Journal of Atmospheric and Terrestrial Physics, Vol. 40, pp. 331–335. Pergamon Press, 1978. Printed in Northern Ireland

Penetration of solar wind plasma elements into the magnetosphere

J. LEMAIRE and M. ROTH
Institut d'Aéronomie Spatiale de Belgigue, 3 Avenue Ciculaire, B-1180 Bruxelles, Belgium

Abstract—Assuming 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 slowed down and stopped within 1 or 2 Earth radii from the magnetopause. Its excess convection kinetic energy is dissipated in the lower polar cusp ionosphere after ~50–500 s, depending on the value of the 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;

Subtraction of magnetic flux from the dayside magnetosphere and its addition to the geomagnetic tail when the magnetic field of the element has a southward component.

1. 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 Fig. 1(a). 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 a 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 COLE (1974) and BAHNSEN and HANSEN (1976), magnetosheath plasma can penetrate through certain portions of the magnetosphere boundary. In this case the sail has holes in it.

Another school of thought describes the magnetopause as a rotational discontinuity across which the *steady and uniform* solar wind plasma would flow, assuming that '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). Recently, however, HEIKKILA (1975) has pointed out a theoretical difficulty related to magnetic field line merging models.

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 ($\Delta t \leq 0.1$ s) 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 Fig. 1(b).

2. PENETRATION OF A PLASMA ELEMENT

Figure 1(b) 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

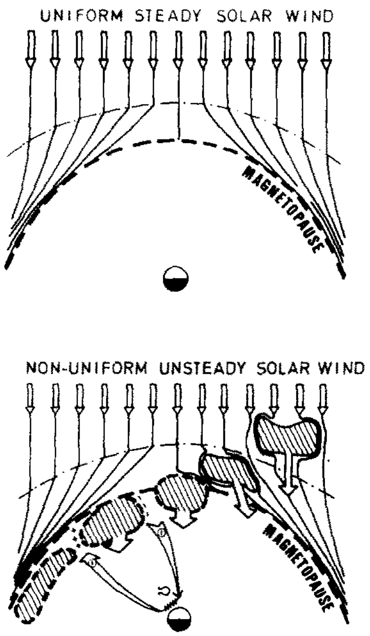

Fig. 1. *Equatorial sections of the magnetosphere.* When the solar wind is steady and uniform the magnetopause position is determined by the pressure balance equation (top), when solar wind plasma elements dent the magnetopause, they can penetrate into the magnetosphere where, finally, they are dissipated by particle precipitation and azimuthal drifts (bottom).

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 Fig. 2. This indentation makes the plasma boundary at the magnetopause convex and unstable with respect to 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 bulk of the magnetosheath plasma. 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 s, or less for perturbations of smaller wavelengths: $\tau_1 = D/c_s$, where c_s is the sound speed.

The **B** × **V** convection electric field resulting from the inward motion causes positive and negative polarisation charges on the eastern and western edges of the plasma element respectively (see Fig. 2). If the ionospheric Pedersen conductivity were 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 would be slowed down and stopped as by a rigid surface. In this case the element will not penetrate any more but 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 slow down the penetrating element in about 500 s (10 min: $\tau_2 = 16L^6N_e l m/B_l^2\Sigma_P$ 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; $N_e = 10\ \text{cm}^{-3}$ is the equatorial density of the element; $m = 1.67 \times 10^{-24}$ g is the proton mass, and $B_l = 6 \times 10^{-5}$ Tesla is the magnetic field intensity in the polar cusp at ionospheric levels). Assuming that 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, (COLE, 1971); this produces an enhancement of the polar cusp ionospheric temperature as was actually observed by THOMAS *et al.* (1966), TITHERIDGE (1976) and WHITTEKER (1976).

3. DISSIPATION OF A PLASMA ELEMENT

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

Protons and alpha particles transported into the magnetosphere, with pitch angles in the loss cone, will precipitate into the atmosphere where they have been observed (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,

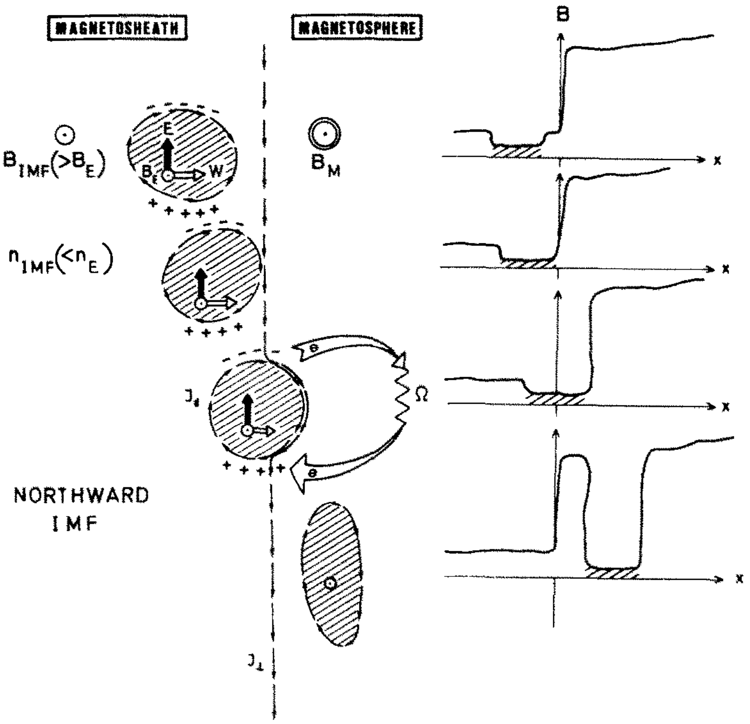

Fig. 2. *Penetration of a magnetosheath plasma element into the magnetosphere.* When a plasma element dents the magnetopause surface, the subsequent plasma boundary becomes convex and therefore flute unstable. This enables the element to be pushed out of the bulk of the magnetosheath plasma. The convection electric field $\mathbf{B}\times\mathbf{V}$ causes polarization 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 slowed down and stopped, and its kinetic energy dissipated by ionospheric Joule heating. Typical magnetic field intensity profiles across the elements are illustrated in the right hand panels.

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 electron (and westward ion) gradient B and curvature drifts. The reflected particles will finally feed the plasma mantle as suggested by ROSENBAUER *et al.* (1975).

Gradient B and curvature drifts of the warm magnetosheath electrons and protons will extend the volume of the element azimuthally at a rate controlled by the minimum value of the integrated Pedersen conductivity. Birkeland currents will flow up on the western side, and downwards on 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 $2\times10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at 800 km altitude (h), it would take 2×10^5 s ($\tau_3 = 3$ days) for a plasma element with an equatorial density of $N_e = 10\,\mathrm{cm}^{-3}$ to be dissipated and to disappear: $\tau_3 = N_e L R_E/F_p[(R_E+h)/LR_E]^3$, 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 $2R_E$ of the magnetopause is confirmed by the observation of similar features in magnetograms when two satellites penetrate the same region of the outer magnetosphere at two universal times separated by several hours (FORMISANO and HEDGECOCK, 1976). This suggests 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, as when it crosses the actual magnetopause. This is illustrated in the right hand side of Fig. 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.

4. SOME OTHER CONSEQUENCES

(a) If the rate of magnetic field merging is zero, the magnetopause boundary is a tangential discontinuity as described by WILLIS (1971, 1975, 1976) and ROTH (1976). This is the likely case where the magnetopause has not been perturbed, or where it has recovered its original position, possibly after 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 Fig. 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 occasionally (SONNERUP and LEDLEY, 1974; SONNERUP 1976).

(c) The interplanetary magnetic flux tubes partially embedded in the magnetosphere can be the channels 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 channels for magnetospheric particles escaping out of the geomagnetic cavity. The presence in the interplanetary medium of proton intensity spikes of magnetospheric origin has recently been found by WILLIAMS (1976). These observations also support the present suggestion.

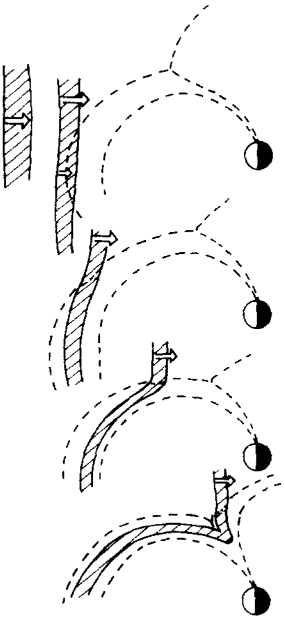

Fig. 3. *Meridional sections of the magnetosphere.* Sequence of events showing a filamentary plasma element penetrating into the magnetosphere and extending finally into the geomagnetic tail.

(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 Fig. 3) the total magnetic flux is reduced in the geomagnetic tail.

When 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 interplanetary magnetic field (IMF) polarity have been shown to be the instigators of substorm events and of related disruptions of equilibrium states in the magnetosphere.

5. CONCLUSION

Assuming that the solar wind is made up of 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 Figs. 1(b) and 3. The wide variety of magnetospheric observations mentioned in this paper support this penetration mechanism which, however, does not rely on magnetic field merging. A similar theory is likely to apply for other planetary magnetopauses (Jupiter, Mercury . . .)

Acknowledgements—The authors wish to thank Professor M. Nicolet for his continuing encouragement, and Professor D. R. Bates and Dr. M. J. Rycroft for their much appreciated advice.

REFERENCES

Anderson K. A., Binsack J. H. and Fairfield D. H. 1968 *J. geophys. Res.* **73**, 2371.

Aubry M. P., Kivelson M. G. and Russell C. T. 1971 *J. geophys. Res.* **76**, 1673.

Bahnsen A. and Hansen A. M. 1976 *Planet. Space Sci.* **24**, 841.

Block L. P. 1972 *Cosmic Electrodynamics* **3**, 349.

Burlaga L. F., Lemaire J., Turner J. M. and Ness N. F. 1977 *J. geophys. Res.* **82**.

Cole K. D. 1971 *Planet. Space Sci.* **19**, 59.

Cole K. D. 1974 *Planet. Space Sci.* **22**, 1075.

Domingo V., Page D. E. and Wenzel K.-P. 1976 *J. atmos. terr. Phys.* **40**, 279; *Trans. Am. Geophys. Un.* **57**, 663.

Formisano V. and Hedgecock P. C. 1976 *Trans. Am. Geophys. Un.* **57**, 663.

Heikkila W. J. 1975 *Geophys. Res. Lett.* **2**, 154.

Holzer T. E. and Reid G. C. 1975 *J. geophys. Res.* **80**, 2041.

Iijima T. and Potemra T. A. 1976 *J. geophys. Res.* **81**, 5971.

Kan J. R. 1975 *J. geophys. Res.* **80**, 2089.

Ledley B. G. 1971 *J. geophys. Res.* **76**, 6736.

Lemaire J. and Scherer M. 1976 *J. atmos. terr. Phys.* **40**, 331.

Longmire C. L. 1963 *Elementary Plasma Physics* (Edited by R. E. Marshak), pp. 196, Interscience, New York.

McCracken K. G. and Ness N. F. 1966 *J. geophys. Res.* **71**, 3315.

Neugebauer M. 1975 *J. geophys. Res.* **80**, 998.

Reid G. C. and Holzer T. E. 1975 *J. geophys. Res.* **80**, 2050.

Rosenbauer H., Grunwaldt H., Montgomery M. D., Paschmann G. and Sckopke N. 1975 *J. geophys Res.* **80**, 2723.

Roth M. 1976 *J. atmos. terr. Phys.* **40**, 323.

Shelley E. G., Sharp R. D. and Johnson R. G. 1976 *J. geophys. Res.* **81**, 2363.

Siscoe G. L., Davis L., Jr., Coleman P. J., Jr., Smith E. J. and Jones D. E. 1968 *J. geophys. Res.* **73**, 61.

Sonnerup B. U. Ö. 1976 *Magnetopause and boundary layer*, in *Physics of Solar Planetary Environments*, p. 541 (Edited by D. J. Williams), Proc. Int. Symp. Solar-Terrestrial Physics, Boulder Co., June 1976, Am. Geophys. Union

Sonnerup B. U. Ö. and Ledley B. G. 1974 *J. geophys. Res.* **79**, 4309.

Southwood D. J. 1968 *Planet Space Sci.* **16**, 587.

Swift D. W. 1975 *J. geophys. Res.* **80**, 2096.

Thomas J. O., Rycroft M. J., Colin L. and Chan K. L. 1966 in *Electron Density Profiles in the Ionosphere and Exosphere* (Edited by J. Frihagen), p. 322. North-Holland, Amsterdam.

Titheridge J. E. 1976 *J. geophys. Res.* **81**, 3221.

Vasyliunas V. M. 1975 *Rev. Geophys. Space Phys.* **13**, 303.

Whitteker J. H. 1976 *J. geophys. Res.* **81**, 1279.

Willis D. M. 1971 *Rev. Geophys. Space Phys.* **9**, 953.

Willis D. M. 1975 *Geophys. J. R. Astr. Soc.* **41**, 355.

Willis D. M. 1976 *J. atmos. terr. Phys.* **40**, 301.

Yeh T. and Axord W. I. 1970 *J. Plasma Phys.* **4**, 207.

Reference is also made to the following unpublished material:

Williams D. J. 1976 Paper presented at symposium on "Interplanetary medium", Amsterdam 7–10 September.