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Impulsive penetration of filamentary plasma elements into the magnetospheres of the earth and jupiter

by

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FOREWORD

This article entitled "Impulsive penetration of filamentary plasma elements into the magnetospheres of the Earth and Jupiter" has been prepared in November 1976 at the Laboratory for Extraterrestrial Physics, NASA/GSFC. The author thanks the University of Maryland, College Park, Maryland, for supporting his sejourn in the United States. This paper will be published in Planetary and Space Sciences.

AVANT-PROPOS

Le travail intitulé " Impulsive penetration of filamentary plasma elements into the magnetospheres of the Earth and Jupiter" a été rédigé en novembre 1976, au Laboratory for Extraterrestrial Physics NASA/GSFC. L'auteur remercie l'Université de Maryland, College Park, Maryland, pour le support qui lui a été fourni lors de son séjour aux Etats-Unis. Ce texte sera publié dans Planetary and Space Sciences.

VOORWOORD

Het artikel getiteld "Impulsive penetration of filamentary plasma elements into the magnetospheres of the Earth and Jupiter" werd geschreven in november 1976 in het Laboratory for Extraterrestrial Physics NASA / GSFC. De auteur dankt de University of Maryland voor de steun die hem werd gegeven tijdens zijn verblijf in de Verenigde Staten. Deze tekst zal gepubliceerd worden in Planetary and Space Sciences.

VORWORT

Dieser Text "Impulsive penetration of filamentary plasma elements into the magnetospheres of the Earth and Jupiter" wird in Planetary and Space Sciences veröffendlicht. Dieser Text wurde in November 1976 als der Verfasser das Laboratory for Extraterrestrial Physics, NASA/GSFC besuchte, geschrieben. Der Verfasser dankt die University of Maryland, College Park, für seine Unterstüzung.

IMPULSIVE PENETRATION OF FILAMENTARY PLASMA ELEMENTS INTO THE MAGNETOSPHERES OF THE EARTH AND JUPITER

by

J. LEMAIRE

Abstract

Assuming that the solar wind plasma is usually non-uniform over distances of 10,000 km or less, it is shown that filamentary plasma elements stretched out from the Sun can penetrate impulsively and become engulfed into the magnetosphere.

The diamagnetic effects associated with these plasma inhomogeneities are observed in outer magnetospheres and magnetosheaths as dips or directional discontinuities in the magnetic field measurements. From the mean penetration distances of these diamagnetic plasma elements one can deduce a mean deceleration time, as well as an approximate value of the integrated Pedersen conductivity in the polar cusp of the Earth and Jupiter.

Résumé

Supposant que le vent solaire est généralement non-uniforme sur des distances égales ou inférieures à 10.000 km, on montre que des éléments de plasma filamentaires, émis par le soleil peuvent pénétrer de manière impulsive dans la magnétosphère et y être englués.

Les effets diamagnétiques associés avec ces inhomogénéités de plasma sont observés dans les magnétosphères planétaires sous forme de dépressions ou de discontinuités directionelles du champ magnétique. Des distances moyennes de pénétration de ces éléments de plasma, on peut déduire le temps de décélération moyen, ainsi qu'une valeur approximative de la conductibilité intégrée de Pedersen dans la "polar cusp" de la Terre et de Jupiter.

Samenvatting

In de veronderstelling dat zonnewindplasma meestal niet uniform is over afstanden van 10.000 km of minder, kunnen we aantonen dat draadvormige plasma-elementen vertrekkende van de zon impulsief de magnetosfeer kunnen binnendringen en erin kunnen worden opgeslorpt.

De diamagnetische effekten die met deze plasma-inhomogeneiteiten gepaard gaan, worden waargenomen als discontinuiteiten bij metingen van het magnetisch veld. Uit de gemiddelde indringingsafstanden van de diamagnetische plasma-elementen kan men een gemiddelde vertragingstijd afleiden alsook een benaderde waarde van de geïntegreerde Pedersen geleidbaarheid in de "polar cusp" van de Aarde en van Jupiter.

Zusammenfassung

Es wird gezeigt dass, when der Sonnenwind ungleichartig ist, fadenförmige Plasma element in die Magnetosphäre eindrigen konnen.

Die diamagnetische Effekte dieser Plasma Inhomogeneitäten sind as directionale Discontinuitäten in der ausseren Magnetosphären beobachtet. Von die mittlere durchdringende Tiefe dieser diamagnetischen Elemente can man eine mittlere Bremszeit abschätzen. Ein approximativen Wert für die Pedersen Leitfähigkeit in der "Polar Cusp" der Erde und des Planeten Jupiter, ist auch abgerechnet worden.

INTRODUCTION

From high resolution interplanetary magnetic field measurements and from plasma observations it can be deduced that the solar wind is usually non-uniform over distances much smaller than the diameter of the magnetosphere (i.e. $<$ 20.000 km) and that the solar wind flow is not steady over time periods smaller than the time to be transported past the magnetospheric cavity (i.e. $<$ 2000 s). Therefore current theories for the formation of the magnetopause, based on the assumption that the incident solar wind is uniform and steady might be oversimplified.

Assuming that the solar wind is a mass of intertwined filamentary structures or plasma inhomogeneities (McCracken and Ness, 1966; Hewish and Symonds, 1969), with transverse dimensions of 10000 km or less, Lemaire and Roth (1976) have proposed a new theory for the penetration of solar wind plasma into the magnetosphere of the Earth. The new mechanism proposed is based on continual impulsive injections of magnetosheath plasma elements; this concept can be applied to other Earth like planetary magnetospheres. The penetration mechanism is briefly described in the next section.

In the following sections the deceleration time of these intruding elements is calculated, and the integrated Pedersen conductivity for the polar cusp of the Earth and Jupiter is deduced from the average penetration distances of the plasma elements.

THE PENETRATION OF A TYPICAL PLASMA ELEMENT

Consider a field aligned plasma element confined in a fluxtube extending out from the Sun, as described by Gold (1959). If this element is convected with the solar wind velocity ($\vec{w}$) and if it has an excess density ($\bar{n} + \Delta n_e$) compared to the surrounding medium ($\bar{n}$), the element of plasma has then an excess momentum compared to the average solar wind in a stationary frame of reference, i.e. planetocentric. The solar wind plasma and the plasma element will both be compressed and decelerated as they pass through the bow shock and the magnetosheath. At the magnetopause (considered here as a tangential discontinuity) the component, w_N, of the solar wind velocity normal to the magnetopause surface, is zero. On the contrary when the plasma element reaches the magnetopause, it moves with a finite velocity, v_e. As a consequence of conservation of momentum, the penetration velocity through the magnetopause is

$$v_e = w \frac{\Delta n_e}{\bar{n} + \Delta n_e} \tag{1}$$

At any location where such filaments encounter the magnetopause surface, they will produce depressions (or bumps, if $\Delta n_e < 0$), as illustrated in Figure 1, where the shaded area represents a meridional cross section of the filamentary plasma element stretched out of the Sun. In this illustration we have assumed that the magnetic induction ($\vec{B}_e$) inside the element is nearly parallel to the Archimedean spiral direction.

As described by Lemaire and Roth (1976), the plasma confined in this fluxtube will penetrate impulsively into the magnetosphere. Since it moves in the outer magnetosphere across a northward magnetic field ($\vec{B}_m$) with a relative velocity ($\vec{v}_e$) it sets up a convection electric field ($\vec{E}_m = -\vec{v}_e \times \vec{B}_m$) creating a negative polarization charge on the western edge of the intruding fluxtube, and a positive charge on the eastern edge (see Figure 2a). These charges are carried away from the boundary region by Birkeland currents flowing along magnetospheric field lines rooted to the Earth's ionosphere (see Figure 2b). The intensity of these parallel currents (and consequently the rate of removal of the polarization charges) is limited by the finite value of the integrated Pedersen conductivity (Σ_p), so that for a larger Σ_p the Birkeland currents ($\vec{J}_\parallel$) will be larger; the rate of decrease of the induced electric field $\vec{E}_m$, will be faster and the braking of the inward velocity $\vec{v}_e$ will be stronger. Note that in the limit of the MHD approximation ($\Sigma_p = \infty$) the mass element would not be able to penetrate through the boundary of an infinitely conducting magnetosphere. This implies that the Pedersen conductivity regulates the rate of deceleration ($d\vec{v}_e/dt$) of the penetrating solar wind plasma elements.

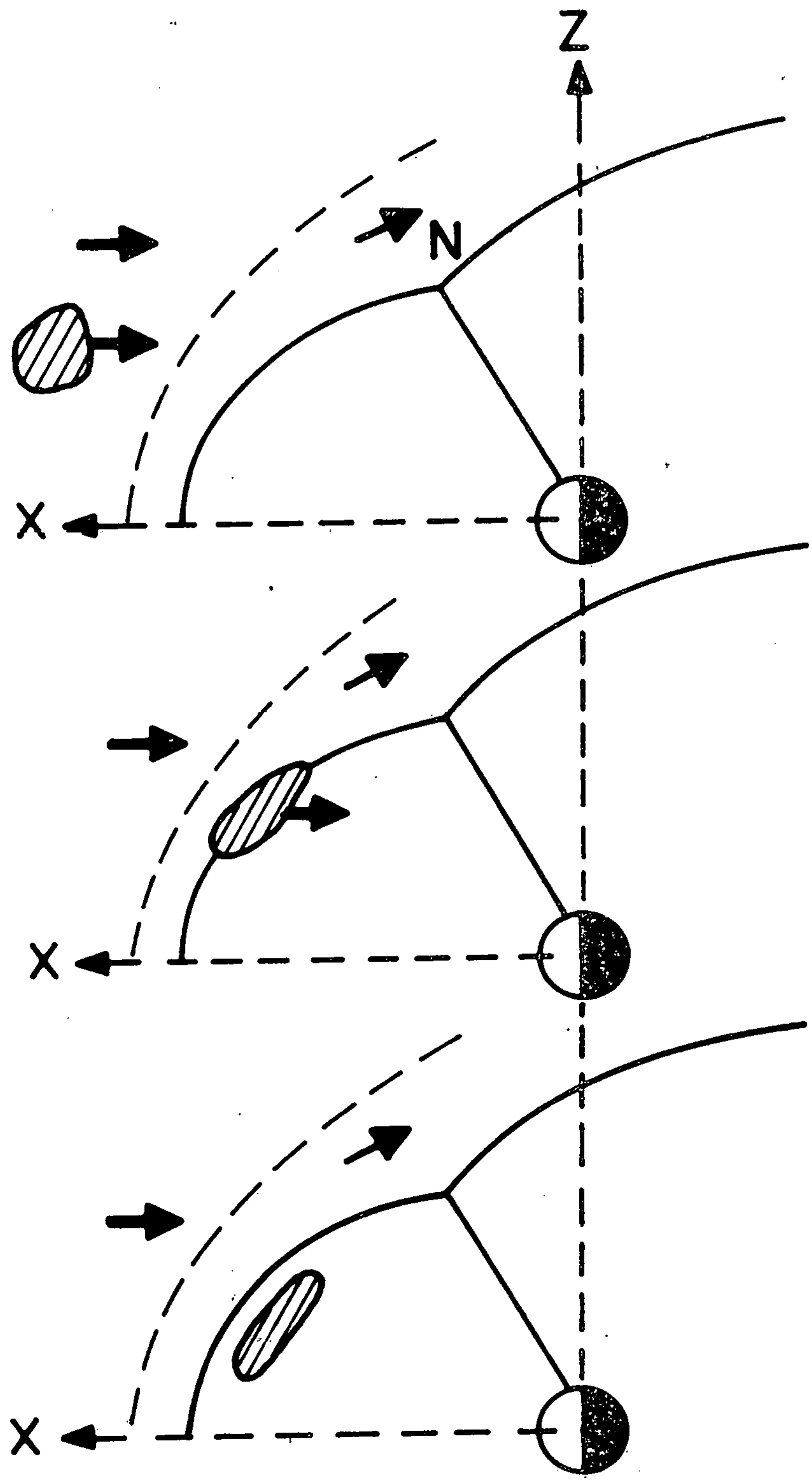

Fig. 1.- Meridional section of the magnetosphere and a typical intrudent plasma element.

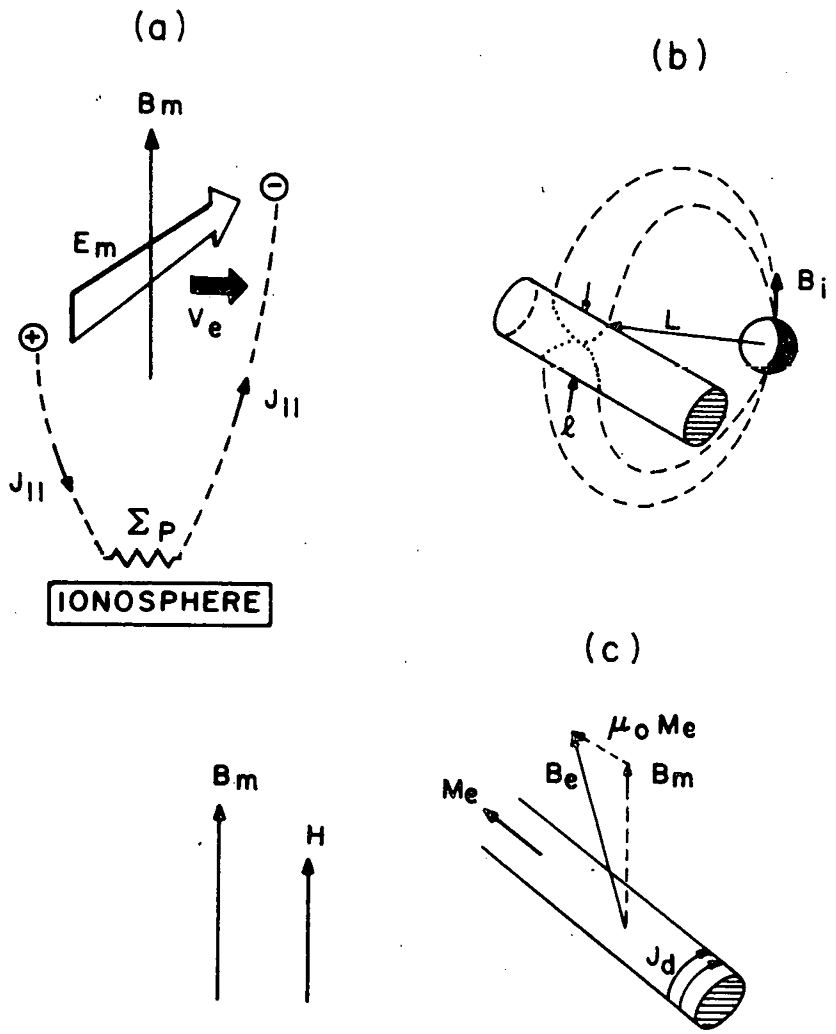

Fig. 2.- Definitions of vector fields.

ESTIMATION OF THE CHARACTERISTIC DECELERATION TIME

The kinetic energy density ($1/2\ n_e m_p v_e^2$) of the absorbed particles is dissipated in Joule heating of the polar cusp atmosphere. The characteristic deceleration time (τ_2) is obtained by balancing the rate of Joule dissipation, $\Sigma_p\ E_i^2$ (where $\vec{E}_i$ is the projection of $\vec{E}_m$ in the ionosphere) and $\frac{d}{dt}(\int_V 1/2\ n_e\ m_p\ v_e^2\ dV)$, the time variation of the kinetic energy integrated over the volume V of the magnetospheric fluxtube crossing the plasma element (see Figure 2b). An order of magnitude for τ_2 can be obtained from

$$\tau_2 = \frac{16\ L^6\ \ell\ n_e\ m_p}{B_i^2\ \Sigma_p} \tag{2}$$

Where L is McIlwain's parameter of the field lines connecting the plasma element and the ionosphere; $\vec{B}_i$ is the local magnetic induction in the ionosphere; ℓ is the diameter of the plasma inhomogeneity along the field line L.

DISTANCE OF PENETRATION

The distance (Δx) travelled by an inward moving solar wind mass element during the exponential deceleration time (τ_2) is equal to

$$\Delta x = 0.36\ v_e\ \tau_2 \tag{3}$$

An average penetration distance ($\overline{\Delta x}$) of absorbed plasma elements can be deduced from the average position of the diamagnetic signatures observed in magnetograms from the outer magnetospheres. For the Earth's magnetosphere $\overline{\Delta x}$ is approximately 2 R_E or 13000 km. For a given average solar wind density and bulk speed ($\bar{n} = 5$ cm^{-3}; w = 400 km s^{-1}) one can estimate the penetration velocity (v_e) at the magnetopause of an element with an excess density $\Delta\ n_e$: eq(1). Considering that $\Delta\ n_e/\bar{n} = 5\%$ is a reasonable mean value one obtains $\bar{v}_e = 20$ km s^{-1} (Table 1). From eq(3) one deduces an average value of $\bar{\tau}_2 = 1800$ s. (30 min). Considering that the element is at 10 Earth's radii when it penetrates through the

TABLE 1 : Determination of the integrated Pedersen conductivity in the polar cusp of the Earth and Jupiter.

	EARTH	JUPITER	UNITS
Δx	2	15	Planetary radius
n	5	0.2	cm^{-3}
w	400	400	$km \cdot sec^{-1}$
$\Delta n_e/n$	5%	5%	---
v_e	20	20	$km\ sec^{-1}$
τ_2	1800	1.5×10^5	sec
L	10	50	Planetary radius
ℓ	10000	100000	km
B_i	6.2×10^{-5}	10^{-3}	Tesla
Σ_p	0.2	0.02	Siemens

magnetopause (L = 10) one can calculate B_i, the magnetic field intensity in the ionosphere : B_i = 6.2 x 10^{-5} T. From the scale lengths of interplanetary magnetic field irregularities, it can be concluded that a significant number of filaments have thicknesses of 10.000 km or less ($\ell \simeq$ 10.000 km). Using eq(2) we are able now to calculate an approximate value for the Pedersen conductivity of polar cusp field lines : Σ_p = 0.2 Siemens (see Table 1). This corresponds well with the value of Σ_p usually given for the high latitude regions of the Earth (Chapman, 1956; Hanson, 1961).

From the average penetration distance of plasma elements in the magnetosphere of Jupiter ($\overline{\Delta x}$ = 15 R_J, deduced from Pioneer 10 and 11, Smith *et al.,* 1975), and other reasonable value of $\bar{n}$, w, L, ℓ and $\Delta n_e/\bar{n}$ (reported in Table 1) one finds Σ_p = 0.02 Siemens for the polar cusps of Jupiter.

According to these calculations the value of the integrated Pedersen conductivity is 10 times smaller in the case of Jupiter than for the Earth. As a consequence plasma interchange motion and Joule heating are probably more important in the Jovian than in the terrestrial magnetospheres and ionospheres.

RELATION BETWEEN THE MAGNETIC FIELD INSIDE AND OUTSIDE A PLASMA ELEMENT

When a plasma inhomogeneity is embedded in an external magnetic field $\vec{H}$, the measured magnetic induction inside this element is given by

$$\vec{B}_e = \mu_o (\vec{H} + \vec{M}_e) \qquad (4)$$

where μ_o is the permeability of free space, and $\vec{M}_e$ is the magnetic polarization vector resulting from diamagnetic currents ($\vec{J}_d$) flowing along the plasma boundary surface (the notations of Stratton, 1941, p. 11, have been used; see also Spitzer, 1956, p. 25); $\vec{H}$ is the sum of the fields due to the Earth's dipole and due to distant current systems; $\vec{M}_e$ is related to $\vec{J}_d$ by

$$\text{curl}\,\vec{M}_e = \vec{J}_d \qquad (5)$$

and contributes to modifying the actual magnetic induction measured inside the finite plasma element (see Figure 2c).

Close to the magnetopause, where β (ratio of kinetic and magnetic pressures) is of the order of unity, and where the magnetospheric field intensity $\vec{B}_m$ (= $\mu_o \vec{H}$) is relatively small, the diamagnetic field $\mu_o \vec{M}_e$ can be of the order of magnitude of $\vec{B}_m$. Therefore near the magnetopause one can expect large differences in the magnitudes and directions between $\vec{B}_m$ (measured outside the element) and $\vec{B}_e$ (as measured inside the plasma inhomogeneity).

However, deeper into the geomagnetic field where $\vec{B}_m$ becomes much larger than $\mu_o \vec{M}_e$, these differences between the magnetic induction outside and inside the filament become progressively smaller as is actually observed in the outer magnetosphere of the Earth and Jupiter (Fairfield, 1976, personal communical; Smith *et al.*, 1975; Kivelson, 1976).

THE PLASMA BOUNDARY

The boundary surface separating the plasma and the external region is a directional discontinuity in the magnetosphere (Burlaga, 1968). It can be either a tangential discontinuity or a rotational discontinuity depending on the angle between $\vec{N}$, the normal to the surface layer and the external field direction $\vec{B}_m$. Where $\vec{N}$ is perpendicular to $\vec{B}_m$, (i.e., $\vec{N} \cdot \vec{B}_m = \vec{N} \cdot \vec{B}_e = 0$) the boundary is a tangential discontinuity, and the magnetic field lines inside and outside the element are both parallel to the surface of separation (Figure 3a). On the contrary, where $\vec{N} \cdot \vec{B}_m \neq 0$, the boundary is a rotational discontinuity, and the magnetic field lines penetrate the surface of separation (Figure 3b). Through these later places of the engulfed plasma boundary where $\vec{N} \cdot \vec{B}_m \neq 0$, particles of solar wind origin can leak into the external region and be precipitated or become trapped along closed magnetospheric field lines. Conversely magnetospheric particles can drift into these solar wind flux-tubes through these same places. Since the filamentary plasma elements still hang out of magnetosphere, as illustrated in Figure 4, magnetospheric particles can be guided along these

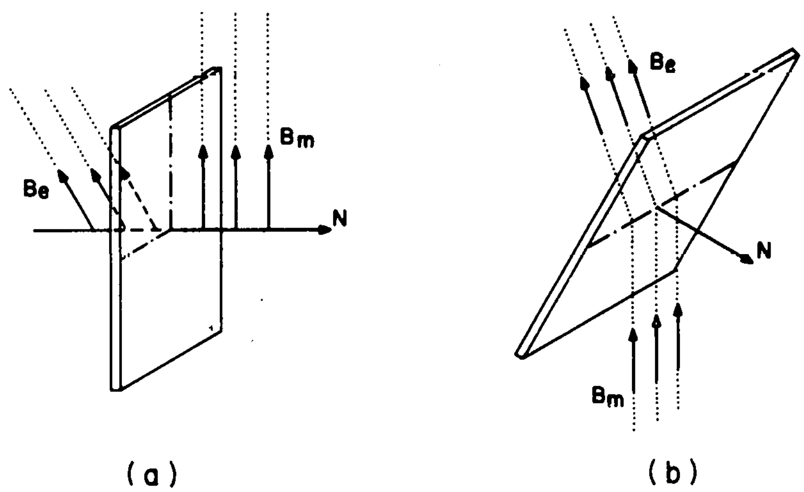

Fig. 3.- Tangential and rotational discontinuities at the plasma boundary.

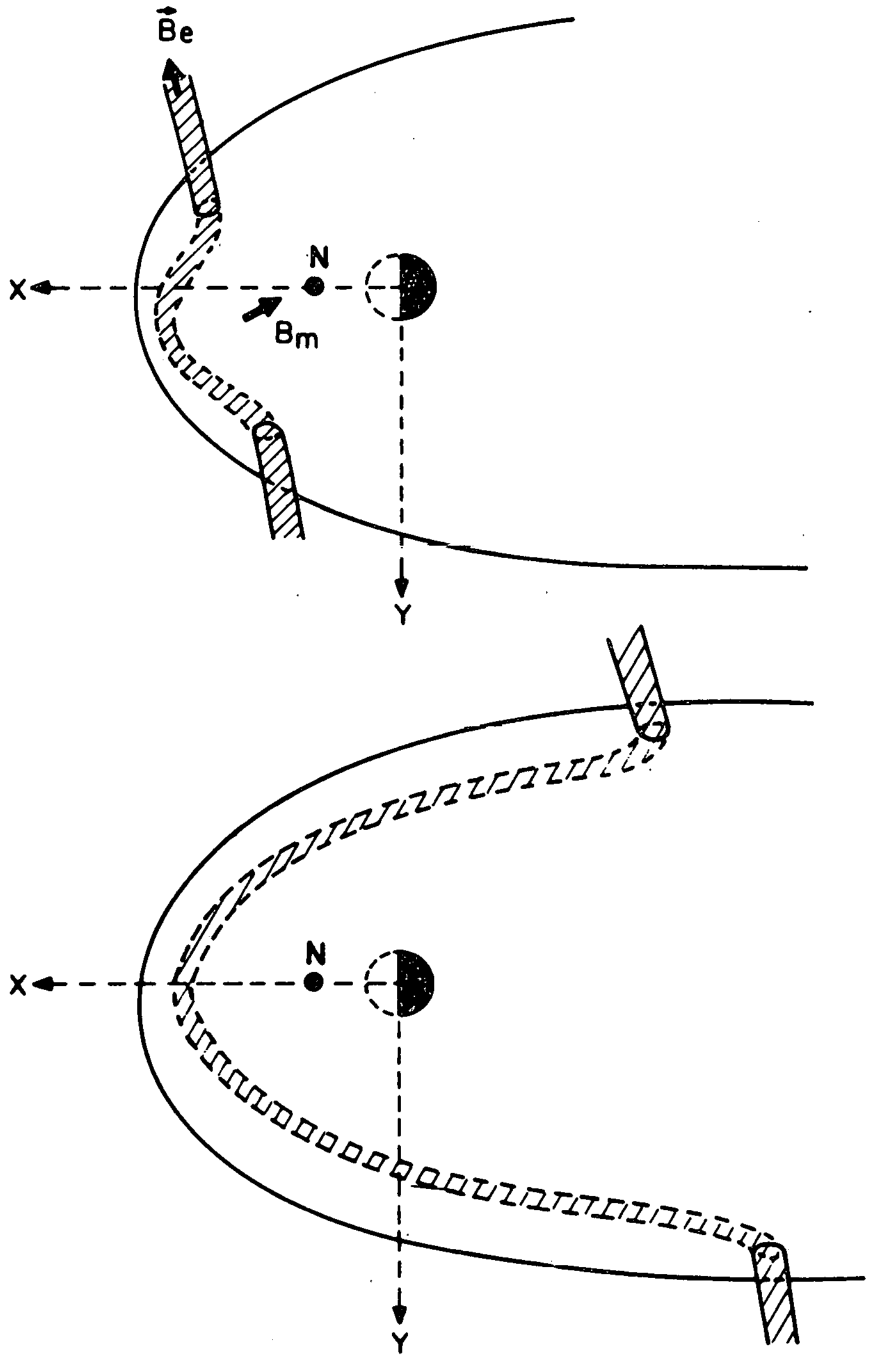

Fig. 4.- Magnetosphere with partially engulfed plasma element as seen from the north pole direction

channels and escape out of the magnetosphere of the Earth or Jupiter. Energetic electrons spikes of terrestrial origin have indeed been observed upstream in the interplanetary medium (Anderson, 1968). On the other hand, Chenette *et al.* (1974) and Teegarden *et al.* (1974) have also detected energetic electron bursts of Jovian origin in solar wind fluxtubes at 1 AU from Jupiter.

CONCLUSIONS

Evidence for continuous injection of filamentary plasma elements into the magnetosphere of the Earth and Jupiter has been presented. The impulsive penetration and subsequent deceleration of these intruding plasma elements has been discussed.

From the average penetration distances and deceleration times approximate values of the integrated Pedersen conductivity in the terrestrial and Jovian polar cusps have been deduced. The diamagnetic effect due to the absorbed plasma filaments is observed in the outer regions of planetary magnetospheres. Trapped magnetospheric electrons (> 40 keV) can drift across the boundary of the plasma element, which is a rotational discontinuity at certain locations of its surface. It is suggested that these energetic particles are ducted out of the magnetosphere, through the magnetopause and magnetosheath, along the engulfed solar wind fluxtubes. This escape mechanism of terrestrial or Jovian electrons is supported by the observations of characteristic energetic electron bursts in the interplanetary medium at large distances from the corresponding planetary magnetospheres.

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