipoles then repel each other. In other words, the diamagnetic current loops responsible for the magnetic field depression inside the plasmoid are then pushed away by the southward oriented earth's dipole $\boldsymbol{M}_E$. The dipole-dipole interaction acts then to reject the intruding small-scale plasma current system out of the inhomogeneous geomagnetic field distribution.[19]

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 magnetosheath are tilted in the antisunward (sunward) direction above the northern (southern) magnetotail surface. A plasmoid with an excess momentum density and an excess thermal pressure has necessarily a magnetic moment pointing in a direction opposite to 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, $\nabla(\boldsymbol{M}\cdot\boldsymbol{B}_E)$, acting on the dipole moment $\boldsymbol{M}$ 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 the magnetotail 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, and 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.[22] Unfortunately, the captions of Figs. 6 and 8 in Ref. 22 have been mixed up. Furthermore, it contains incorrect statements concerning repulsive and attractive current systems on pages 50 and 51. However, the conclusions in this article remain essentially valid when the two-dimensional planar current sheaths are replaced by three-dimensional diamagnetic current loops, which have a finite magnetic dipole moment $\boldsymbol{M}$.

THE INFLUENCE OF IMF B_y ON IMPULSIVE PENETRATION

The dipole-dipole force acting on a magnetosheath diamagnetic 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 $\boldsymbol{M}$, there is always a place in the vicinity of the neutral points where the magnetic field direction in the magnetosheath is antiparallel to the magnetospheric field. This is where the magnetic force $\nabla(\boldsymbol{M}\cdot\boldsymbol{B}_E)$ 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 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 Fig. 2a and c. The directions of these shifts is reversed in both hemispheres when IMF $B_y < 0$.

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 ambient magnetospheric plasma is pushed aside and flows along the flanks of the intruding plasma body. Figure 3a represents a cross section through the northern magnetotail. The reader is looking toward the direction of the sun.

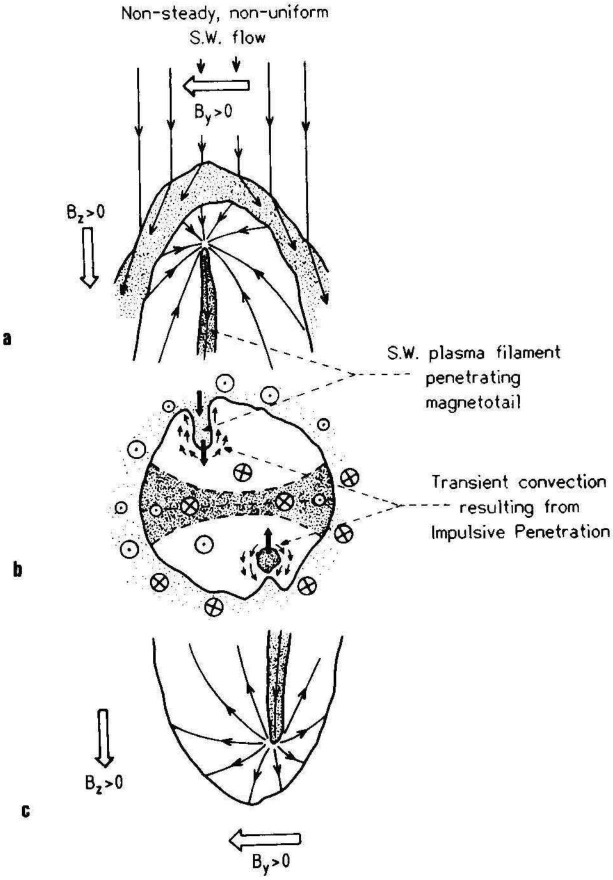

Figure 2—Cartoons illustrating the bumpy shape of the magnetosphere in a nonsteady and nonuniform solar-wind flow. The top panel (a) shows an elongated solar-wind plasma filament penetrating across the surface of the northern magnetotail lobe when the IMF has a northward B_z (NBZ). The neutral point 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 plasma sheet (dotted area). The transient flow of magnetospheric plasma around impulsively injected solar-wind plasmoids is illustrated by small arrows. In the central panel, the observer is facing the sun.

The direction of the bulk velocity vectors in the surrounding magnetospheric plasma is opposite to the impact velocity 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 away from the center of the magnetotail.

The convection electric field, $\boldsymbol{E}$, 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

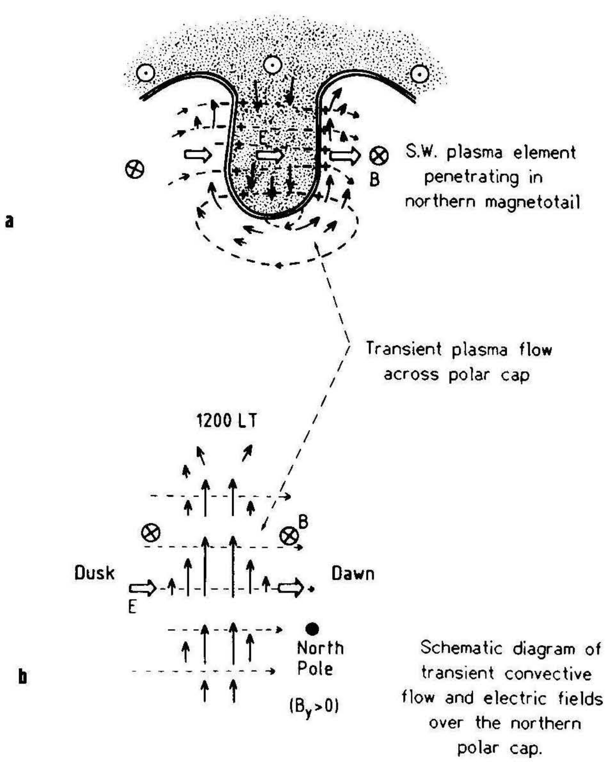

Figure 3—Transient flow pattern around a solar-wind plasma element penetrating impulsively in the northern magnetotail lobe. The observer is facing the sun in the top panel (a). The dusk-to-dawn convection electric field is indicated as well as electric field lines (dashed lines). The bottom panel (b) 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 $B_y > 0$.

sun in the northern tail lobe, the electric field, $\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$, 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 necessarily map into the ionosphere since the magnetic field lines traversing this plasma element may not yet be 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.

Sunward flow of ionospheric plasma over the northern and southern polar caps 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[23] and substantiated by data by Burke et al.[24] and by Zanetti et al.[25] The locations of these observations were 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.

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 and closed stream lines. 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 nonsteady interaction model discussed here, it is not relevant to draw closed equipotential contours. Indeed, like in nonstationary hydrodynamic fluid motion (e.g., eddies or whirls), stream lines are not closed; drawing stationary equipotential patterns is then misleading.

The nonstationary 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,[26] Reiff,[27] Reiff and Burch,[28] Lyons et al.,[29] Lyons,[30] or Kan and Burke.[31] 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 large-scale quasistationary sunward convection flow pattern over the poles, quite like those described in the steady-state antiparallel merging models mentioned above. Indeed, like it is 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 as it does on the width and length of the solar-wind volume where the plasma is turbulent and patchy. If the solar wind is nonuniform and patchy over heliocentric radial distances greater than 35,000,000 km, the shower of plasmoids penetrating in the magnetosphere will last longer than one day. In these circumstances a quasistationary 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.

NBZ BIRKELAND CURRENT SYSTEM

In the laboratory experiments of Demidenko et al.[6,7] and Baker and Hamel[17] reported above, the injected plasmoids were characterized by low-β values. The solar-wind plasmoids are characterized by β values of the order of unity, and the kinetic energy density is then of the order of the magnetic energy density. A larger value of β does not impede penetration of plasmoids when their dipole magnetic moment has the right orientation. The entry of high-β diamagnetic solar-wind plasma elements in the magnetotails, however, perturbs the geomagnetic field distribution as illustrated in Fig. 4a and b.

The superimposed geomagnetic-field and plasmoid magnetic-field distribution are not curl free. When the direction of the magnetic field inside the plasmoid is not strictly parallel to the ambient geomagnetic field, curl $\boldsymbol{B}$ has a nonzero component in the direction parallel to $\boldsymbol{B}$; i.e., parallel to the magnetic field lines. The parallel component of curl $\boldsymbol{B}$ is nonzero when the magnetic-field distribution is sheared, i.e., when magnetic lines are not parallel to each other. These magnetic shears are produced by Birkeland currents whose intensity is equal to

$$J_{\parallel} = \frac{1}{\mu_0} (\text{curl } \boldsymbol{B})_{\parallel} \tag{2}$$

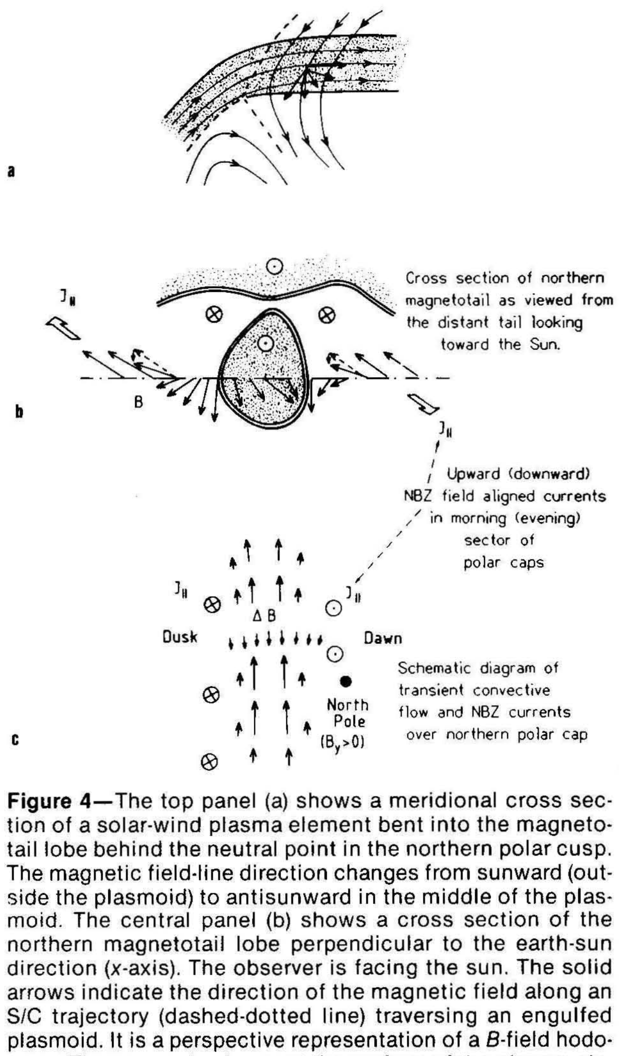

Figure 4—The top panel (a) shows a meridional cross section of a solar-wind plasma element bent into the magnetotail lobe behind the neutral point in the northern polar cusp. The magnetic field-line direction changes from sunward (outside the plasmoid) to antisunward in the middle of the plasmoid. The central panel (b) shows a cross section of the northern magnetotail lobe perpendicular to the earth-sun direction (x-axis). The observer is facing the sun. The solid arrows indicate the direction of the magnetic field along an S/C trajectory (dashed-dotted line) traversing an engulfed plasmoid. It is a perspective representation of a B-field hodogram. The magnetic shears at the surface of the plasma element (where curl $\boldsymbol{B}$ has a component parallel to $\boldsymbol{B}$) drive sunward (downward) field-aligned currents on the duskside and antisunward (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 can more easily close into the ionosphere. In the bottom panel (c), the arrows pointing toward 1200 LT (i.e., toward the top of the figure) represent the sunward plasma convection over the polar cap for NBZ condition (also shown in Fig. 3b). The array of smaller arrows pointing in the 0000 LT direction represent the magnetic field perturbation produced by the NBZ Birkeland current system flowing down into the ionosphere on the duskside and out of the ionosphere on the dawnside of the patch where sunward convection is observed. The magnetic field signature of Hall and Pedersen currents is not illustrated.

Birkeland-current sheaths can be generated in collisionless plasma layers like those studied by Lemaire and Burlaga.[32] The intensity of the field-aligned currents in a diamagnetic plasma sheath is determined by the velocity distribution of the electrons and ions in the transition layer between the plasma of magnetospheric origin and the plasma of magnetosheath origin. The kinetic models of plasma slabs studied by Lemaire and Burlaga[32] and Roth[33] indicate that not only the magnetic field intensity but also the direction of $\boldsymbol{B}$ vary smoothly across plasma sheaths when the plasma densities, temperatures, ionic compositions, and magnetizations are different on both sides of the transition region. These plasma sheaths are at least a few ion Larmor gyroradii thick. The hodograms of calculated magnetic field vectors are very much like those measured when a spacecraft traverses a magnetopause surface or, equivalently, when it penetrates through the surface of one of the many intruding plasma elements, as illustrated in Fig. 4b.

Figure 4a and b, tries to illustrate how magnetic shears produced by the solar wind diamagnetic elements in the geomagnetic field are associated with Birkeland currents flowing downward (upward) 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 that indeed have been observed in the polar cap with the MAGSAT satellite. 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 Iijima et al.,[34] Potemra et al.,[35] Zanetti et al.[25] and Baumjohann and Friis-Christensen.[36]

In the northern (southern) polar cap, the location where NBZ currents shift toward dusk (dawn) have been observed when the IMF B_y becomes positive. These shifts correspond precisely to those expected for the preferred impulsive penetration region 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 $\boldsymbol{B}$ is enhanced as well as $J_{\parallel}$ according to Eq. 2 and to the model calculations by Lemaire and Burlaga.[32]

The observations indicate also that the NBZ field-aligned current intensities are generally larger when the polar angle of the IMF (measured from the $+z$ axis) is small, i.e., for IMF $B_z > 0$ but $B_y \sim 0$.[37,38] These experimental results can be interpreted in a similar manner when the polar angle of the IMF is small, i.e., when the angle between the IMF field lines in the magnetosheath near the magnetotail surface is almost antiparallel to the geomagnetic field as shown in Fig. 2a and c. The magnetic shear is then maximum; consequently, curl $\boldsymbol{B}_{\parallel}$ and the NBZ current densities, $J_{\parallel}$, are also maximum.

It is not yet clear why the IMF B_z must be larger than 5 nT for significant NBZ Birkeland current and convection flow patterns to occur in the polar cap.[34] A quantitative and time-dependent simulation of impulsive penetration of high-β 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 antiparallel merging theories mentioned above.

PEDERSEN CURRENTS

In a quasisteady state, 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 either (a) at high altitude in the vicinity of the intruding plasmoid via complex curvature drift currents, as discussed in Appendix 1, or (b) in the ionospheric E-region via Hall and Pedersen currents where the electric conductivity has a finite (nonzero) value.

The amount of field-aligned currents that are diverted toward the ionosphere and that close there via horizontal currents depends on the value of the 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.[39] 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 greater than unity, the Hall currents are expected to be greater 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., where the dusk-to-dawn convection electric field, $\boldsymbol{E}$, is maximum. This is confirmed by MAGSAT data.[25]

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, i.e., 0.3 – 3 degrees 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.

APPENDIX 1: FIELD ALIGNED AND CURVATURE DRIFT CURRENTS

In the one-dimensional planar plasma sheaths or tangential discontinuities modeled by Lemaire and Burlaga[32] or Roth[33,40] 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 nonconducting walls wherein the straight magnetic field lines are supposed to be anchored. Furthermore, in these one-dimensional 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 one-dimensional model; they are plasma clouds of finite extent in all directions and the field-aligned currents created at their surfaces are not uniform planar current sheaths but are nonuniformly 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 localized 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 rise to complex additional electric currents that are perpendicular to the radius of curvature of the magnetic field lines. In three-dimensional models these additional curvature drift currents can be closure currents for the field-aligned currents, $J_{\parallel}$, generated elsewhere.

But three-dimensional plasma current distributions and magnetic field distributions produced by high-β plasma clouds in an external background magnetic field have not yet been worked out in general.

Although simulations of the geomagnetic field perturbations by simple cylindrical current systems have been illustrated by Lemaire,[41] a three-dimensional generalization of Lemaire and Burlaga's one-dimensional plasma slab model for tangential discontinuities is presently beyond our grasp.

In conclusion, although complete three-dimensional models of high-β 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

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 antiparallel to the magnetic moment of the earth.

Plasmoids penetrating in the front-side plasma boundary layers produce a wide spectrum of diamagnetic field signatures among which flux transfer events (FTE) are especially characteristic ones.[21,42-45] Impulsive penetration events (IPE) or plasma transfer events (PTE) most likely correspond to the same "events" as well as plasma inclusions or intrusions observed by Sckopke et al.[46] near the magnetopause. The clouds or blobs of boundary layer plasmas considered by Lundin and Evans[47] to be a source for high-altitude, early afternoon auroral arcs are also other words for the same physical plasma field entities, i.e., plasmoids as pointed out by Lemaire[4] and Heikkila.[48]

The ionospheric signature of plasmoids penetrating in the front-side magnetosphere for southward B_z conditions has been observed in the region of the high-latitude troughs or polar clefts. Impulsive magnetosheath particle precipitation in the polar cleft was then reported by Carlson and Torbert.[49] Furthermore, short-lived small-scale irregularities moving northward have been observed in dayside auroral events by Sandholt et al.[50] Similar northward motions have been detected in the high-latitude trough ionosphere, using the STARE radar system.[51] The observed northward motion of these ionospheric plasma irregularities corresponds to a transient and localized flow of magnetospheric plasma toward the magnetopause boundary as illustrated in Fig. 3a. The magnetospheric plasma flows around the intruding plasmoid in a direction opposite to the velocity of the solar-wind plasmoid itself. Therefore, these observations by Sandholt et al.[50] and Goertz et al.,[51] fully support the IPE theory, quite contrary to conclusions proposed in these papers.

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