Planet. Space Sci., Vol. 25, pp. 887 to 890. Pergamon Press, 1977. Printed in Northern Ireland

RESEARCH NOTES

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

(*Received* 14 *February* 1977)

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.

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 10,000 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 Earthlike 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 (**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. When the plasma element reaches the magnetopause, its velocity, v_e is non-vanishing. 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 Fig. 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 ($\mathbf{B}_e$) 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 ($\mathbf{B}_m$) with a relative velocity ($\mathbf{v}_e$) it sets up a convection electric field ($\mathbf{E}_m = -\mathbf{v}_e \times \mathbf{B}_m$) creating a negative polarization charge on the western edge of the intruding fluxtube, and a positive charge on the eastern edge (see Fig. 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 Fig. 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 ($\mathbf{J}_\parallel$) will be larger; the rate of decrease of the induced electric field $\mathbf{E}_m$, will be faster and the braking of the inward velocity $\mathbf{v}_e$ 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 ($d\mathbf{v}_e/dt$) of the penetrating solar wind plasma elements.

ESTIMATION OF THE CHARACTERISTIC DECELERATION TIME

The kinetic energy density ($\frac{1}{2}n_e m_p v_e^2$) 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, $\Sigma_p E_i^2$

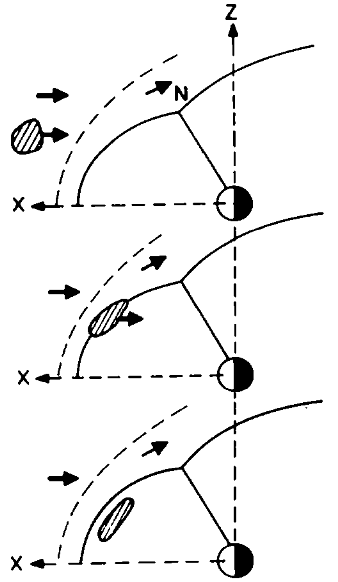


FIG. 1. MERIDIONAL SECTION OF THE MAGNETOSPHERE AND A TYPICAL INTRUDENT PLASMA ELEMENT.

(where $\mathbf{E}_i$ is the projection of $\mathbf{E}_m$ in the ionosphere) and

$$\frac{d}{dt}\left(\int_V \tfrac{1}{2} n_e m_p v_e^2 dV\right),$$

the time variation of the kinetic energy integrated over the volume V of the magnetospheric flux tube crossing the plasma element (see Fig. 2b). An order of magnitude for τ_2 can be obtained from

$$\tau_2 = \frac{16 L^6 l n_e m_p}{B_i^2 \Sigma_p}, \qquad (2)$$

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

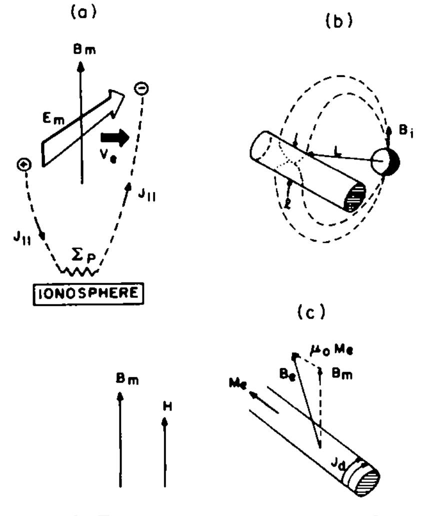


FIG. 2. DEFINITIONS OF VECTOR FIELDS.

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

$$\Delta x = 0.36 v_e \tau_2. \qquad (3)$$

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 13,000 km. For a given average solar wind density and bulk speed ($\bar{n} = 5 \text{cm}^{-3}$; $w = 400 \text{ km s}^{-1}$) one can estimate the penetration velocity (v_e) at the magnetopause of an element with an excess density Δn_e: equation (1). Considering that $\Delta n_e / \bar{n} = 5\%$ is a reasonable mean value one obtains $\bar{v}_e = 20 \text{ km s}^{-1}$ (Table 1). From equation (3) one deduces an average value of $\bar{\tau}_2 = 1800$ s (30 min). Considering that the element is at $10 R_E$ when it penetrates through the magnetopause ($L = 10$) one can calculate B_i, the magnetic field intensity in the ionosphere: $B_i = 6.2 \times 10^{-5}$ 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 ($l \simeq 10{,}000$ km). Using equation (2) we are able now to calculate an approximate value for the Pedersen conductivity of polar cusp field lines: $\Sigma_p = 0.2$ 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 values of $\bar{n}$, w, L, l, and $\Delta n_e / \bar{n}$ (reported in Table 1) one finds $\Sigma_p = 0.02$ 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.

TABLE 1. DETERMINATION OF THE INTEGRATED PEDERSEN CONDUCTIVITY IN THE POLAR CUSP OF THE EARTH AND JUPITER

	Earth	Jupiter	Units
$\overline{\Delta x}$	2	15	Planetary radius
$\bar{n}$	5	0.2	cm^{-3}
$\bar{w}$	400	400	km sec^{-1}
$\Delta n_e / \bar{n}$	5%	5%	—
$\bar{v}_e$	20	20	km sec^{-1}
$\bar{\tau}_2$	1,800	1.5×10^5	sec
L	10	50	Planetary radius
l	10,000	100,000	km
B_i	6.2×10^{-5}	10^{-3}	Tesla
Σ_p	0.2	0.02	Siemens

RELATION BETWEEN THE MAGNETIC FIELD INSIDE AND OUTSIDE A PLASMA ELEMENT

When a plasma inhomogeneity is embedded in an external magnetic field **H**, the measured magnetic induction inside this element is given by

$$\mathbf{B}_e = \mu_0(\mathbf{H}+\mathbf{M}_e) \tag{4}$$

where μ_0 is the permeability of free space, and $\mathbf{M}_e$ is the magnetic polarization vector resulting from diamagnetic currents ($\mathbf{J}_d$) flowing along the plasma boundary surface (the notations of Stratton, 1941, p. 11, have been used; see also Spitzer, 1956, p. 25); **H** is the sum of the fields due to the Earth's dipole and due to distant current systems; $\mathbf{M}_e$ is related to $\mathbf{J}_d$ by

$$\text{curl } \mathbf{M}_e = \mathbf{J}_d \tag{5}$$

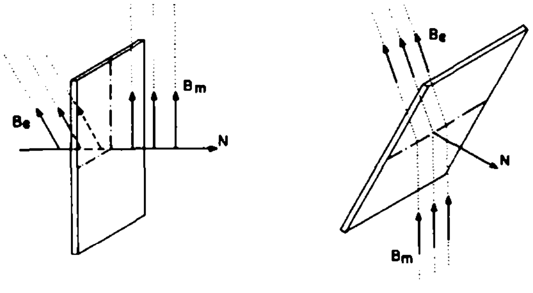
and contributes to modifying the actual magnetic induction measured inside the finite plasma element (see Fig. 2c).

Close to the magnetopause, where β (ratio of kinetic and magnetic pressures) is of the order of unity, and where the magnetospheric field intensity $\mathbf{B}_m$ ($= \mu_0\mathbf{H}$) is relatively small, the diamagnetic field $\mu_0\mathbf{M}_e$ can be of the order of magnitude of $\mathbf{B}_m$. Therefore, near the magnetopause, one can expect large differences in the magnitudes and directions between $\mathbf{B}_m$ (measured outside the element) and $\mathbf{B}_e$ (as measured inside the plasma inhomogeneity).

However, deeper into the geomagnetic field where $\mathbf{B}_m$ becomes much larger than $\mu_0\mathbf{M}_e$, 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 communication; 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 **N**, the normal to the surface layer and the external field direction $\mathbf{B}_m$. Where **N** is perpendicular to $\mathbf{B}_m$, (i.e. $\mathbf{N}\cdot\mathbf{B}_m = \mathbf{N}\cdot\mathbf{B}_e = 0$) the boundary is a tangential discontinuity, and the magnetic field lines inside and outside the element are both parallel to the surface of separation (Fig. 3a). However, where $\mathbf{N}\cdot\mathbf{B}_m \neq 0$, the boundary is a rotational discontinuity, and the magnetic field lines penetrate the surface of separation (Fig. 3b). It is through these positions of the engulfed plasma boundary where $\mathbf{N}\cdot\mathbf{B}_m \neq 0$, that 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 bulge out of the magnetosphere, as illustrated in Fig. 4, magnetospheric particles can be guided along these channels and escape out of the magnetosphere of the Earth or Jupiter. Energetic electron 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 flux tubes at 1 A.U. from Jupiter.



(a) (b)

FIG. 3. TANGENTIAL AND ROTATIONAL DISCONTINUITIES AT THE PLASMA BOUNDARY.

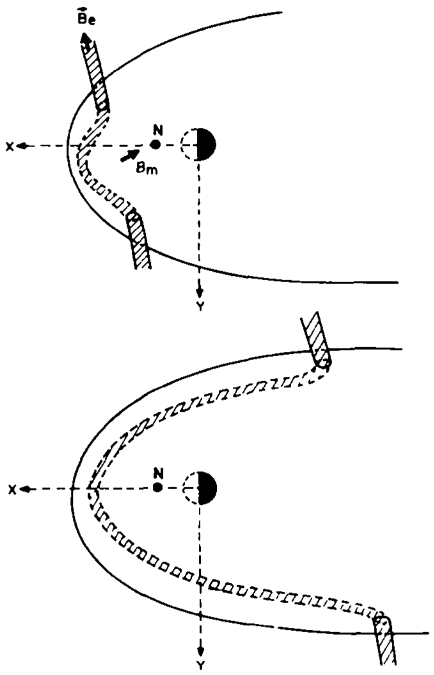


FIG. 4. MAGNETOSPHERE WITH PARTIALLY ENGULFED PLASMA ELEMENT AS SEEN FROM DIRECTION OF THE NORTH POLE.

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 parts 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 flux tubes. 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.

Acknowledgements—I would like to thank Professor M. Nicolet for his suggestion to write this Note, and Dr. N. F. Ness for his very apposite suggestions and for his advice when I prepared the manuscript. My grateful thanks are also due to Dr. K. W. Ogilvie for his support during my visit at University of Maryland. I appreciated also very much the stimulating discussions with Professor C. C. Chang, L. F. Burlaga, T. E. Eastman, D. H. Fairfield and Y. C. Whang.

J. Lemaire*

Laboratory for Extraterrestrial Physics,
NASA/Goddard Space Flight Center,
Greenbelt, MD 20771, U.S.A.
and
University of Maryland,
College Park, MD, U.S.A.

REFERENCES

Anderson, K. A. (1968). Energetic electrons of terrestrial origin upstream in the solar wind. *J. geophys. Res.* **73**, 2387.

Burlaga, L. F. (1968) Microscale structures in the interplanetary medium. *Solar Phys.* **4**, 67.

Chapman, S. (1956). The electrical conductivity of the ionosphere: A review. *Nuovo Cimento* (Suppl.) **4** 1385.

Chenette, D. L., Conlon, T. F. and Simpson, J. A. (1974). Burst of relativistic electrons from Jupiter observed in interplanetary space with time variation of the planetary rotation period. *J. geophys. Res.* **79**, 3551.

Gold, T. (1959). Motions in the magnetosphere of the Earth. *J. geophys. Res.* **64**, 1219.

Hanson, W. B. (1961). Structure of the ionosphere, in *Satellite Environment Handbook* (Ed. F. S. Johnson), pp. 25–46. Stanford University Press, Stanford.

Hewish, A. and Symonds, M. D. (1969). Radio investigation of the solar plasma. *Planet. Space Sci.* **17**, 313.

Kivelson, M. G. (1976). Jupiter's Distant Environment (preprint).

Lemaire, J. and Roth, M. (1976). Penetration of solar wind plasma elements into the magnetosphere. *Aeron. Acta* (A) No. 161; paper presented at the EGS symposium: The Magnetopause Regions. Amsterdam, 7–10 September 1976.

McCracken, K. G. and Ness, N. F. (1966). The collimation of cosmic rays by the interplanetary magnetic field. *J. geophys. Res.* **71**, 3315.

Spitzer, L., Jr. (1956). *Physics of Fully Ionized Gases*, pp. 105. Interscience, New York.

Stratton, J. A. (1941). *Electromagnetic Theory*. McGraw-Hill, New York.

Smith, E. J., Davis, L., Jr., Jones, D. E., Coleman, P. J., Jr., Colburn, D. S., Dyal, P. and Sonett, C. P. (1975). Jupiter's magnetic field, magnetosphere and interaction with the solar wind: Pioneer 11. *Science* **188**, 451.

Teegarden, B. J., McDonald, F. B., Trainor, J. H., Weber, W. R. and Roelof, E. C., (1974). Interplanetary MeV electrons of Jovian origin, *J. geophys. Res.* **79**, 3615.

NOTE ADDED IN PROOF

Large localized variations in the magnetic field intensity and direction have been occasionally observed as deep as the geostationary orbit [Skillman, T. L. and Sugiura, M. (1971). *J. geophys. Res.* **76**, 44; Russell, C. T. (1976). *Geophys. Res. Lett.* **3**, 593]. These rare events, likely, are signature of deeply engulfed solar wind plasma elements which had exceptionally large excesses of momentum when they penetrated into the magnetosphere.

---

* Permanent address: The Institute of Space Aeronomy, 3 Avenue Circulaire, B 1180 Brussels, Belgium.

Planet. Space Sci., Vol. 25, pp. 890 to 892. Pergamon Press, 1977. Printed in Northern Ireland

ON THE COINCIDENCE OF THE POSITION OF MERCURY WITH THE 90-DAY OSCILLATION OF JUPITER'S RED SPOT

(*Received* 4 *January* 1977)

Abstract—Recent observations have been utilized to investigate the proposed temporal connection between the 90-day oscillation of Jupiter's Red Spot and the inferior conjunction of Mercury. The oscillations appear to be synchronized with the inferior conjunction of a "mean Mercury" rather than the real Mercury implying that the period of oscillation of the Red Spot is constant. Although the probability of a synchronization due to chance is small, the failure of the oscillation to coincide with the motion of the real Mercury offers a strong argument against a physical connection between the two phenomena.

INTRODUCTION

Attention has been directed to an apparent temporal connection between the inferior conjunctions of Mercury and the 90-day oscillations in the longitude of Jupiter's Red Spot (Link, 1975). Link points out that (1) the mean period of the Red Spot's oscillation is very nearly the same as the synodic revolution of Mercury–Jupiter, and (2) the eastern elongations of the Red Spot occur near the time when Mercury is at inferior conjunction with the Sun as seen from Jupiter. (Eastern elongation of the Red Spot is defined as that time when the observed longitude of the Red Spot is at a minimum compared to its mean longitude.)