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How can the IMF direction control the mean radial distance of the magnetopause ?

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FOREWORD

The paper "How can the IMF direction control the mean radial distance of the magnetopause? " has been given at the "Solar-Terrestrial-Physics Symposium" (Innsbruck, 29 May - 3 June 1978). The manuscript will be published in the proceedings of this conference.

AVANT-PROPOS

L'article "How can the IMF direction control the mean radial distance of the magnetopause? " a été présenté au "Solar-Terrestrial-Physics Symposium" (Innsbruck, 29 mai - 3 juin 1978). Ce texte paraîtra dans les comptes rendus de cette conférence.

VOORWOORD

De tekst "How can the IMF direction control the mean radial distance of the magnetopause? " werd voorgedragen op de "Solar-Terrestrial-Physics Symposium" (Innsbruck, 29 mei - 3 juni 1978). Hij zal gepubliceerd worden in de Proceedings van deze konferentie.

VORWORT

Dieses Artikel "How can the IMF direction control the mean radial distance of the magnetopause? " wurde zum "Solar-Terrestrial-Physics Symposium" (Innsbruck, 29 Mai - 3 Juni 1978) vorgetragen. Dieser Tekst wir in die Proceedings dieser Konferenz veröffendlicht.

HOW CAN THE IMF DIRECTION CONTROL THE MEAN RADIAL DISTANCE OF THE MAGNETOPAUSE ?

by

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Abstract

Many observations indicate that the position of the dayside magnetopause depends upon the orientation of the interplanetary magnetic field (IMF). Considering that the solar wind plasma is inhomogeneous and irregular, field aligned density irregularities can penetrate impulsively into the magnetosphere when their magnetization vectors ($\underline{M}$) have a positive component along the direction of the magnetospheric field ($\underline{B}^M$). This happens when the diamagnetic currents flowing at the surface of these irregularities are opposed to the Chapman-Ferraro currents at the magnetopause.

As a consequence of this non-stationary interaction model, the mean position of the dayside magnetopause moves to a smaller radial distance when the IMF turns from a Northward to a Southward direction.

It is also suggested that the "Magnetopause Penetration Parameter"

$$e_M = (\underline{B}^M - \underline{B}^{MS}) \cdot \underline{B}^{MS}/\mu_o$$

with $\underline{B}^{MS}$ the magnetosheath field, is an apposite variable to correlate the IMF direction with magnetospheric phenomena depending on the penetration of solar wind particles into the magnetosphere.

Résumé

De nombreuses observations indiquent que la position du "nez" de la magnétopause dépend de l'orientation du champ magnétique interplanétaire. Considérant que le plasma du vent solaire est inhomogène et irrégulier, des irrégularités de densité de plasma peuvent pénétrer par à-coup dans la magnétosphère lorsque leur vecteur de magnétisation ($\underline{M}$) possède une composante positive dans la direction du champ géomagnétique ($\underline{B}^{M}$). Ceci se produit lorsque les courants diamagnétiques existant à la surface de ces irrégularités sont opposés aux courants de Chapman-Ferraro à la magnétopause.

Dans ce modèle d'interaction non-stationnaire du vent solaire et du champ géomagnétique, la position moyenne du nez de la magnétopause se rapproche de la Terre lorsque la direction du champ magnétique interplanétaire change du nord au sud.

Il est suggéré que le "Paramètre de Pénétration de la Magnétopause", défini par

$$e_M = (\underline{B}^{M} - \underline{B}^{MS}) \cdot \underline{B}^{MS}/\mu_0$$

où $\underline{B}^{MS}$ est le champ d'induction magnétique dans la "Magnétogaine", est une variable appropriée dans les études de corrélations entre l'orientation du champ magnétique interplanétaire et les phénomènes magnétosphériques qui dépendent de la pénétration du vent solaire dans la magnétosphère.

Samenvatting

Vele waarnemingen wijzen er op dat de plaats van de "neus" van de magnetosfeer afhankelijk is van de oriëntatie van het interplanetair magneetveld. Het plasma van de zonnewind is inhomogeen en ongelijk. Deze onregelmatigheden in de dichtheid van het plasma kunnen in de magnetosfeer binnendringen wanneer hun magnetisatie vektor (M) een positieve componente bezit in de richting van het geomagnetische veld. Dit geschiedt wanneer de diamagnetische stromen die optreden aan de oppervlakte van de onregelmatigheden, tegengesteld zijn aan de Chapman- Ferraro stromen aan de magnetopauze.

In deze niet-stationaire modelberekening van de interactie van de zonnewind met het aardse magneetveld, komt de "neus" van de magnetosfeer dichter bij de aarde te liggen, wanneer de richting van het interplanetaire magneetveld verandert van noord naar zuid.

We stellen voor dat de "magnetopauze penetratieparameter" gedefinieerd door

$$e_M = (\underline{B}^{M} - \underline{B}^{MS}) \cdot \underline{B}^{MS}/\mu_o$$

waarin $\underline{B}^{MS}$ het magnetische inductie veld voorstelt in de magnetoschede, de geschikte grootheid is voor de studie van de correlaties tussen de oriëntatie van het interplanetaire magneetveld en de magnetosferische verschijnselen die afhangen van het binnendringen van de zonnewind in de magnetosfeer.

Zusammenfassung

Verschiedene Beobachtungen erweisen dass die Lage der forderen Magnetopause von die Richtung des interplanetaren magnetisches Feld abhängen. In Anbetracht dass der Sonnenwind inhomogen ist, konnen Plasmasirregularitäten sich impulsiv in der Magnetosphäre eindrigen wenn die Magnetization ($\underline{M}$) eine positive Komponent in der Richtung des geomagnetischen Feldes hat. Dieses gescheht wenn die diamagnetische Strömen der Irregularitäten und die Chapman-Ferraro Ströme der Magnetopauze entgegen wirken.

Als Konsequenz dieses zeitabhängische Interactionsmodell, schränkt die Magnetopauze näher bei der Erde wenn das interplanetare magnetische Feld sich von nordliche nach südliche Richtungen umdreht.

Es ist eingegeben dass das Penetrations Parameter

$$e_M = (\underline{B}^M - \underline{B}^{MS}) . \underline{B}^{MS}/\mu_o$$

wo $\underline{B}^{MS}$ das Magnetische Feld in der Magnetosheath ist, eine geeignete Korelations variable ist.

INTRODUCTION

Observations of the interplanetary medium (e.g. McCracken and Ness, 1966, Hewish and Symonds, 1969, and Burlaga *et al.*, 1977) show that the solar wind is *not* a uniform, homogeneous medium. They show that there are magnetic field changes and plasma density irregularities with temporal scales $\gtrsim$ 2 sec. These inhomogeneities are convected away from the sun by the solar wind; therefore their spatial scales are $\gtrsim$ a few hundred km. They are very small compared with the overall dimensions of the magnetosphere.

These inhomogeneities are aligned along the Archimedean spiral angle. They are, therefore, discrete flux tubes in the interplanetary direction. In this paper, we consider what happens when these flux tubes first touch the magnetosphere and then drape themselves around it, i.e. we consider the interaction of these flux tubes with the magnetosphere.

It is necessary to realize that such a filamentary irregularity has diamagnetic currents flowing on its boundary. If these currents are entirely circumferential, around the skin of the filament of thickness Δ (see Fig. 1), then the magnetization $\underline{M}$ is along the axis of the filament. This situation, with no field aligned currents, is the simplest case to visualize.

It the filamentary irregularity has an enhanced plasma density, or an enhanced plasma velocity, above that of the surrounding solar wind, it will penetrate deeper into the magnetosphere than the existing magnetopause because of its excess momentum density there.

Associated with this excess momentum density, there is an excess kinetic energy. Part of this goes into the compression, i.e. heating, of the plasma within the filament.

The current on the surface of the filament can change because curl $\underline{B}$ changes as the filament moves into a region of stronger magnetic field. The field aligned part of the current can go into the ionosphere, in the cleft region; energy dissipation occurs there due to Joule heating.

At the edge of the filament, there is an electric potential difference

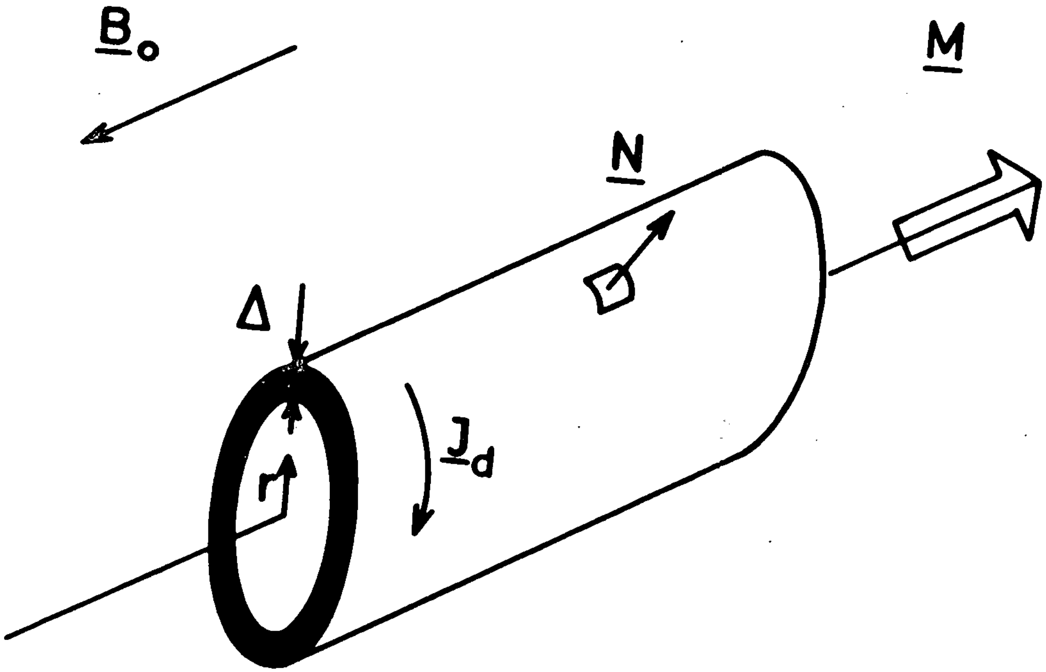


Fig. 1.- Idealized diagram showing diamagnetic current flowing in the surface of a filamentary irregularity, of thickness Δ, and producing a magnetization $\underline{M}$. The outward directed normal is $\underline{N}$. In this simple case, the field aligned current is zero. The magnetic field inside the filament ($\underline{B}_i = \underline{B}_o + \mu_o \underline{M}$) is less than that outside ($\underline{B}_o$).

$$\phi \cong k\,\Delta T/e$$

where ΔT is the temperature difference between the plasma inside and outside the filament, k is Boltzmann's constant and e is the charge on the electron.

This filament containing magnetosheath plasma preserves its identity until the forces acting upon the charged particles, e.g. due to electric fields, the gradient of $\underline{B}$ and the curvature of $\underline{B}$, have removed them from it.

After this descriptive introduction, we consider the situation theoretically using a fluid treatment and classical electromagnetism.

THEORY OF MAGNETOPAUSE PENETRATION BY A FILAMENTARY IRREGULARITY

We consider an isolated solar wind filament in the interplanetary medium. The magnetic field outside the plasma irregularity is determined by all external sources, e.g. by electric currents flowing at the interface of other filaments, along sector boundaries, at the magnetopause (Chapman-Ferraro currents), and in the earth's core.

At the surface of the plasma inhomogeneity, the diamagnetic current density $\underline{J}_d$ is determined by local gradients of the plasma density and temperature (see Fig. 1.). $\underline{K}$ is the electric current density integrated over the thickness of the filament, Δ, which is a few ion gyro radii.

$$\underline{K} = \int_\Delta \underline{J}_d \, dr$$

Also

$$|\underline{K}| = |\underline{B}_i - \underline{B}_o| / \mu_o$$

where $\underline{B}_i$ is the magnetic flux density inside the filament and $\underline{B}_o$ is the magnetic flux density outside it. Also

$$\underline{K} = \underline{M} \wedge \underline{N}$$

where $\underline{N}$ is the outward directed normal of the filament (Stratton, 1941, p. 242). Depending on the orientation of $\underline{N}$ and on the direction of the currents $\underline{J}_d$, the magnetic moment of the filament, i.e. the integral of $\underline{M}$ over the volume of the filament, can have any direction with respect to the external field $\underline{B}_o/\mu_o$.

The magnetic force exerted on unit surface area of a diamagnetic plasma element by an external magnetic field is

$$\underline{F} = \int_\Delta \underline{J}_d \wedge \underline{B}_o \, dr = \underline{K} \wedge \underline{B}_o$$

Combining these equations, we have

$$\underline{F} = \underline{N}\,(\underline{M}.\underline{B}_o) - \underline{M}\,(\underline{N}.\underline{B}_o)$$

The plasma boundary is a rotational discontinuity, or, when $\underline{N}.\underline{B}_o = 0$ as it is where the filament first encounters the nose of the magnetosphere, it is a tangential discontinuity.

The hydromagnetic pressure $(-\underline{N}.\underline{F})$ normal to the boundary of the element needed to retain the filament as an entity balances the plasma pressure inside the filament.

Now at the magnetopause the field external to the filament $\underline{B}_o$ changes more or less abruptly from $\underline{B}^{MS}$ in the magnetosheath to $\underline{B}^M$ in the magnetosphere. Then

$$\Delta \underline{B}_o = \underline{B}^M - \underline{B}^{MS}$$

Thus as a filament with excess momentum density goes into the magnetosphere, the change of the hydromagnetic pressure normal to the surface element is

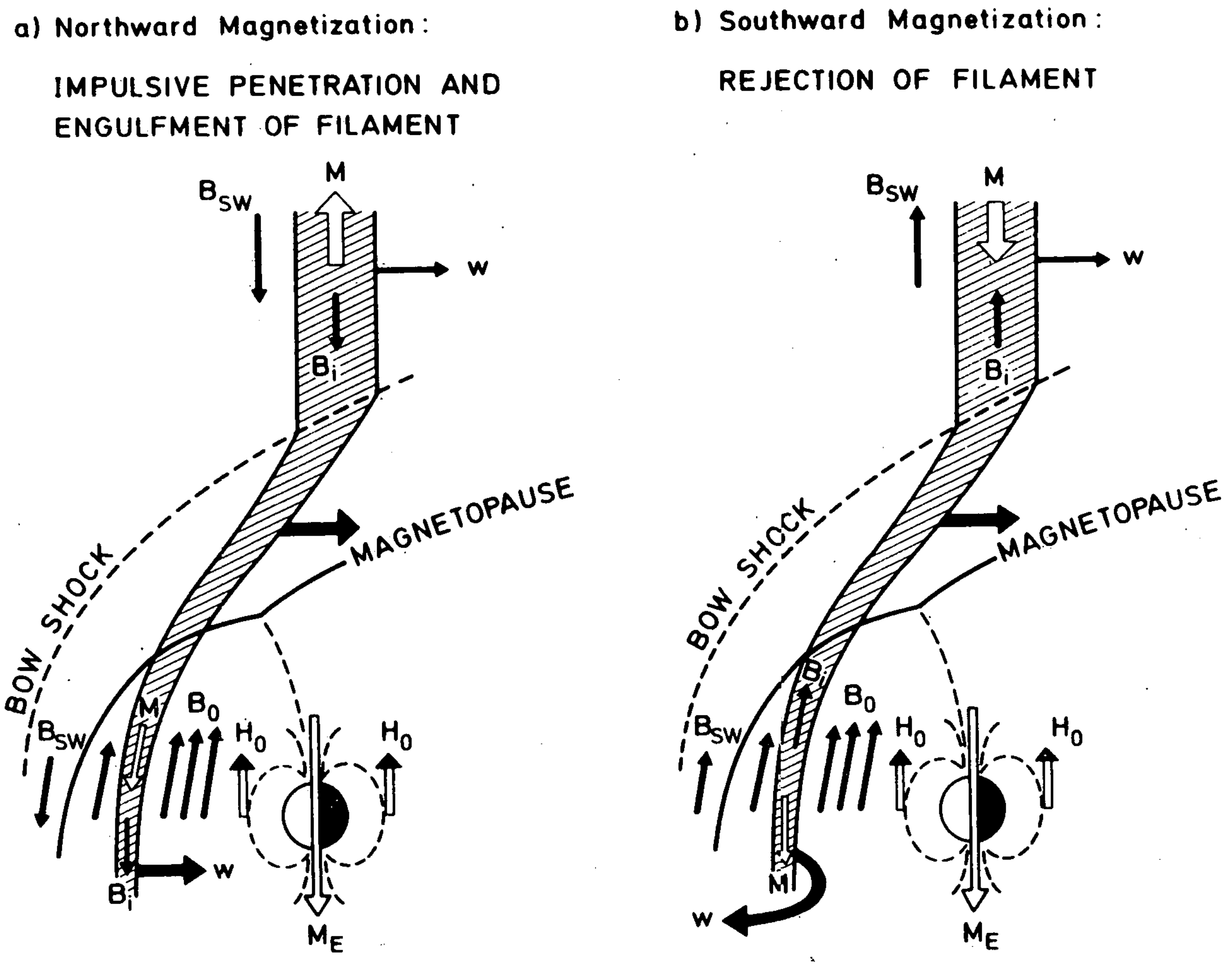
$$\begin{aligned}\Delta p_{\text{magnetic}} &= -\underline{N}.\Delta\underline{F} \\ &= -\underline{N}.\Delta[\underline{N}(\underline{M}.\underline{B}_o)] \\ &= -\underline{M}.\Delta\underline{B}_o\end{aligned}$$

if $\underline{M}$ does not change. This is a most important relation, the consequences of which will be examined.

Remembering that $\underline{M}$ is the magnetization of the filament when in the magnetosheath, then, if $\underline{M}.\Delta\underline{B}_o > 0$, $\Delta p_{\text{magnetic}} < 0$, so that the hydromagnetic pressure on the filament from outside becomes less than the plasma pressure from inside. Therefore, the plasma at the leading edge of the filament is accelerated towards the interior of the magnetosphere (see left hand side, a) of Fig. 2). This corresponds to the penetration of the local magnetopause by the filament, to the injection of the filament into the magnetosphere, and to its capture by the magnetosphere. Once inside the magnetosphere its magnetization can change (see Fig. 2a)).

Conversely, as is shown in Fig. 2b), when $\underline{M}.\Delta\underline{B}_o < 0$, $\Delta p_{\text{magnetic}} > 0$, and so the leading edge of the filament is retarded. Its volume is decreased and its kinetic pressure thus increased; the plasma is heated up somewhat. For a filament with a ~ 10% excess momentum density, it is decelerated and stopped ~ one earth radius inside the magnetopause. The element is still repelled, and moves outwards; it is returned to the magnetosheath.

Summarizing the results illustrated in Fig. 2, what happens to the filament depends upon the angle between $\underline{M}$ and $\Delta\underline{B}_o$. Now at the subsolar point and in the equatorial region of the magnetosphere, the magnetic field $\underline{B}^M$ is Northwards, i.e. in solar magnetospheric coordinates it has a positive B_z component. Since the magnetic field in the magnetosheath is often smaller than inside the magnetosphere, then, in the limit of $|\underline{B}^{MS}| << |\underline{B}^M|$, $\Delta\underline{B}_o$ is



a) Northward Magnetization:

IMPULSIVE PENETRATION AND ENGULFMENT OF FILAMENT

b) Southward Magnetization:

REJECTION OF FILAMENT

Fig. 2.- Meridional cross sections of the magnetosphere showing a solar wind plasma filament a) captured and b) stopped at the frontside magnetopause. $\underset{\sim}{M}$ is the magnetization vector; $\underset{\sim}{B}$ is the magnetic induction; $\underset{\sim}{w}$ represents the bulk velocity of the penetrating plasma irregularity.

essentially along the z axis. Then a positive value of $\underline{M}.\Delta\underline{B}_o$, necessary for penentration of the magnetosphere and capture of the filament shown in Fig. 2a corresponds to $M_z > 0$; the magnetization of the filament is Northward. Thus, if there are many filaments with excess momentum density and $M_z > 0$, incident on the entire dayside of the magnetosphere or, equivalently, if there is one large slab also of excess momentum density and $M_z > 0$, the magnetosheath plasma will penetrate well beyond the original magnetopause. This process corresponds to erosion of magnetic flux from the dayside magnetosphere. It creates a new magnetopause which is closer to the earth than before.

Conversely, a negative value of $\underline{M}.\Delta\underline{B}_o$, which causes deceleration of the filament and its repulsion back into the magnetosheath as shown in Fig. 2b corresponds to $M_z < 0$; the magnetization of the filament is Southward.

An alternative way of viewing this phenomena is via the $\underline{J} \times \underline{B}$ 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 ($\underline{J}_{CF}$) are from dawn to dusk. The diamagnetic currents ($\underline{J}_d$) 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 $\underline{J}_d$ must have a northward component in order to 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 $(\underline{J}_d + \underline{J}_{CF}) \times \underline{B}$ 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 $\underline{J}_d \times \underline{B}$ and $\underline{J}_{CF} \times \underline{B}$ add to each other to oppose the enhanced plasma pressure gradient force.

Lemaire et al. (1978) have extended this idea to consider any angle between $\underline{M}$ and the z axis and between $\underline{B}^{MS}$ and the z axis. The results of this study are, for typical solar wind conditions with $|\underline{M}| \simeq |\underline{B}^{MS}|/\mu_o$, which corresponds to $\beta^{MS} \sim 1$, that a plasma irregularity with enchanced pressure can penetrate the magnetopause when the angle between $\underline{B}^{MS}$ and the z axis (Northwards) lies between 120° and 240°, i.e. when $\underline{B}^{MS}$ lies within a cone whose axis points Southwards and whose semi-angle is 60°, if the magnetization is Northwards (see Fig. 3).

For a 30° angle between $\underline{M}$ and the z axis (Northwards), an enhanced momentum density irregularity will penetrate the magnetopause when the angle that $\underline{B}^{MS}$ makes with the z axis lies between 90° and 210°. For a 60° angle between $\underline{M}$ and $\hat{\underline{z}}$, $\underline{B}^{MS}$ must make an angle to the $\hat{\underline{z}}$ axis which lies in the range 60° to 180°. For $\underline{M}$ perpendicular to $\hat{\underline{z}}$, $\underline{B}^{MS}$ must make an angle with $\hat{\underline{z}}$ which lies between 30° and 150° (see Fig. 3).

Thus when the IMF ($\underline{B}^{MS}$) has a Southward component, a filamentary irregularity with excess momentum and pressure can penetrate the magnetopause for almost all angles ($< 90°$) that $\underline{M}$ makes with $\hat{\underline{z}}$. There is a small range of angles between $\underline{M}$ and $\hat{\underline{z}}$ for which penetration is possible even if $\underline{B}^{MS}$ has a Northward component (fig. 3).

Although it has become customary for certain magnetospheric phenomena to be correlated with either the South-North (B_z) or the dawn-dusk (B_y) component of the interplanetary magnetic field, our analysis shows that a more appropriate parameter would be $\underline{M}.\Delta\underline{B}_0$. Since, unfortunately, $\underline{M}$ is not directly measured by instruments aboard satellites, whereas $\underline{B}^{MS} \triangleq -\mu_0 \underline{M}$ is, we introduce a parameter termed the "Magnetopause Penetration Parameter", defined as

$$e_M = (\underline{B}^M - \underline{B}^{MS}) . \underline{B}^{MS}/\mu_0$$

which may be useful for correlative studies in this context. This parameter, $-\Delta\underline{B}_0.\underline{M}$ as is evident from this discussion, has the dimensions of energy density. It is only in the equatorial plane that e_M depends upon the Southward component of the magnetosheath magnetic field alone. We hope that it may be possible to check these theoretical concepts using data sets both old and new, e.g. from ISEE-1 and -2.

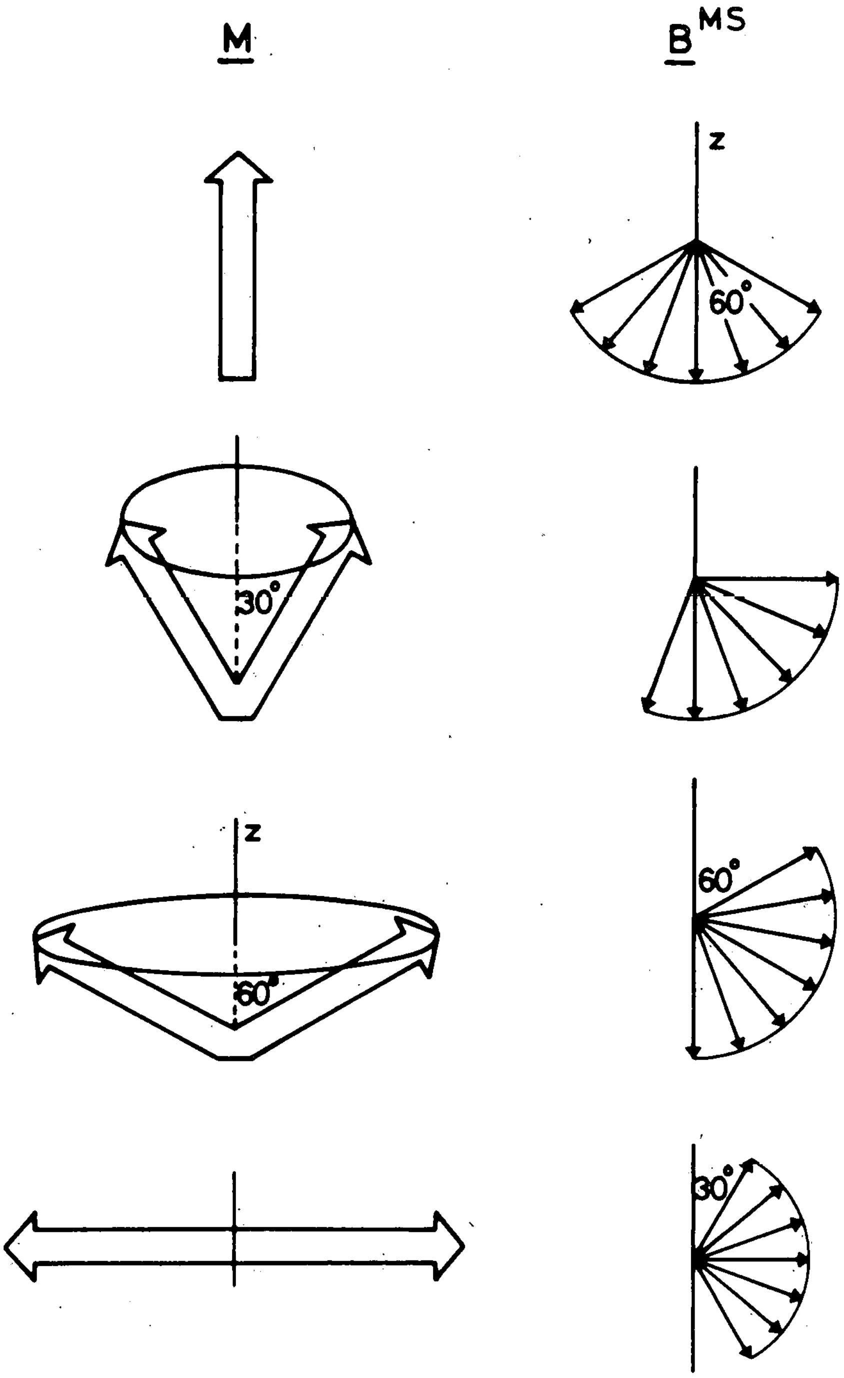


Fig. 3.- Orientations of the magnetization ($\underline{M}$) of an interplanetary filament and the magnetosheath magnetic field ($\underline{B}^{MS}$) required for the filament, having an excess pressure density over that of the surrounding solar wind, to penetrate the magnetopause.

Lemaire *et al.* (1978) have also applied these ideas to the penetration of magnetosheath plasma in the cusp, or cleft, region of the magnetosphere, and also in the Northern and Southern lobes of the magnetotail. The ideas introduced here could be generalized further, removing the simplifications that have been introduced.

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