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CONTROL OF IMPULSIVE PENETRATION OF SOLAR WIND IRREGULARITIES INTO THE MAGNETOSPHERE BY THE INTERPLANETARY MAGNETIC FIELD DIRECTION

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Abstract—Impulsive penetration of a solar wind filament into the magnetosphere is possible when the plasma element has an excess momentum density with respect to the background medium. This first condition is satisfied when the density is larger inside than outside the plasma inhomogeneity. In this paper we discuss the second condition which must be satisfied for such a plasma element to be captured by the magnetosphere: the magnetization vector (**M**) carried by this plasma must have a positive component along the direction of $\mathbf{B}_0$, the magnetic field where the element penetrates through the magnetopause. On the contrary, when $\mathbf{M}\cdot\mathbf{B}_0<0$, the filament is stopped at the surface of the magnetopause. Thus the outcome of the interaction of the filament with the magnetosphere depends upon the orientation of the Interplanetary Magnetic Field. For instance, penetration and capture in the frontside magnetosphere implies that $\mathbf{B}_{SW}$, the Interplanetary Magnetic Field, has a southward, or a *small* northward, component. Penetration and capture in the northern lobe of the magnetotail is favoured for an IMF pointing away from the Sun; in the southern lobe $\mathbf{B}_{SW}$ must be directed towards the Sun for capture. Finally, for capture in the vicinity of the polar cusps the magnetospheric field ($\mathbf{B}_0$) assumes a wider range of orientations. Therefore, near the neutral points, it is easier to find a place where the condition $\mathbf{M}\cdot\mathbf{B}_0>0$ is satisfied than elsewhere. As a consequence, the penetration and capture of solar wind irregularities in the cleft regions is possible for almost any orientation of the interplanetary magnetic field direction. All observations made to date support these theoretical conclusions.

1. INTRODUCTION

The irregular particle flow observed in the entry layer and in the polar cusps by Paschmann *et al.* (1976, 1977) has been interpreted by Haerendel (1977) as "evidence of eddy turbulence generated in the magnetosheath flow past the indentation of the magnetopause. As an ordinary fluid streaming around a corner," the solar wind plasma is assumed to become turbulent in the magnetosheath and to diffuse through the polar cusp magnetopause as a consequence of some localized "merging" mechanism.

A similar idea was proposed by Chang (1962) who suggested that irregular motions and oscillations of the polar cusp magnetopause could be generated by the interchange (flute) instability in the vicinity of the "neutral points" where the magnetosheath plasma boundary is convex and consequently unstable.

According to these theories the solar wind becomes turbulent only at the "neutral points," i.e. at or behind the indentations of the magnetopause. However, Lemaire and Roth (1976) consider that the solar wind is already irregular and non-uniform before it traverses the bow shock. Indeed, radio scintillations and high resolution interplanetary magnetic field observations indicate that the solar wind is made up of field aligned plasma irregularities (McCracken and Ness, 1966; Hewish and Symonds, 1969; Houminer, 1973; Burlaga *et al.*, 1977). The dimensions of these solar wind filaments vary over a wide range, and are often smaller than the diameter of the magnetosphere. Lemaire and Roth (1977) suggested that any filament with an excess density (nm) or bulk speed (**w**) will penetrate deeper into the geomagnetic field than the average solar wind because of its excess momentum density ($nm\mathbf{w}$).

In the magnetosheath, behind the bow shock, the filament is compressed and its mechanical energy ($(\frac{1}{2})mnw^2$) is converted into kinetic energy ($(\frac{3}{2})nkT$). Both effects increase the plasma density and the plasma temperature (Auer *et al.*, 1976). At the magnetopause, where the average solar wind has a zero normal velocity component, a faster or denser solar wind filament still has an excess velocity, i.e. excess mechanical energy. For instance, a filament with an excess density of only 5% would penetrate through the magnetopause with a velocity equal to 5% of the solar wind speed, i.e. $\sim 20\,\mathrm{km\,s^{-1}}$ (Lemaire, 1977).

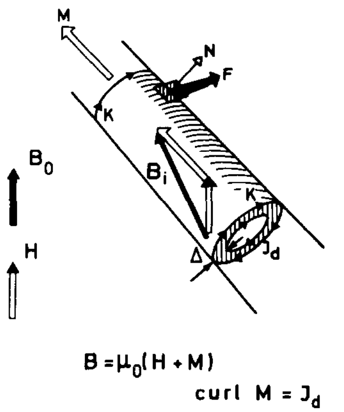

FIG. 1. DEFINITION OF THE MAGNETIC INDUCTION VECTOR **B**, MAGNETIC FIELD **H** AND MAGNETIZATION **M** INSIDE AND OUTSIDE A CYLINDRICAL PLASMA ELEMENT.

As soon as the filamentary plasma irregularity enters the geomagnetic cavity, it is surrounded by magnetic field lines connected with the polar cusp ionosphere. Part of the excess mechanical energy is dissipated by Joule heating in the ionosphere below the polar cusp via field aligned currents. The remainder is transformed into kinetic energy of charged particles by induced electric fields satisfying the equation

$$\mathrm{curl}\, E_{\mathrm{ind}} = -\frac{\partial \mathbf{B}}{\partial t}. \tag{1}$$

When the element penetrates into regions of higher magnetic fields, the perpendicular energy of the particles increases linearly with the intensity of the local magnetic field (B). This is a consequence of the adiabatic invariance of the magnetic moment $((\frac{1}{2})mv_{\perp}{}^2/B)$.

Besides the excess momentum (or the excess density) which is the primary condition for penetration of a solar wind irregularity into the magnetosphere, there is a second condition which must be satisfied to avoid the repulsion of the plasma at the surface of the magnetopause. It is the purpose of this article to discuss this other condition and to show that the direction of the solar wind magnetic field ($\mathbf{B}_{\mathrm{sw}}$) controls the capture or the repulsion of solar wind irregularities by the magnetosphere.

2. THE MAGNETIC FLUX CONSERVATION

Figure 1 shows the magnetization vector (**M**) associated with diamagnetic currents ($\mathbf{J}_d$) flowing at the surface of an isolated plasma filament. If **H** is the external magnetic field determined by non-local currents (**J**) or by magnetized bodies in S.I. units, the magnetic induction is defined by

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}). \tag{2}$$

The direction of **B** is, in general, different inside ($\mathbf{B}_i$) and outside ($\mathbf{B}_0$) the plasma inhomogeneity (see Fig. 1).

Let us consider an isolated solar wind filament in the interplanetary medium or in the magnetosphere. The magnetic field ($\mathbf{H}_0$) outside the plasma irregularity is determined by all external sources, e.g. by the distant electric currents flowing at the interfaces of nearby filaments or along solar wind sector boundaries, by the Chapman–Ferraro magnetopause currents, and also by the Earth's magnetic dipole.

At the surface of a plasma inhomogeneity, the magnetization current density ($\mathbf{J}_d$) is determined by the total ion and electron fluxes. Within this thin current layer (a few ion gyroradii thick) local gradients in the plasma density (n) and plasma temperatures($T_{\parallel}$, $T_{\perp}$) produce surface currents. The electric current density integrated over the thickness (Δ) of the current sheet ($\mathbf{K} = \int_\Delta \mathbf{J}_d\, \mathrm{d}r$) is the surface current density, which is given by

$$K = |\mathbf{B}_i - \mathbf{B}_0|/\mu_0 \quad \text{and} \quad \mathbf{K} = \mathbf{M} \times \mathbf{N} \tag{3}$$

where **N** is the outward directed normal at the plasma boundary (Stratton, 1941, p. 34, p. 242). Depending on the orientation of **N** and on the direction of the currents **K** or $\mathbf{J}_d$, the magnetic moment $\mathbf{m}(=\int_V \mathbf{M}\, \mathrm{d}V)$ of the filament can have any direction with respect to the external field $\mathbf{H}_0$.

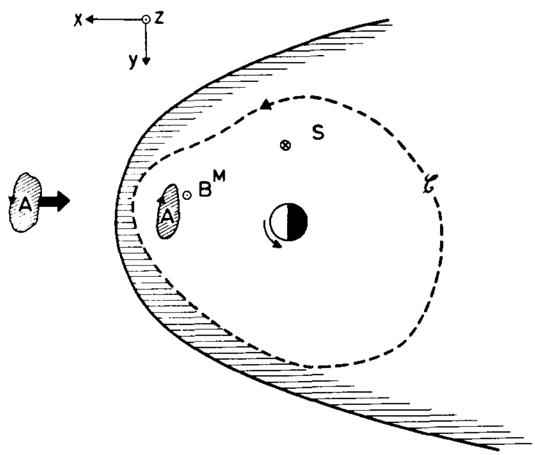

FIG. 2. EQUATORIAL SECTION OF THE MAGNETOSPHERE. The shaded area A corresponds to the cross-section of a plasma irregularity penetrating the magnetopause. The magnetic flux through A is conserved; the magnetic flux through the surface S is not necessarily constant.

When a plasma filament penetrates impulsively into the magnetosphere, its magnetic flux is conserved. Following the motion of this plasma element, its cross-section (A) in the xy (equatorial) plane decreases as the magnetic induction (B_i) gradually increases. When the diamagnetic plasma irregularity has moved inside the curve ζ (shown in Fig. 2) its cross section A' is given by

$$A' = A \cdot \frac{(B_i)_z}{(B_i')_z}$$

where $(B_i)_z$ and $(B_i')_z$ are the z components of the magnetic induction inside the element at the positions A and A', respectively.

When a plasma irregularity penetrates inside the closed curve ζ, the magnetic flux through a fixed surface is not necessarily conserved (see Fig. 2). The change of this magnetic flux depends on the final magnitude and direction of the magnetization vector ($\mathbf{M}'$) when the irregularity is at A'. Note that the magnetization $\mathbf{M}$ of a filament is not conserved but changes due to the changing distribution of the diamagnetic currents at the surface of the moving element.

3. CONDITION FOR CAPTURE

The magnetic force exerted on a unit surface of a diamagnetic plasma element by a constant external magnetic field ($\mathbf{B}_0/\mu_0$) is given by

$$\mathbf{F} = \int_\Delta \mathbf{J}_d \times \mathbf{B}_0 \, \mathrm{d}r = \mathbf{K} \times \mathbf{B}_0. \tag{4}$$

$\mathbf{F}$ is the well-known hydromagnetic force exerted by the external field on the current $\mathbf{K}$ (see Stratton, 1941, p. 130, p. 152). Using equation (3), (4) becomes

$$\mathbf{F} = \mathbf{N}(\mathbf{M} \cdot \mathbf{B}_0) - \mathbf{M}(\mathbf{N} \cdot \mathbf{B}_0). \tag{5}$$

If the surface element is not parallel to the external field (i.e. $\mathbf{N} \cdot \mathbf{B}_0 \neq 0$) the plasma boundary is either a rotational discontinuity or an oblique electrostatic shock (Landau and Lifchitz, 1969, pp. 294–301). In this case, $\mathbf{F}$ has a component along $\mathbf{M}$ i.e. parallel to the surface (hydromagnetic tension).

On the contrary when $\mathbf{N} \cdot \mathbf{B}_0 = 0$, the plasma surface element is a tangential discontinuity, the hydromagnetic force has only a normal component (hydromagnetic pressure) which is balanced by the equilibrium plasma pressure. This hydrodynamic equilibrium is probably reached in the interplanetary medium when the irregularities all move with the same solar wind speed.

When the leading surface of a filament reaches the magnetopause, the hydromagnetic pressure normal to the surface element changes discontinuously because the external magnetic field varies from $\mathbf{B}^{MS}$, in the magnetosheath, to $\mathbf{B}^{M}$ in the magnetosphere;

$$\Delta \mathbf{B}_0 = \mathbf{B}^{M} - \mathbf{B}^{MS}. \tag{6}$$

If the diamagnetic current system $\mathbf{K}$ and its associated magnetization $\mathbf{M}$ would remain unchanged, the change of hydromagnetic pressure due to the variation of the external field intensity is equal to

$$\Delta p_m = \mathbf{N} \cdot \Delta \mathbf{F} = -\mathbf{M} \cdot \Delta \mathbf{B}_0. \tag{7}$$

Because of the concomitant change in the diamagnetic current densities and magnetization vector, the actual change of hydromagnetic pressure is half the value given by (7) (Stratton, 1941, p. 126).

During the hydromagnetic interaction of the diamagnetic currents ($\mathbf{J}_d$) and the Chapman–Ferraro current at the magnetopause, the kinetic plasma pressure inside the filament remains almost constant, at least it does not change discontinuously as the hydromagnetic pressure. If $\mathbf{M} \cdot \Delta \mathbf{B}_0$ is positive, Δp_m is negative and the hydromagnetic pressure becomes smaller than the plasma pressure. As a result of this pressure imbalance the plasma near the leading surface is accelerated towards the interior of the magnetosphere. The trailing surface of the filament being still in the magnetosheath is not yet accelerated. Therefore the cross-section and volume of the element steadily increases until the trailing edge has penetrated into the magnetospheric field $\mathbf{B}^M$. As a consequence, the plasma density and pressure steadily decrease below their initial values. When the trailing edge reaches the magnetopause it is also accelerated. As a consequence, the cross-section and volume of the captured part of the filament shrinks. The density and kinetic pressure are increased to a new equilibrium value. Possible overshooting of these values can trigger periodic compressional Alfvèn waves in the magnetosphere. The periods of these hydromagnetic waves will range from 10 sec to 10 min, depending on the size of the intruding and oscillating plasma filament.

On the contrary, when $\mathbf{M} \cdot \Delta \mathbf{B}_0$ is negative, the hydromagnetic force (5) experienced by the leading surface exceeds the kinetic plasma pressure. As a consequence, the plasma is decelerated, its volume is compressed and its kinetic pressure is enhanced. The bulk velocity of the plasma element decreases. The filament is eventually stopped and returned to the magnetosheath by the enhanced hydromagnetic force which is directed away from the magnetopause.

An approximate value for τ_4, the characteristic slowing down time, can be obtained by equating the excess pressure Δp_m (equation 7) to the inertial force per unit area $(-nmwl/\tau_4)$ where l is the diameter of the filament, w is its residual velocity, and nm its mass density

$$\tau_4 = \frac{nmwl}{|\Delta p_m|}. \tag{8}$$

Other characteristic times τ_1, τ_2 and τ_3 have been defined by Lemaire and Roth (1976). Order of magnitude calculations show that this slowing down time τ_4 is typically 5–10sec for filaments with the following characteristics: $n = 5\ \mathrm{cm}^{-3}$, $l =$ 10,000 km, $w = 20\ \mathrm{km\ sec}^{-1}$, $B_i = 5\ nT$, $B_0 = 15\ nT$. From equation (3) one finds $M \approx K = 8 \times 10^{-3}$ A/m; for $|\Delta \mathbf{B}_0| = |\mathbf{B}^M - \mathbf{B}^{MS}| = 30\ nT$ we obtain $\Delta p_m = -2.4 \times 10^{-10}\ \mathrm{N\ m}^{-2}$, and from equation (8) $\tau_4 =$ 6 sec. This time interval is almost equal to the time required for the edge of the plasma element to traverse the magnetopause layer (~ 200 km thick), assuming a constant penetration velocity of $20\ \mathrm{km\ sec}^{-1}$. Therefore, when the magnetization ($\mathbf{M}$) is oriented unfavorably for magnetopause penetration with respect to the vector $\Delta \mathbf{B}_0$, the intruding plasma is slowed down over a distance approximately equal to the thickness of the magnetopause itself. The filament is halted in the magnetosheath and its leading edge forms a new local magnetopause boundary.

For favourably oriented magnetization vectors (i.e. for $\mathbf{M} \cdot \Delta \mathbf{B}_0 > 0$), τ_4 corresponds to the characteristic acceleration time of the filament crossing the magnetopause. The leading plasma surface is accelerated first. The volume of the element is now expanded. The plasma density is temporarily depressed. When the trailing edge of the plasma irregularity passes the magnetopause, it is similarly accelerated as described above.

These sequences are illustrated in Figures 3a and b. An alternative way of viewing this phenomenon is via the $\mathbf{J} \times \mathbf{B}$ force which balances the pressure gradient force when plasmas and fields are in equilibrium. Considering the simplest case in the equatorial plane the Chapman–Ferraro magnetopause currents ($\mathbf{J}_{CF}$) are from dawn to dusk. The diamagnetic currents ($\mathbf{J}_d$) circulating around a plasma pressure and density enhancement are counterclockwise when the magnetosheath field is Southward ($B_z^{MS} < 0$); indeed in this case the magnetic field produced by the current system $\mathbf{J}_d$ must have a northward component in order to

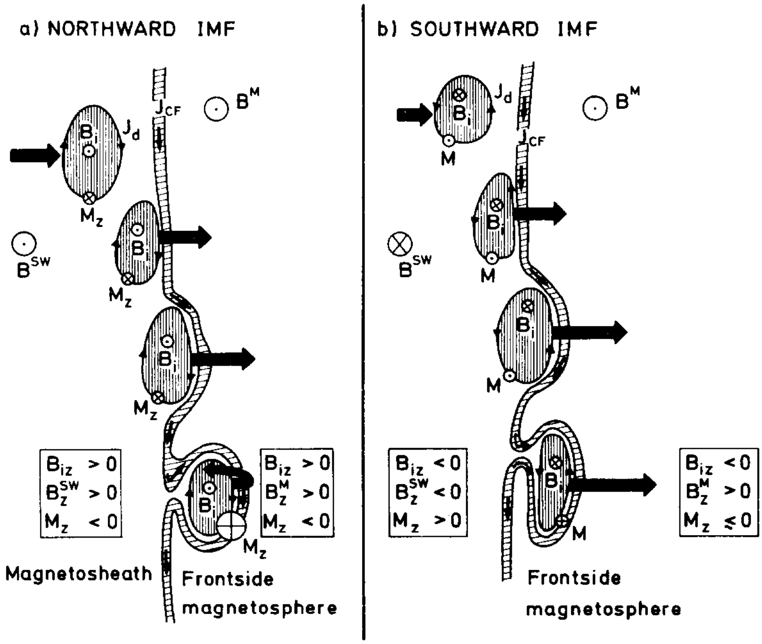

FIG. 3. EQUATORIAL CROSS-SECTION OF THE FRONTSIDE MAGNETOPAUSE REGION (A) FOR A NORTHWARD, (B) FOR A SOUTHWARD SOLAR WIND MAGNETIC FIELD.

In case (b) the Chapman–Ferraro currents ($\mathbf{J}_{CF}$) attract the diamagnetic currents ($\mathbf{J}_d$) of the filament. In case (a) the latter are repelled by the magnetopause current system.

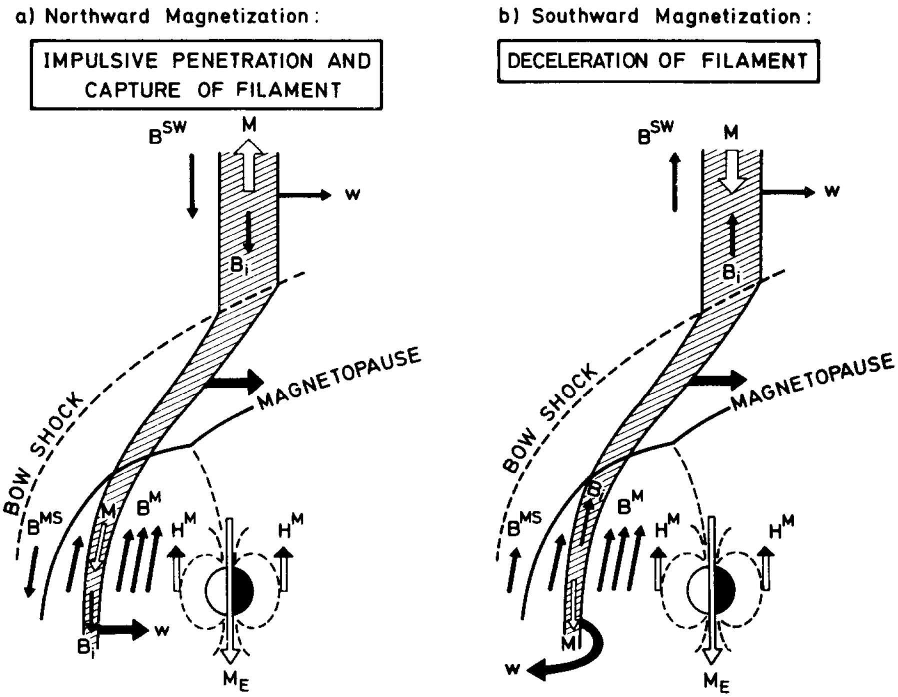

FIG. 4. MERIDONAL CROSS-SECTIONS OF THE MAGNETOSPHERE SHOWING A SOLAR WIND PLASMA FILAMENT (A) CAPTURED AND (B) STOPPED AT THE FRONTSIDE MAGNETOSPAUSE.
M is the magnetization vector; **B** is the magnetic induction; **w** represents the bulk velocity of the penetrating plasma irregularity.

reduce the magnetic pressure inside the filament to keep the total pressure nearly constant. When these diamagnetic currents at the leading plasma edge combine with the oppositely directed Chapman–Ferraro current, the net $(\mathbf{J}_d+\mathbf{J}_{CF})\times\mathbf{B}$ force is suddenly reduced at the place where the filament impacts the magnetopause surface. On the other hand, the plasma pressure gradient force at the leading edge of the plasma element is enhanced. As a consequence of the imbalance of forces acting on the boundary, the plasma irregularity is accelerated toward the inside of the magnetosphere. However, when the IMF or the field in the magnetosheath is northward the $\mathbf{J}_d\times\mathbf{B}$ and $\mathbf{J}_{CF}\times\mathbf{B}$ forces add to each other to oppose the enhanced plasma pressure gradient force.

From this discussion it can be concluded that free access to, or rejection by, the magnetosphere of impulsively injected plasma irregularities is controlled by the angle γ between the vectors $\mathbf{M}$ and $\Delta\mathbf{B}_0$, where $\mathbf{M}$ is the initial magnetization of the filament when it reaches the magnetopause, and where $\Delta\mathbf{B}_0$ is the difference of the magnetic inductions inside and outside the magnetopause. When $\gamma>90°$, or $\mathbf{M}\cdot\Delta\mathbf{B}_0<0$, the filament does not penetrate into the magnetosphere but is stopped at the magnetosheath–magnetopause boundary. On the contrary, when

$$\gamma<90°, \quad \text{or} \quad \mathbf{M}\cdot\Delta\mathbf{B}_0>0, \tag{9}$$

the filament is injected impulsively through the magnetopause.

4. ACCESS TO THE DIFFERENT REGIONS OF THE MAGNETOSPHERE

A. *Frontside magnetosphere*

At the subsolar point and in the equatorial region of the magnetosphere, the magnetic field ($\mathbf{B}^M$) is directed northward and has a positive B_z component. The magnetic field ($\mathbf{B}^{MS}$) in the magnetosheath is generally smaller than inside the magnetosphere. In the limit of $|\mathbf{B}^{MS}|\ll|B^M|$, the vector $\Delta\mathbf{B}_0$ is approximately parallel to the oz-axis. Then, condition (9) becomes

$$M_z>0. \tag{10}$$

To penetrate and to become captured by the frontside magnetosphere, a filament with excess

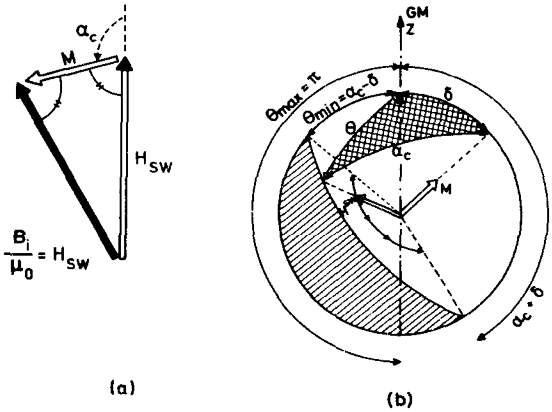

FIG. 5. (A) DEFINITIONS OF THE CRITICAL ANGLE α_c FOR WHICH THE MAGNETIC ENERGY DENSITY IS THE SAME INSIDE AND OUTSIDE AND OUTSIDE THE PLASMA FILAMENT. (B) DEFINITION OF THE COLATITUDE ANGLES δ AND θ OF THE MAGNETIZATION (M) AND THE INTERPLANETARY MAGNETIC FIELD IN THE SOLAR WIND ($\mathbf{H}_{SW}$), RESPECTIVELY.

momentum must have a northward oriented magnetization vector $\mathbf{M}$, at least when $\Delta\mathbf{B}_0$ is parallel to the oz axis. This case is also illustrated in Fig. 4a. On the contrary, when $M_z < 0$, the filament is stopped at the magnetopause surface as shown in Fig. 3b.

Since the initial direction of $\mathbf{M}$ and the direction of the magnetic field in the solar wind ($\mathbf{H}_{SW}$) are not unrelated, condition (10) imposes some restrictions on the direction of interplanetary magnetic field (IMF) for penetration and capture; these are now examined. When $\mathbf{M}$ and $\mathbf{H}_{SW}$ are antiparallel (Fig. 4a) the magnetic induction $\mathbf{B}_i$, measured at a point P inside the plasma element where $\mathbf{B}_i = \mu_0(\mathbf{M}+\mathbf{H}_{SW})$, is smaller than $\mathbf{B}_{SW}$ which is the induction measured at any other point P' outside, where $\mathbf{B}_{SW} = \mu_0\mathbf{H}_{SW}$ (see Fig. 1). The magnetic energy density ($B_i^2/2\mu_0$) in the plasma is then smaller than the magnetic energy density ($B_{SW}^2/2\mu_0$) outside the volume of the element. The excess

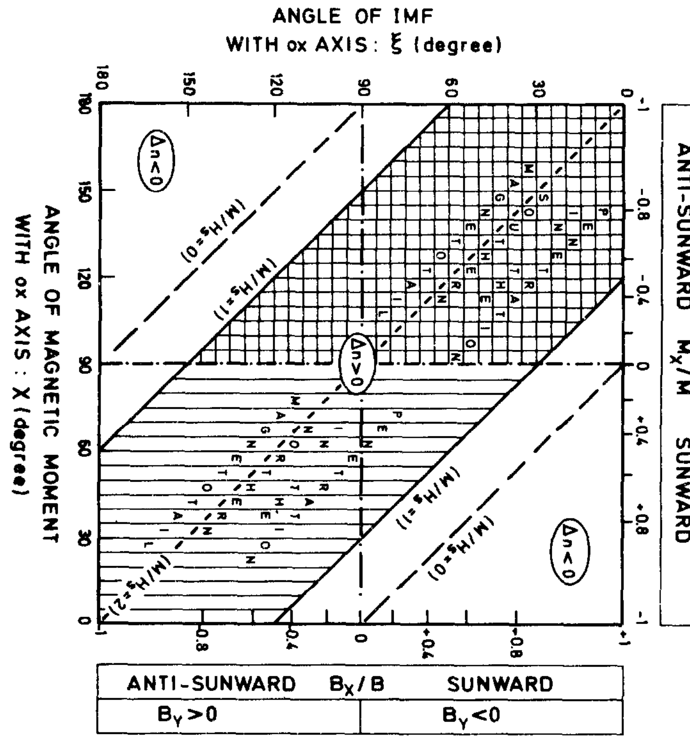

FIG. 6. MAGNETIZATION AND INTERPLANETARY MAGNETIC FIELD COLATITUDES (δ, θ) CORRESPONDING TO IMPULSIVE PENETRATION AND CAPTURE (OR REPULSION) OF SOLAR WIND IRREGULARITIES.

For fixed values of the angles δ and α_c, the IMF colatitude leading to penetration can take any value between $\alpha_c - \delta$ and $2\pi - \alpha_c - \delta$: furthermore capture in the frontside magnetosphere requires a northward magnetization for the plasma irregularity, i.e. $\delta < 90°$. The critical angle α_c depends on M/H_{SW} through equation (12).

kinetic pressure inside the plasma irregularity allows total pressure balance across the boundary of the filament, i.e.

$$\sum_{+-} n_i k T_i + \frac{B_i^2}{2\mu_0} = \sum_{+-} n_{SW} k T_{SW} + \frac{B_{SW}^2}{2\mu_0}. \quad (11)$$

This equation is satisfied when the plasma inside a filament is in hydrodynamic equilibrium and when it moves with the same bulk velocity as the plasma outside.

As a consequence of equation (11), a solar wind irregularity, with an excess of kinetic pressure ($n_i T_i > n_{SW} T_{SW}$), must carry a magnetization moment (**M**) which combines with the external field ($\mathbf{H}_{SW}$) to reduce the magnetic energy density inside the volume element. This implies that the angle (a) between **M** and $\mathbf{H}_{SW}$ is larger than some critical value (a_c) given by

$$\cos a_c = -\frac{M}{2H_{SW}}. \quad (12)$$

When $a = a_c$, B_i is equal to B_{SW}. This case is illustrated in Fig. 5a. On the contrary when $a < a_c$ the field inside is larger than the field outside the filament; but according to equation (11) this implies that $n_i < n_{SW}$ and/or $T_i < T_{SW}$.

Note that a_c is defined by equation (12) only when the magnetization M is smaller than $2H_{SW}$. For $M = H_{SW}$, a_c is equal to 120°; for $M \ll H_{SW}$, a_c is close to 90°; for $M = 2H_{SW}$, a_c is equal to 180°. On the contrary, when $M > 2H_{SW}$, the magnetic induction inside the plasma filament is always larger than outside, and $n_i T_i$ must be smaller than $n_{SW} T_{SW}$ whatever the relative orientation between the vectors **M** and $\mathbf{H}_{SW}$. This extreme case can only be encountered in a high-beta solar wind plasma, i.e. when $nkT \gg B^2/2\mu_0$.

Conversely, it can be deduced from equations (2) and (11) that any solar wind filament with an excess of kinetic pressure ($\Delta nkT = k(n_i T_i - n_{SW} T_{SW}) > 0$) carries a magnetization moment whose angle with the external interplanetary magnetic field is larger than a_c.

The spherical triangle in Fig. 5b illustrates the relation between the angle a_c and the colatitudes δ and θ of the vectors **M** and $\mathbf{H}_{SW}$ respectively. For a fixed value of δ, the values of θ for which $a > a_c$ range between $\theta = a_c - \delta$ and $\theta = \pi$ when $\delta < \pi - a_c$ or between $\theta = a_c - \delta$ and $\theta = 2\pi - a_c - \delta$ when $\delta > \pi - a_c$. This range of colatitudes θ for which $a > a_c$ corresponds to the shaded spherical cap in Fig. 5b. The shaded area in Fig. 6 also shows the range of values of θ and δ for which $a > a_c$. The critical value a_c corresponding to the shaded area represented in Fig. 6 is $a_c = 120°$, which is the solution of equation (12) for $M = H_{SW}$. Note that when $M = 2H_{SW}$, $a_c = 180°$ and in this case the shaded area of Fig. 6 shrinks toward the diagonal AB. On the other hand when M/H_{SW} tends to zero, the shaded area is bounded by the dashed lines also shown in Fig. 6. Note that these lines correspond to $\theta = a_c - \delta$ and $\theta = 2\pi - a_c - \delta$ (see Fig. 5b).

For any colatitude θ and δ within the shaded area, the magnetic energy density is smaller inside than outside the filament and, consequently, $\Delta nkT > 0$. This latter condition is satisfied when

$$\Delta n > 0 \quad (13a)$$

as long as

$$\frac{\Delta T}{T} > -\frac{\Delta n}{n}. \quad (13b)$$

As noted in the introduction, equation (13a) is a primordial condition for impulsive penetration. Considering that the inequality (13b) is usually satisfied in the solar wind, impulsive penetration is only possible when the angles θ and δ range between the limits of the shaded area in Fig. 6.

On the other hand, capture by the magnetosphere is only possible when equations (9) or (10) are also satisfied, i.e. when the colatitude of **M** is smaller than 90°. The doubly shaded area in Fig. 6 defines the limits of θ and δ for which $\Delta n > 0$ and $M_z > 0$, simultaneously.

It can be seen from Fig. 6 that a southward orientation of the IMF favours impulsive penetration in the frontside of the magnetosphere. Even for slightly positive values of $(H_{SW})_z$, dayside capture of solar wind plasma filaments is also possible. But for such a northward IMF, the angles δ leading to penetration and capture must be within a more restricted interval of colatitudes.

At the beginning of this section the assumption was made that $\Delta\mathbf{B}_0$ is strictly parallel to the oz axis. Even if this is true on a statistical basis it may be incorrect for individual cases when the IMF in the solar wind or in the magnetosheath has an intensity comparable to the magnetospheric field at the magnetopause. Under such circumstances, condition (10) is too restrictive and penetration of irregularities through the frontside magnetopause will be possible even for slightly negative values of M_z. This enlarges somewhat the doubly shaded region of Fig. 6 towards the right hand side.

The preferential penetration and capture of filaments in the frontside magnetosphere when the Interplanetary Magnetic Field has a southward

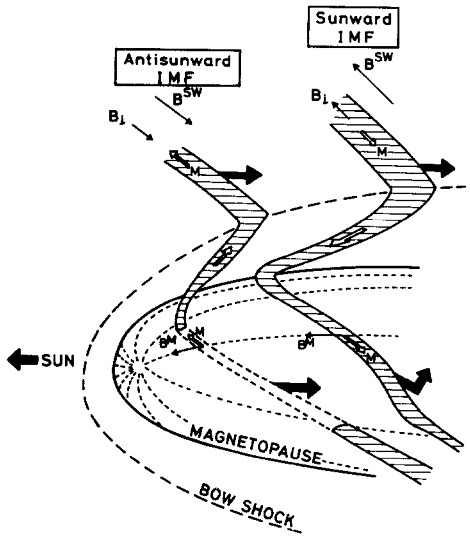

FIG. 7. ILLUSTRATION OF THE MAGNETOSPHERE AS SEEN FROM ABOVE THE NORTH POLE.

The filament with a sunward directed magnetization **M** (i.e. for an away IMF polarity) can penetrate and sink down in the northern lobe of the magnetotail. The other filament corresponding to a sunward (or toward) IMF will be rejected at the magnetopause surface as indicated by the broken black arrow.

component is indeed supported by observations of magnetic holes or blobs (Skillman and Sugiura, 1971) in the outer magnetosphere of the Earth (Sugiura, personal communication, 1977). Considering the plasma mantle (Rosenbauer *et al.*, 1975) and the boundary layer (Eastman *et al.*, 1976) as consequences of the impulsive penetration of small scale plasma irregularities in the dayside and equatorial magnetosphere, one can expect the occurrence of these phenomena to be correlated with the North-South direction of the interplanetary magnetic field. According to Sckopke *et al.* (1976) and Paschmann *et al.* (1976), the plasma mantle is indeed always present when the IMF has a southward, or a small northward, component. But it is absent when B_z^{MS} assumes large positive values.

Aubry *et al.* (1970) have observed the inward motion of the dayside magnetopause in response to a southward turning of the interplanetary magnetic field even though the hourly average of the dynamic solar wind pressure remains constant to within 10%. Fairfield (1971) has also shown that when the magnetosheath field is southward, the magnetopause is on the average one Earth radius closer to the Earth. Russell *et al.* (1971) and Gladyshev *et al.* (1974) have shown that the polar cusp moves equatorwards in the presence of a

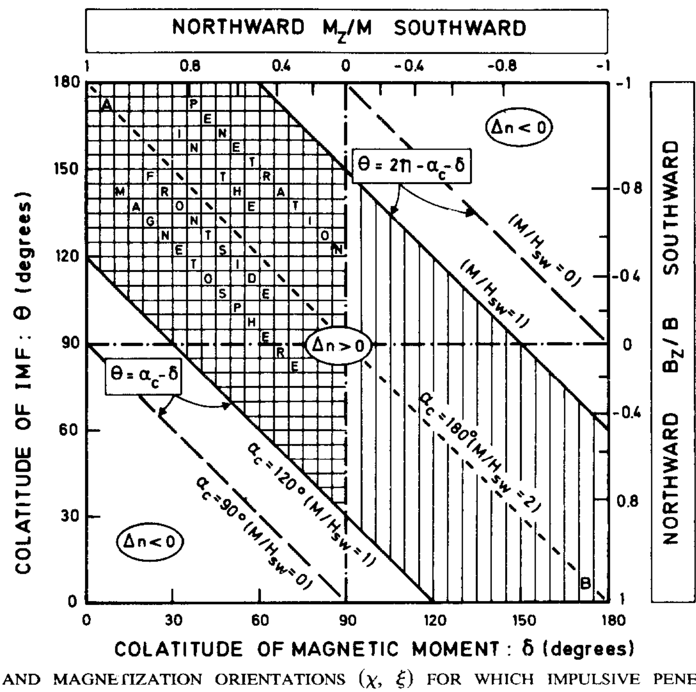

FIG. 8. IMF AND MAGNETIZATION ORIENTATIONS (χ, ξ) FOR WHICH IMPULSIVE PENETRATION AND CAPTURE OF SOLAR WIND SLABS IS POSSIBLE IN THE NORTHERN AND SOUTHERN LOBES OF THE MAGNETOTAIL.

For a fixed value of M/H_{SW} the angles χ and ξ corresponding to penetration and capture in the northern (/southern) lobe are given by the light (/doubly) shaded area.

southward interplanetary magnetic field. All these observations seem to confirm that small scale solar wind irregularities penetrate deeper into the front-side magnetosphere when the solar wind magnetic field has a southward component. The average magnetopause is then at the mean distance of penetration of impulsively injected small scale interplanetary filaments.

B. *Cleft region*

Entry of solar wind plasma elements through the polar cusp magnetopause is expected to be possible for a wider range of the IMF directions. Indeed in these funnel shaped regions the magnetospheric field ($\mathbf{B}^M$) assumes a wide range of directions, and there is always likely to be some position where $\mathbf{M}\cdot\Delta\mathbf{B}_0$ is positive.

This conclusion is supported by HEOS2 observations (Haerendel *et al.*, 1977) indicating that the high latitude entry layer is observed for any orientation of the magnetic field in the nearby magnetosheath region.

C. *Magnetotail lobes*

According to the arguments developed in section (3), the penetration of solar wind filaments into the northern lobe of the magnetotail is expected to be possible when their magnetization vectors point towards the Sun. Indeed the magnetic field in the northern lobe of the tail is directed towards the Sun as illustrated in Fig. 7. Assuming again that the magnetic induction outside the magnetopause is much smaller than inside, it can be said that, at least on a statistical basis, $\Delta\mathbf{B}_0$ is approximately parallel to the ox axis. It can therefore be concluded that access of solar particles to the northern polar cap region is possible when the magnetization has a positive M_x component.

$$M_x > 0. \tag{14}$$

In the opposite case, when $\mathbf{M}$ points away from the Sun, the solar wind filaments cannot generally penetrate into the northern lobe of the magnetotail. They then slip around the surface of the magnetopause as also illustrated in Fig. 7.

It is clear that these conclusions must be reversed for the southern lobe of the magnetotail, where the magnetic field $\mathbf{B}^M$ is directed in the opposite direction i.e. anti-parallel to ox.

Since the magnetization $\mathbf{M}$ and the magnetic field $\mathbf{H}_{SW}$ in the solar wind are not fully unrelated (equation 2), condition (14) again imposes some restrictions on the direction of $\mathbf{H}_{SW}$. Following the same arguments as in section 4A, and taking into consideration equations (13a) and (14), one obtains the results illustrated in Fig. 8.

(1) Impulsive penetration of solar wind plasma filaments into the northern lobe of the magnetotail is mainly possible when the interplanetary magnetic field has an anti-sunward (away) direction or a small sunward component (singly shaded area in lower right of Fig. 8). Assuming that the IMF is generally parallel to the 45° Archimedian spiral direction, $(H_{SW})_x$ is equal to $(-H_{SW})_y$. As a consequence the preceding condition for capture can be interpreted also in the following terms: capture of solar wind plasma irregularities in the northern lobe of the magnetospheric tail is allowed mainly when the interplanetary magnetic field has a positive or a small negative y component.

(2) On the other hand penetration and capture in the southern lobe is possible when $\Delta n > 0$ and $M_x < 0$. This happens predominantly when the magnetic field in the magnetosheath assumes a sunward (toward) polarity, i.e. for $(H_{SW})_x > 0$ and $(H_{SW})_y < 0$. These conditions are satisfied when the angle (χ) between $\mathbf{M}$ and ox, and the angle (ξ) between H_{SW} and ox, both range within the limits of the doubly shaded area in Fig. 8.

For the same reason as before these conclusions must be taken on a statistical basis, since condition (14) is a too restrictive application of equation (9).

The north/south asymmetry of charged particle fluxes in polar regions and their correlation with the IMF sector direction have been reviewed by Mizera and Fennell (1978). All the observations reported by these authors indicate that direct access of solar wind plasma to the northern (southern) lobe occurs for an away (toward) interplanetary magnetic field. These experimental results fully support our conclusions. Furthermore, small scale polar cap magnetic irregularities probably associated with field aligned electric currents and plasma filaments captured in the northern (southern) lobe of the magnetotail, are also well correlated with the away (toward) IMF direction (Saflekos *et al.*, 1977).

5. CONCLUSIONS

The impulsive penetration of solar wind plasma irregularities into the different parts of the magnetosphere is possible if their momentum density is larger than the average momentum density of the interplanetary medium. This occurs, for instance, when the density is larger inside than outside the solar wind filament (equation 13a). The second condition for access into, and capture by, the magnetosphere is that the magnetization vector **M** carried by filaments has a positive component along $\Delta\mathbf{B}_0$, the difference between the magnetospheric field ($\mathbf{B}^M$) and the magnetic induction in the magnetosheath at the point of penetration. This condition is expressed by equation (9).

Using the pressure balance equation (11) and equation (12) we have determined the preferential orientations of the IMF direction leading to capture of solar wind irregularities. A southward IMF orientation favours penetration and capture in the frontside magnetosphere. Therefore the turning of the interplanetary magnetic field from Northward to Southward corresponds to unlocking the door to the magnetosphere and allowing the impulsive entry of plasma irregularities. This southward turning of the IMF is known to be correlated with geomagnetic activity and with auroral activity. The observed "erosion" of the dayside magnetosphere, when B_z becomes negative, is also a straightforward consequence of the penetration control mechanism by the north/south IMF direction.

The penetration and capture in the polar cusps is much less restricted than in the equatorial regions of the magnetosphere. Indeed near the neutral points the magnetospheric field direction ($\mathbf{B}^M$) varies over a wider range of angles; equation (8) can be satisfied for almost any orientation of the incident magnetization vector (**M**). As a consequence, turbulent plasma motions can be observed nearly all the time in the cleft regions. The capture of solar wind irregularities near the neutral points should not be correlated with the B_z nor with the B_y components of the magnetosheath or interplanetary magnetic field.

Finally, it has been shown that an anti-sunward (away) IMF polarity favours penetration and capture of plasma in the northern lobe of the magnetotail. The opposite IMF polarity makes the southern lobe accessible to solar wind plasma.

It has become customary to correlate magnetospheric events either with the B_z component (South–North) or with the B_y component (dawn–dusk) of the Interplanetary Magnetic Field. From our discussion, it appears, however, that a more appropriate parameter to organize such correlative studies would be $\mathbf{M}\cdot\Delta\mathbf{B}_0$ or, more practically,

$$e_M = \mathbf{B}^{MS}\cdot(\mathbf{B}^M - \mathbf{B}^{MS})/\mu_0. \qquad (15)$$

This parameter has the dimensions of an energy density; we call it the "Magnetopause Penetration parameter". It is a quadratic function of the three IMF components B_x^{MS}, B_y^{MS} and B_z^{MS}. It is only under special circumstances that e_M is proportional to B_z^{MS} (at the equatorial plane), to B_x^{MS} (for the southern magnetotail) and to $-B_x^{MS}$ (for the northern lobe).

It would be interesting to reexamine earlier correlation studies of geophysical phenomena with B_z^{MS} and B_y^{MS}, and to check whether e_M, the Magnetopause Penetration Parameter, organizes the data better or not.

The future results from ISEE A and B will surely provide a test platform for the present suggestions.

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