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Penetration of solar wind plasma elements into the magnetosphere

by

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FOREWORD

The paper "Penetration of solar wind plasma elements into the magnetosphere" by J. Lemaire and M. Roth has been presented at the symposium "Magnetopause Regions" held 7-10 September 1976 in Amsterdam as part of the Third meeting of the European Geophysical Society. This paper will be published in the Proceedings of the conference, and will appear in Journal of Atmospheric and Terrestrial Physics.

AVANT-PROPOS

L'article intitulé "Penetration of solar wind plasma elements into the magnetosphere" par J. Lemaire and M. Roth, a été présenté au symposium "Magnetopause Regions" qui s'est tenu du 7 au 10 septembre 1976 à Amsterdam dans le cadre de la 3ème réunion de la "European Geophysical Society". Il sera publié dans les comptes rendus du symposium qui paraîtront dans Journal of Atmospheric and Terrestrial Physics.

VOORWOORD

Het artikel getiteld "Penetration of solar wind plasma elements into the magnetosphere" door J. Lemaire en M. Roth, werd voorgedragen op het symposium "Magnetopause Regions" dat gehouden werd van 7 tot 10 september 1976, te Amsterdam, in het kader van de derde bijeenkomst van de "European Geophysical Society". Het zal gepubliceerd worden in "Journal of Atmospheric and Terrestrial Physics.

VORWORT

Dieser Text "Penetration of solar wind plasma elements into the magnetosphere" von J. Lemaire und M. Roth wurde während des Symposium "Magnetopause Regions" der in Amsterdam im Rahmen der dritten Sammlung des European Geophysical Society zwischen 7 und 10 September 1976 gehalten wurde, vorgetragen worden. Dieses Artikel wird in die Proceedings des Symposiums herausgegeben, und in Journal of Atmospheric and Terrestrial Physics veröffendlicht.

Additions to Aeronomica Acta A n° 166 - 1976

1. add on page 9 l. 9 after : "is actually observed by"

   THOMAS et al., 1966,

2. add on page 5 l. 21 after : "HOLZER, 1975)".

   Recently, however, HEIKKILA (1975) has pointed out a theoretical difficulty related to magnetic field line merging models.

3. add on page 14 between l. 14 and l. 15 :

   HEIKKILA, W.J., 1975, Geophys. Res. Letters, 2, 154.

4. add on page 15 between l. 11 and l. 12 :

   THOMAS, J.O., RYCROFT, M.J., COLIN, L. and CHAN, K.L., 1966, p. 322, in Electron density profiles in the ionosphere and exosphere, edited by J. FRIHAGEN, North-Holland publ. Co., Amsterdam.

PENETRATION OF SOLAR WIND PLASMA ELEMENTS INTO THE MAGNETOSPHERE

by

J. LEMAIRE and M. ROTH

Abstract

Considering that the solar wind is unsteady and non-uniform, it is suggested that field aligned plasma elements dent the magnetopause surface. This indentation makes the magnetopause boundary convex and therefore locally unstable with respect to flute instabilities. The intruding element is braked and stopped within 1 or 2 Earth radii from the magnetopause. Its excess convection kinetic energy is dissipated in the lower polar cusp ionosphere in time lapses of 50-500 seconds depending on the value of integrated Pedersen conductivity. Once the plasma element has been engulfed, keeping its identity, the warm plasma content is dissipated by precipitation and by drifting. The magnetosheath particles with large pitch angles are mirrored, and feed the plasma mantle flow. Several consequences of this penetration mechanism are pointed out : ionospheric heating beneath the polar cusp ; Birkeland currents on the eastward and westward edges of the plasma element ; diamagnetic field fluctuations within 1-2 R_E from the magnetopause (multiple magnetopause crossings) ; oscillation of the magnetopause surface after a new element has penetrated ; exit of energetic particles out of the magnetosphere, and entry of energetic solar wind particles into the magnetosphere along the magnetic field lines of the intruding element ; magnetic flux is substracted from the dayside magnetosphere and added to the geomagnetic tail when the magnetic field of the element has a southward component.

Résumé

Considérant que le vent solaire est non-stationnaire et non uniforme, il est suggéré que des éléments de plasma du milieu interplanétaire défoncent la surface de la magnétopause. Ce renfoncement rend la surface de la magnétopause convexe et par conséquent localement instable par rapport aux "Instabilités de Flûte". L'élément de matière pénétrant dans la magnétosphère est freiné et arrêté à 1 ou 2 rayons terrestres à partir de la magnétopause. L'excès d'énergie cinétique de l'élément de plasma est dissipé dans l'ionosphère de la "polar cusp", en 50-500 secondes suivant la valeur de la conductivité intégrée de Pedersen. Dès que l'élément de plasma est englouti, le plasma chaud qu'il contient est dissipé par précipitation dans l'atmosphère et par dérive dans le champ magnétique. Les particules de la magneto-sheath dont l'angle d'inclinaison est grand sont réfléchies et alimentent le flux de particules observé dans le "plasma mantle". Plusieurs conséquences de ce nouveau mécanisme de pénétration sont mis en évidence : le chauffage ionospherique sous la "polar cusp"; les courants de Birkeland s'écoulant le long des cotés Est et Ouest de l'élément de plasma; les fluctuations diamagnétiques dans la région de la magnétopause (passage multiples au travers de la magnétopause); les oscillations de la magnétopause après la pénétration d'un nouvel élément; l'échappement de particules magnétosphériques hors de la magnétosphère, et la pénétration de particules énergétiques du vent solaire à l'intérieur de la magnétosphère le long des lignes de force de l'élément englouti; du flux magnétique est soustrait de la magnétosphère diurne et ajouté à la queue magnétosphérique lorsque le champ magnétique de l'élément possède une composante sud.

Samenvatting

Aangezien de zonnewind niet stationair en niet uniform is, wordt hier gesuggereerd dat interplanetaire plasma-elementen het oppervlak van de magnetopauze indenken. Door dit proces wordt het oppervlak konvex en dus onstabiel ten opzichte van de zogenaamde "flute instabilities". Het binnendringend plasma-element wordt afgeremd en het komt tot stilstand op een afstand van 1 à 2 aardstralen gerekend vanaf de magnetopauze. Zijn overtollige kinetische energie gaat verloren in de ionosfeer van de "polar cusp", een tijdsinterval dat kan variëren van 50 tot 500 sekonden, naargelang de waarde van de geïntegreerde Pedersen konduktiviteit. Het warme plasma dat tot het plasma-element behoort, ondergaat naderhand een precipitatie in de atmosfeer of beweegt zich in het magnetisch veld. Deeltjes van de "magnetosheath" die een grote hellingshoek bezitten worden gereflecteerd en voeden de deeltjesflux die in de plasmamantel wordt waargenomen. Een aantal gevolgen kunnen uit dit indringingsmechanisme getrokken worden : verwarming van de ionosfeer onder de "polar cusp": Birkeland stromen die langs de oostelijke en westelijke randen van het plasma-element zullen vloeien; diamagnetische veldfluctuaties op een afstand van 1 à 2 aardstralen van de magnetopauze (met verschillende doorgangen door het oppervlak); oscillaties van dat oppervlak telkens een nieuw element is binnengedrongen: uittreden van energetische deeltjes uit de magnetosfeer en binnentreden van energetische zonnewinddeeltjes in de magnetosfeer langs de magnetische veldlijnen van het indringend plasma-element: de magnetische flux wordt kleiner langs de dagzijde van de magnetosfeer en vergroot in de magnetische staart wanneer het magnetisch veld van het plasma-element een zuidwaarts gerichte komponente heeft.

Zusammenfassung

Es wird vorgeschlagen dass die Magnetopauze durch Plasma Elemente deswird. Diese Anschwellungen machen die Magnetopauze Oberfläche konvex und deswegen lokalweise ünstabil für "Flute Instabilitäten". Das eindringende Massenelement wird gebremst und innerhalb 1 oder 2 Erderadius von der Magnetopauze zurück gehalten. Das Energieexcess des Element wird in der "polar cusp" Ionosphäre in 50-500 Sekunden zerstreuet sobalt das Plasma Element in der Magnetosphäre verschlungen ist, werden die Plasmateilchen durch Hinabstürzung in der Atmosphäre und durch Abweichung in die magnetischen und elektrischen Felder der Magnetosphäre zerstreut. Die Magnetosheath-teilchen mit grosse Inclinationswikeln werden zurück gespiegelt und nähren den "Plasma Mantle" Fluss. Einige Konsequenzen dieses neues Mechanismus sind aufmerksam betrachtet worden: z.B., die Erwärmung der "polar cusp" Ionosphäre; die Birkeland Ströme die längs die Seiten des Elementes fliessen; die diamagnetischen Schwanckungen in der Nähe der Magnetopauze; die magnetohydrodynamische Wellen die über die Magnetopauze laufen; die Auströmung der magnetosphärischen Teilchen in dem Interplanetaren Sonnen Wind; das Einfliessen energetische Teilchen der Sonne in der Magnetosphäre entlang der Feldlinien des Elementes; die Abnahme des magnetischen Fluss in dem vorderen Teil der Magnetosphäre, und die Zunahme die magnetischen Fluss im geomagnetischen Schweif wenn das interplanetare magnetisches Feld eine sudliche Richtung einnimmt.

INTRODUCTION

In current theories of the magnetopause formation, the solar wind is considered as a *steady and uniform* plasma flow deflected by the geomagnetic field at distances where the total pressure balance equation is satisfied as illustrated in figure 1a. When the solar wind momentum flux increases uniformly, it is admitted that the whole magnetopause surface moves inwards with a certain speed. It is then accepted that these forward (and backward) magnetopause motions explain the multiple magnetopause crossings sometimes observed by the satellite (AUBRY *et al.*, 1971). The plasma on both sides of the magnetopause, considered here as a tangential discontinuity, moves forward (and backward) with the same speed as the boundary. According to this description, the magnetopause may be compared to an "air-tight" (plasma-tight) boundary surface which is pushed to different distances from the earth like a sail, depending on the strength of the solar wind.

However, if an electric field is applied parallel to the magnetopause surface as suggested by BAHNSEN and HANSEN (1976), magnetosheath plasma can penetrate through certain portions of the magnetosphere boundary. In this case the sail would be permeable to the wind.

Another school describes the magnetopause as a rotational discontinuity across which the *steady and uniform* solar wind plasma would flow, assuming "magnetic field merging" is in operation (VASYLIUNAS, 1975; YEH and AXFORD, 1970). Increasing the rate of merging should lead to dayside erosion of the magnetosphere and to an inferred inward motion of the magnetopause (REID and HOLZER, 1975).

Actually, we know from observations that the solar wind flow is *neither steady nor uniform* but, on the contrary, that it has sometimes been compared to a bundle of spaghetti (McCRACKEN and NESS, 1966; SISCOE *et al.*, 1968) or to a mass of intertwined filamentary plasma elements or inhomogeneities. Indeed, high resolution ($\Delta t \leqslant 0.1$ sec.) interplanetary magnetic field observations clearly indicate that the magnetic field intensity and (especially) its direction are changing almost all the time over distances of 5000 km or less (NEUGEBAUER, 1975; BURLAGA *et al.*, 1976). Considering that these field- frozen-in diamagnetic variations reveal the presence of plasma inhomogeneities of similar dimensions, we conclude that the solar wind plasma impinging on the magnetosphere is unsteady and non-uniform as represented in figure 1b.

PENETRATION OF A PLASMA ELEMENT

Figure 1b illustrates a sequence of events representing solar wind plasma elements moving relative to an otherwise steady and uniform solar wind. Let us consider that these field aligned plasma inhomogeneities have an excess bulk velocity compared to the plasma outside the filamentary structure. As a consequence of its excess of momentum, such a mass element will dent the magnetopause as also illustrated in figure 2. This indentation makes the plasma boundary at the magnetopause convex, and unstable with respect to the flute instabilities (LONGMIRE, 1963, p. 241). As a consequence, the magnetopause bulges out more and more until the penetrating element of plasma becomes detached from the magnetosheath plasma bulk. For an element of 1 R_E diameter (D), the growth rate of the flute instability is characterised by a time constant (τ_1) of 10 seconds, or less for perturbations of smaller wavelengths : $\tau_1 = D/c_s$ where c_s is the sound speed.

The $\vec{B} \times \vec{V}$ convection electric field resulting from the inward motion drags positive and negative polarisation charges on the eastern and western edges of the plasma element (see figure 2). If the ionospheric Pedersen conductivity would be infinite along the magnetospheric field lines adjacent to the intruding plasma element, these polarisation charges would immediately be neutralized by cold electrons flowing up and down into the infinitely conducting ionosphere. As a consequence, the convection electric field which supports the inward motion would vanish immediately. Hence, the inward motion will be braked and stopped as by a rigid surface. In this case the element will not penetrate any longer but it will spread over the envelope of the (supposed) infinitely conducting magnetosphere.

In reality, the integrated Pedersen conductivity (Σ_p) is not infinite but of the order of 1 Siemens (or 1 mho) for polar cusp field lines. This is still a large enough value to brake the

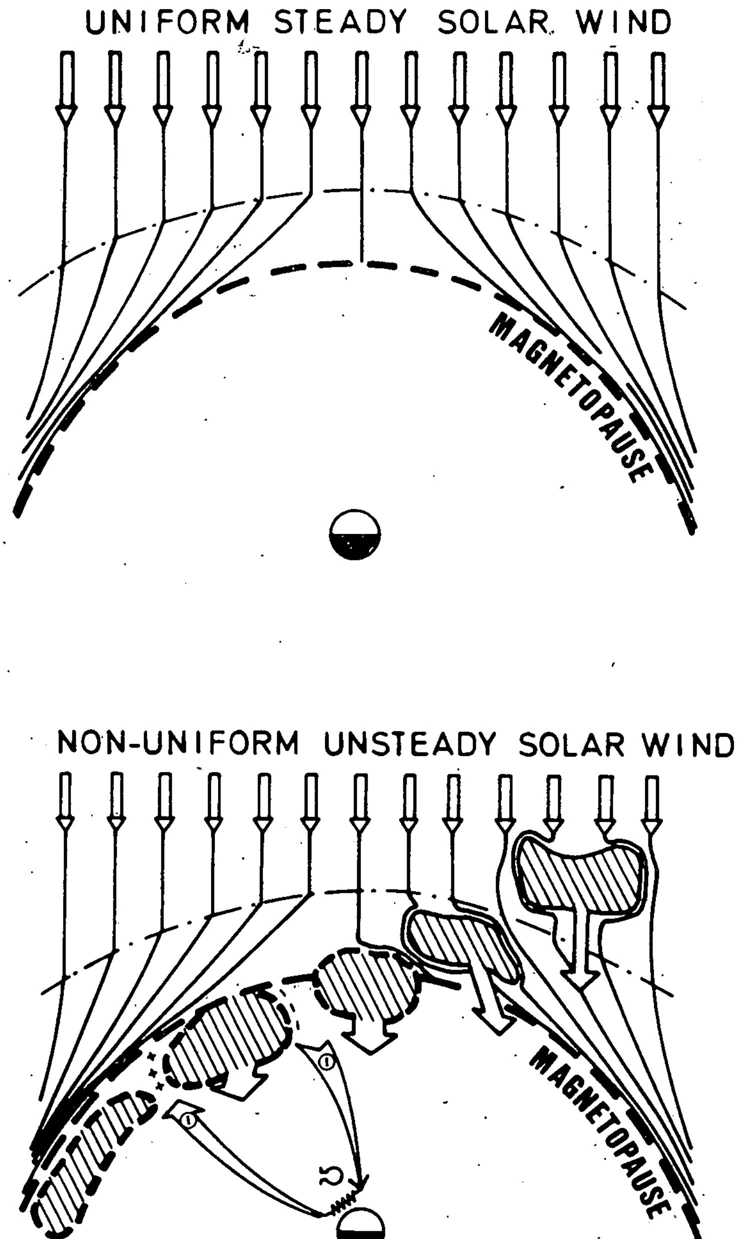

Fig. 1.- *Equatorial sections of the magnetosphere.*

When the solar wind is steady and uniform the magnetopause position is determined by the pressure balance equation (left); when solar wind plasma elements dent the magnetopause, they can penetrate into the magnetosphere where, finally, they are dissipated by particles precipitations and azimuthal drifts (right hand side panel).

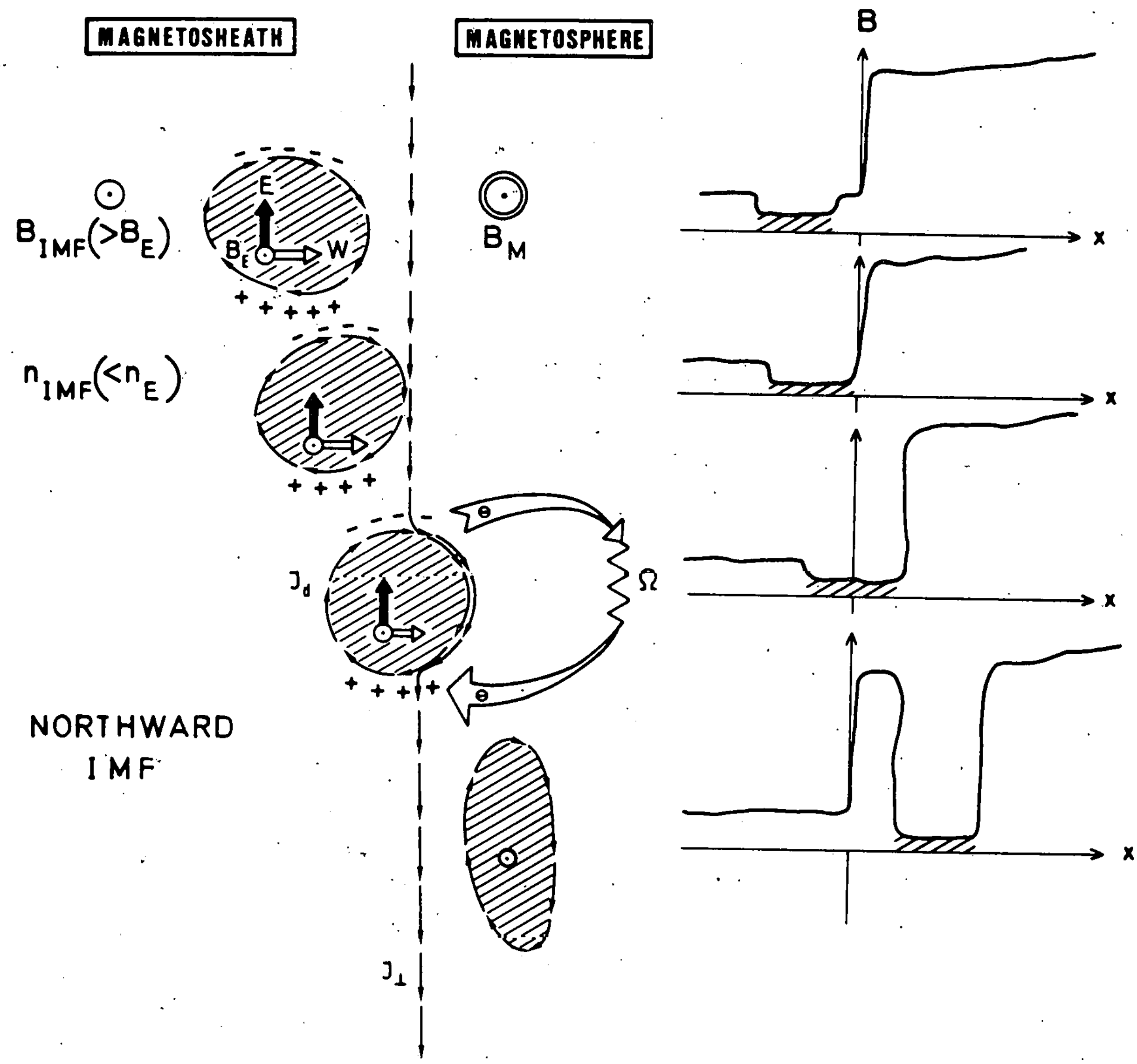

Fig. 2.- *Penetration of a magnetosheath plasma element in the magnetosphere.*

When a plasma element dents the magnetopause surface, the later plasma boundary becomes convex and therefore flute unstable. This aids the element to be pushed out of the magnetosheath plasma bulk. The convection electric B x V drags polarisation charges on the edges of the intruding element. These tend to be neutralized by Birkeland currents which are limited by the integrated Pedersen conductivity. As a consequence, the plasma element is braked and stopped, and its kinetic energy dissipated by ionospheric Joule heating. Typical magnetic field intensity profiles across the elements are illustrated in the left hand side panels.

penetrating element in about 500 seconds (10 minutes : $\tau_2 = 16\,L^6\,N_e\,l\,m/B_I^2\,\Sigma_p$, where $L = 10$ is the equatorial distance in (Earth radii) of the magnetopause field lines; $l = 10^4$ km is the length of the plasma element along the magnetic field direction; $N_e = 10\ cm^{-3}$ is the equatorial density of the element; $m = 1.67 \times 10^{-24}$ gr. is the proton mass, and $B_I = 6 \times 10^{-5}$ Tesla, is the magnetic field intensity in the polar cusp at ionospheric level). Assuming the element has an initial velocity of 20 km/s, it will be stopped within a distance of 1 or 2 earth radii from the magnetopause. The convection kinetic energy of the element is dissipated in the ionosphere by Joule heating; this produces an enhancement of the polar cusp ionospheric temperature as is actually observed by TITHERIDGE (1976) and WHITTEKER (1976).

DISSIPATION OF A PLASMA ELEMENT

Once the filamentary element has been partially engulfed inside of the magnetosphere, retaining its identity as illustrated in figure 3, the magnetopause recovers its original position as would the surface of a lake, after a drop water has fallen into it. The captured or swallowed magnetosheath plasma will spread out in the magnetosphere, first, by precipitating along polar cusp field lines and, secondly, by drifting perpendicular to the magnetic field.

Protons and alpha particles transported inside the magnetosphere with pitch angles in the loss cone will precipitate into the atmosphere where they have been observed by SHELLEY *et al.* (1976) with downward bulk speeds of about 300 km/s at 800 km altitude. Protons and alpha particles with larger pitch angles or smaller energies will be mirrored or reflected by the converging magnetic configuration or by the oblique double potential layer (electrostatic shock; BLOCK (1972); SWIFT (1975), KAN (1975)) built up at the low altitude edges of the plasma element (LEMAIRE and SCHERER, 1976). These slower ions spend a longer time drifting polewards in the polar cap dawn-dusk polarisation electric field. This electric field is set up inside the element by the eastward electrons (and westward ions) gradient B and curvature drifts. The reflected particles will finally feed the plasma mantle as suggested by ROSENBAUER *et al.* (1975).

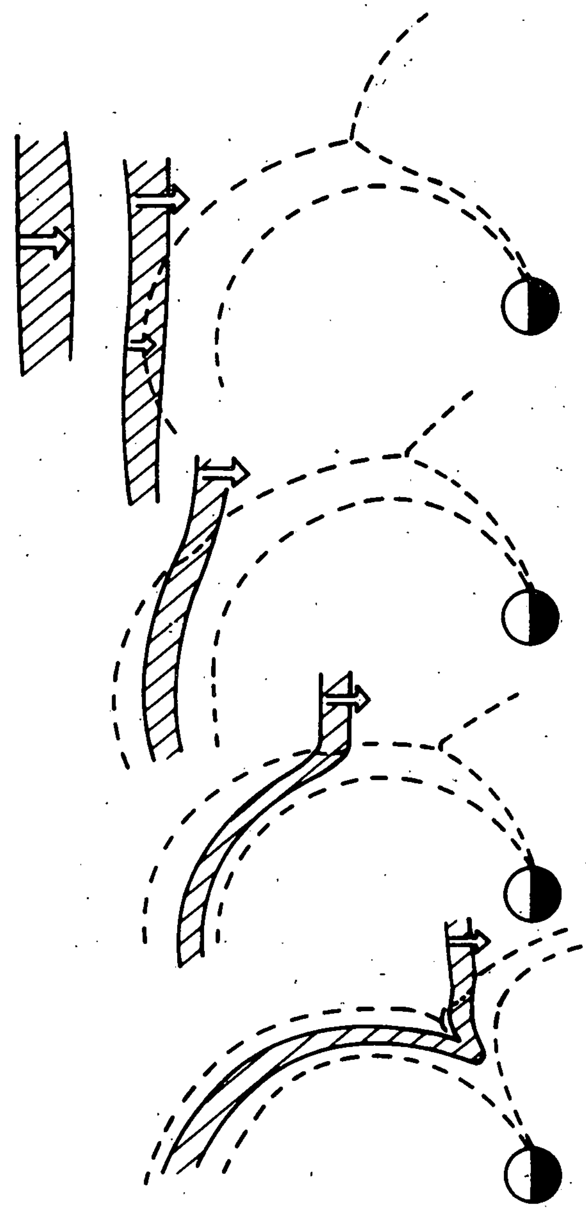

Fig. 3.- *Meridional sections of the magnetosphere*.
Sequence of events showing a filamentary plasma element penetrating into the magnetosphere and extending finally into the geomagnetic tail.

Gradient B and curvature drifts of the warm magnetosheath electrons and protons will extend the volume of the element azimuthaly at a rate controlled by the minimum value of the integrated Pedersen conductivity. Birkeland currents will flow up at the western side, and downwards at the eastern side where warm electrons tend to build up a negative charge density. The magnetic effects of these parallel electric currents have been observed by IIJIMA and POTEMRA (1976).

The maximum precipitation rate of warm ions determines the time during which the plasma element of magnetosheath origin retains its identity inside the magnetosphere. Assuming a proton precipitation flux (F_p) of 2×10^8 cm^{-2} sec^{-1} at 800 km altitude (h), it would take 2×10^5 seconds (τ_3 = 3 days) for a plasma element with an equatorial density of N_e = 10 cm^{-3} to be dissipated and to disappear: $\tau_3 = N_e \, L \, R_E / F_p [(R_E + h)/L \, R_E]^3$, where R_E is the Earth radius. Therefore it is expected that for about 3 days a freshly engulfed plasma element can reveal its presence inside the magnetosphere by the diamagnetic effects it produces, as a consequence of the electric currents flowing (undissipated) parallel to its boundary surface. The rather long persistence of plasma inhomogeneities within 2 R_E from the magnetopause is confirmed by the observation of similar features in magnetograms when two satellites penetrate in the same region of the outer magnetosphere at two universal times separated by several hours. (FORMISANO and HEDGECOCK, 1976). This suggests also a new interpretation of multiple magnetopause crossings. Indeed, a magnetometer can measure the same type of magnetic field variations when it penetrates with its orbital velocity in or out of an engulfed plasma element, than when it crosses the actual magnetopause. This is illustrated in the right hand side of figure 2, where the magnetic field intensity profiles across the plasma elements are represented. These theoretical signatures are similar to those commonly observed in the magnetopause regions. The many diamagnetic field fluctuations generally observed just inside the magnetopause can, according to the present picture, be interpreted as the pile up of dying plasma elements of magnetosheath origin traversed by satellites along their orbit.

SOME OTHER CONSEQUENCES

a) If the rate of magnetic field merging is zero, the magnetopause boundary is a tangential discontinuity as described theoretically by WILLIS (1971, 1975, 1976) and ROTH (1976). This is likely the case where the magnetopause has not been perturbed, or where it has recovered its original position after possibly some hydromagnetic oscillation periods. SONNERUP (1976) has discussed magnetic field observations which indicate that on many occasions the magnetopause actually looks like a tangential discontinuity. The possible existence of hydromagnetic oscillations of the magnetopause is supported by observations (ANDERSON *et al.*, 1968; LEDLEY, 1971; AUBRY *et al.*, 1971) as well as by theory (SOUTHWOOD, 1968; HOLZER and REID, 1975). According to the present theory, these oscillations would be excited by solar wind plasma elements impinging on the magnetopause.

b) From figure 3, it can be seen that there are places at the surface of the magnetosphere where the filamentary plasma elements are still connected to the magnetosheath and solar wind through the "magnetopause". At all these places where the interplanetary magnetic flux tubes hang out the magnetosphere, a rotational discontinuity is expected. "Magnetopause" crossings of this nature (rotational discontinuity) have also been observed sometimes. (SONNERUP and LEDLEY 1974; SONNERUP, 1976).

c) The interplanetary magnetic flux tubes partially imbeded in the magnetosphere can be the pipes along which the high energy solar wind particles can flow down the geomagnetic tail into the polar cap ionosphere (DOMINGO *et al.*, 1976).

d) These interplanetary magnetic flux tubes partially engulfed in the dayside trapping region of the magnetosphere can also be a channel for magnetospheric particles escaping out of the geomagnetic cavity. The presence in the interplanetary medium of protons intensity spikes of magnetospheric origin has recently been found by WILLIAMS (1976). These observations also support the present suggestion.

e) If the magnetic field of the intruding plasma element has a northward component, the total magnetic flux of the dayside magnetosphere is increased. As soon as the plasma element extends into the tail region (as illustrated in the lowest sketch of figure 3) the total magnetic flux is reduced in the geomagnetic tail.

When the IMF (or the magnetic field of the solar wind element) turns southward, the opposite effects must be expected, and accumulation of magnetic flux is expected to start in the geomagnetic tail. Note that changes in the IMF polarity has been shown to be the instigators of substorm events and of related disruptions of equilibrium states in the magnetosphere.

CONCLUSION

Considering that the solar wind is made up with intertwined filamentary plasma elements with dimensions smaller than the diameter of the magnetosphere, we have suggested that these elements can dent the magnetopause, and that they can become partially engulfed in the magnetosphere as illustrated in figures 1b and 3. The wide variety of magnetospheric observations mentioned in this paper, support this penetration mechanism which, however, does not appeal to magnetic field merging. A similar theory is likey to apply for other planetary magnetopauses (Jupiter, Mercury ...)

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