550.385

REVIEW OF MAGNETOSPHERIC BOUNDARY LAYER PHENOMENA AND RELATIONS TO CURRENT THEORIES

by

WALTER J. HEIKKILA* and LARS P. BLOCK**

Abstract

Recent observations on the magnetopause and boundary layer are reviewed. A region with magnetosheath-like plasma is found in an entry layer inside the magnetopause, at least partly on closed field lines. There is no enhanced flow near the magnetopause, in contrast to what would be expected on the basis of reconnection theories. Inside the magnetopause there is a boundary layer, which must be polarized. Parallel electric fields and currents are involved, thus invalidating the mapping of the electric field along magnetic field lines. Access to the entry layer must be impulsive or diffusive in nature.

This review is essentially the same as that given in Grenoble two years ago. Some recent observations largely confirm that conventional ideas in magnetospheric physics are in serious trouble.

Figure 1 shows a cut through the magnetosphere along the noon-midnight meridians (HEIKKILA, [14]). In the magnetosheath the magnetic field lines are either entirely solar wind lines, or open geomagnetic lines. Inside the magnetopause we have the plasma mantle reported by ROSENBAUER *et al.* [25], which is most likely on open field lines. A new feature called the entry layer by HAERENDEL and PASCHMANN [9], and PASCHMANN *et al.* [23], exists on the dayside; this entry layer was totally unexpected on the basis of current ideas. It has been shown by the

---

* The University of Texas at Dallas, Richardson, Texas 75080, USA

** Royal Institute of Technology, Department of Mechanics, S-10044 Stockholm – Sweden

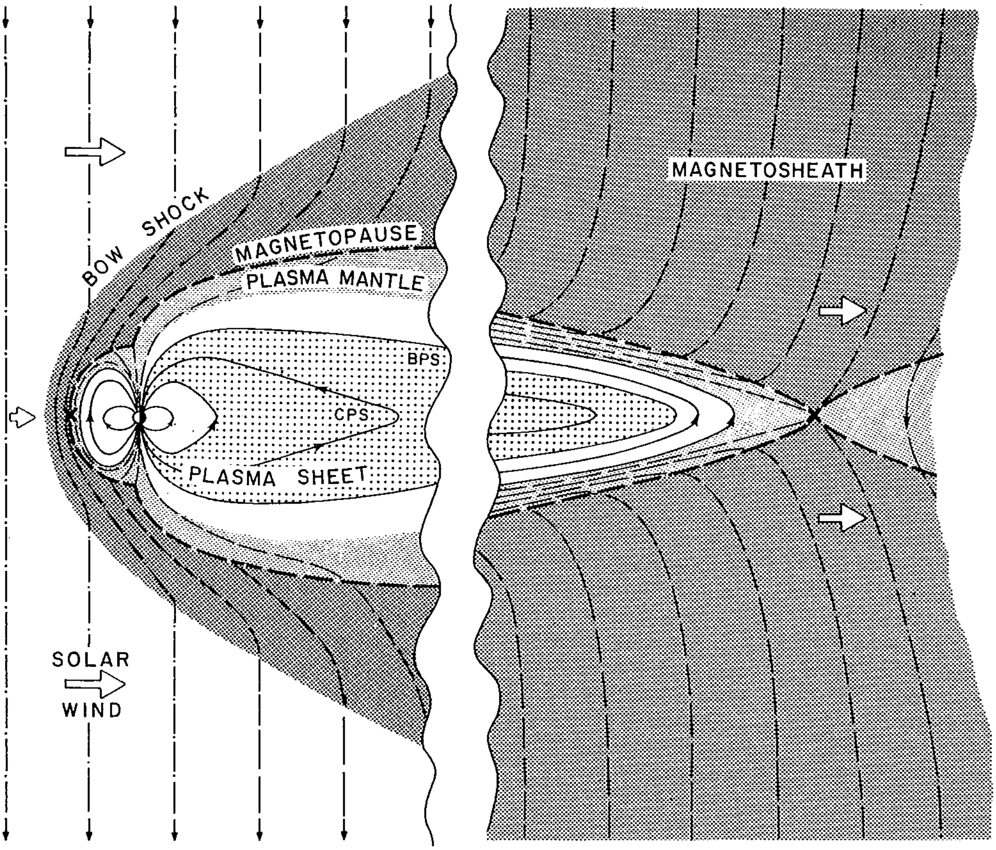

Figure 1. The locations of the limits of closed magnetic field lines on the day and night sides suggests this revision to the Dungey model of the magnetosphere. Here the plasma sheet is contained within a bottle of closed magnetic field lines. The nightside X-line is at the distant magnetopause, isolated from plasma sheet and auroral processes. The entry layer is on the dayside, at least partly on closed magnetic field lines.

German investigators, and by McDiarmid and Burrows [20], to be at least partly on closed field lines. Along each of the flanks there is a boundary layer with antisunward flow, shown by Freeman *et al.* [8], and Hones *et al.* [16]. The magnetic field in the boundary layer is probably also on closed field lines (Palmer *et al.*, [22]).

We will first discuss the properties of the dayside magnetopause and the entry layer. Shown in Figure 2 are 6 HEOS-2 magnetopause crossings. Paschmann *et al.* [24] have reported 41 such crossings, several of them at lower latitudes than shown here. Particle and field data from an outbound pass is shown in Figure 3.

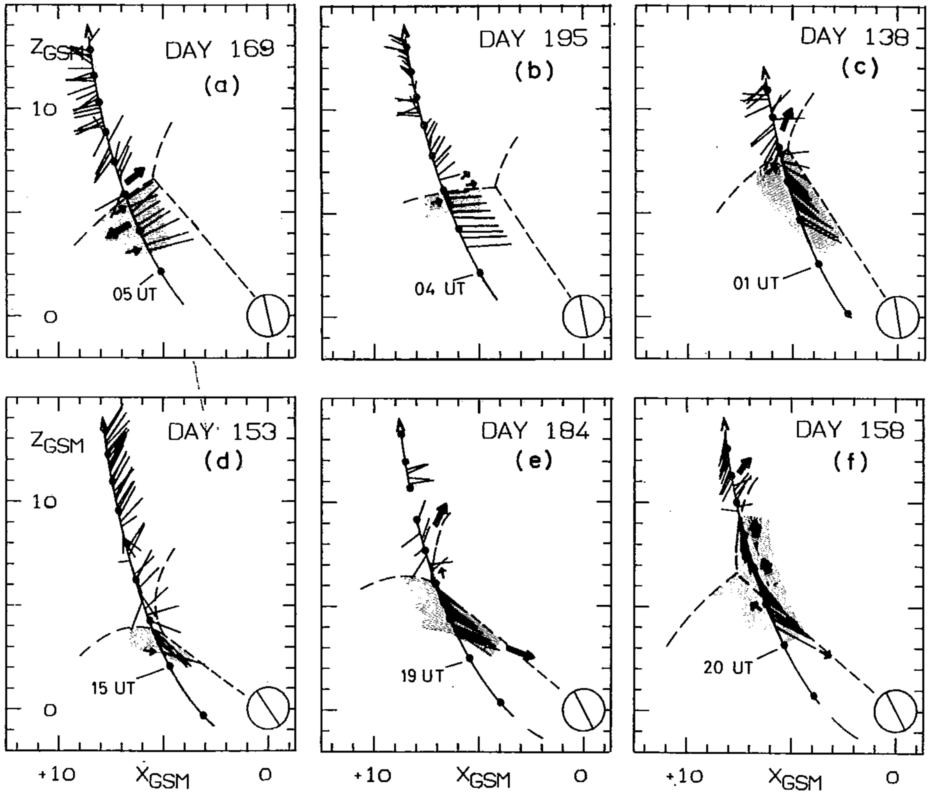

Figure 2. Location of 6 outbound passes of HEOS-2 projected into the X-Z plane of the GSM coordinate system reported by PASCHMANN *et al.*, [23]. The inclination of the earth's dipole axis at the time of magnetopause traversal is indicated. Dots along the orbit mark full hours. 10-minute averages of the X-Z component of *B* are shown by short lines in logarithmic scaling. Conjectured contours of magnetopause and demarcation line are shown by dashed lines. The width of the cusp plasma layer is indicated by grey shading. Proton flow vectors are shown by heavy arrows.

The entry layer is the grey area, just inside the magnetopause which is defined by the sudden change in magnetic field direction. Note that the proton density and temperature hardly vary at all across the magnetopause, but the bulk velocity increases by a factor 3 or so and gets more steady in the magnetosheath, compared to the entry layer.

Figure 4 shows data from an outbound HEOS-2 magnetopause crossing, reported by HANSEN *et al.* [11]. Here, also, the magnetic field changes direction abruptly at

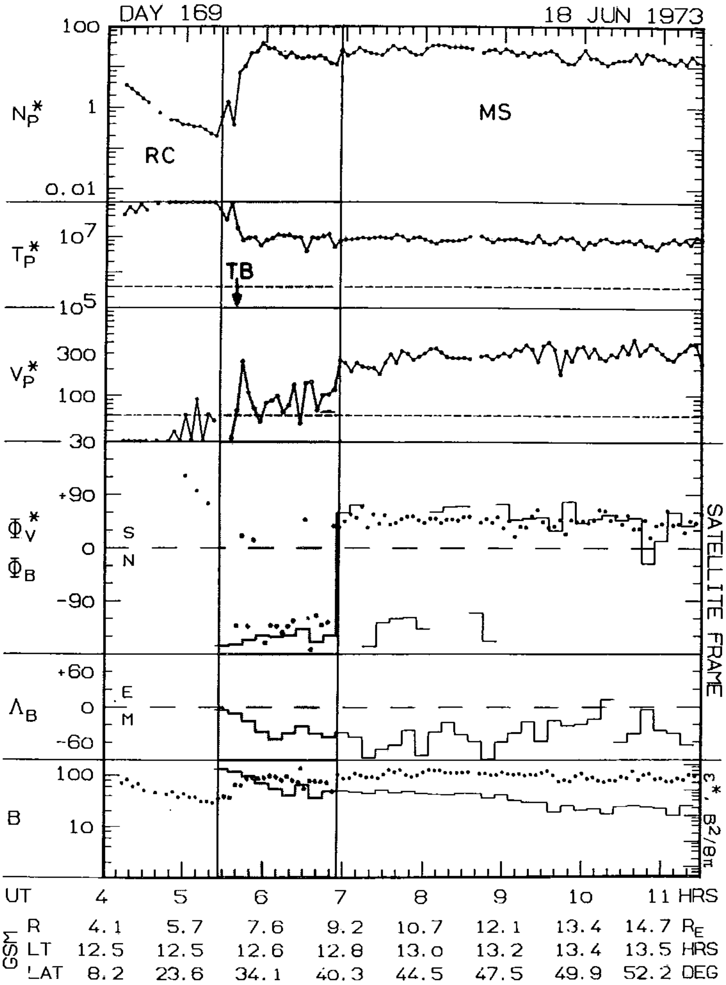

Figure 3. Proton parameters (dotted lines) and magnetic field data (solid lines) as a function of universal time for the HEOS-2 magnetopause crossing on day 169 (PASCHMANN *et al.*, [23]). From top to bottom the figure shows the proton density N_p^* (in cm^{-3}): temperature T_p^* (in degrees Kelvin): bulk speed V_p^* (in km s^{-1}): directions of the bulk flow ϕ_V^* and of the magnetic field ϕ_B, both in the spacecraft equatorial plane: elevation of the magnetic field Λ_B: magnetic field magnitude B (in gammas): and proton energy density ϵ (ranging from 4×10^{-12} to 10^{-7} erg cm^{-3}). The location of the spacecraft is given in the solar magnetospheric (GSM) coordinate system. The letters S, N, E, and M stand for south, north, evening, and morning. TB denotes the trapping boundary.

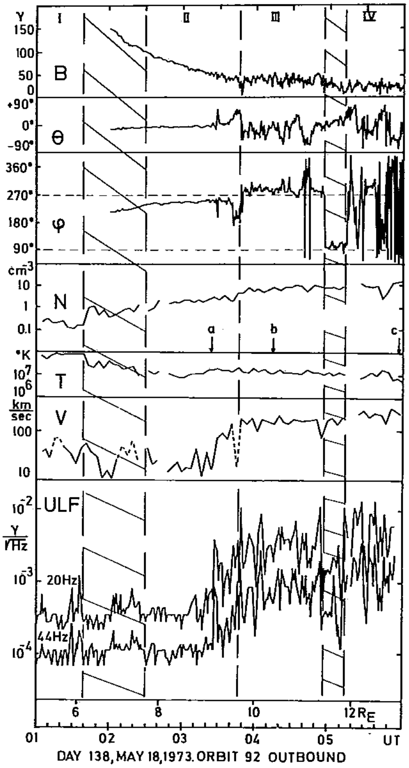

Figure 4. HEOS-2 observations reported by HANSEN *et al.* [11]. The magnetopause between regions 2 and 3 is identified by the abrupt change in the direction of the magnetic field. The plasma observations show little or no change in thermodynamic properties at the magnetopause, and a reduced flow, in contrast with the predictions of reconnection models.

the magnetopause, they note that the velocity does not reach its full magnetosheath value until further out in region 4. That feature is also evident in Figure 3. Again there is little change in particle density or temperature across the magnetopause.

The next figure illustrates what we should expect to see according to reconnection theory. The observed change in magnetic field direction necessarily implies a current J_{MP} along the magnetopause. The electric field E_R must be there, by definition, if reconnection occurs at all. Since $E_R \cdot J_{MP} > 0$ electromagnetic energy is transformed into particle kinetic energy. According to YANG and SONNERUP [29] this energy should appear in the form of one northward and one southward directed plasma beam going either into the cleft as indicated by arrows marked C, or into the polar regions as indicated by the arrows marked P. The total power conversion should be of the order of $10^{11} - 10^{12}$ W.

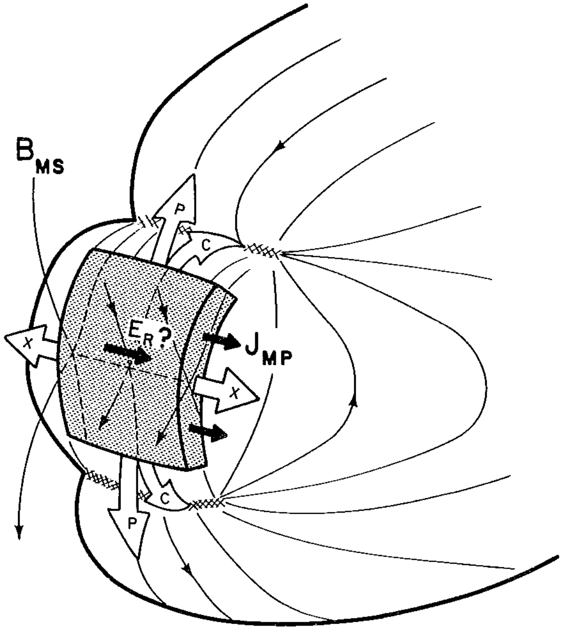

Figure 5. In the presence of the reconnection electric field E_R the magnetopause current should dissipate energy within some volume such as that shown shaded. The energy should then be carried out by the plasma in one or more of the directions indicated by the open arrows.

Figure 6 illustrates the process locally, in the immediate vicinity of a satellite crossing the magnetopause. The electric field component E_{MS} is associated with the general magnetosheath flow V_{MS} along the magnetopause. The reconnection component E_R parallel to the magnetopause current J_{MP} produces a beam with velocity V_R poleward. The surface current density may be deduced from the observed discontinuity in the magnetic field, so that the local rate of energy dissipation is given by

$$w = E \cdot J = E_R \Delta B / \mu_0$$

Here $\Delta B = |B_{GM} - B_{MS}|$ is the magnitude of the vector difference between the magnetic fields inside and outside. The same electric field will convect magnetosheath plasma inward at the rate

$$f = NV_n = N_{MS} E_R / B_{MS}$$

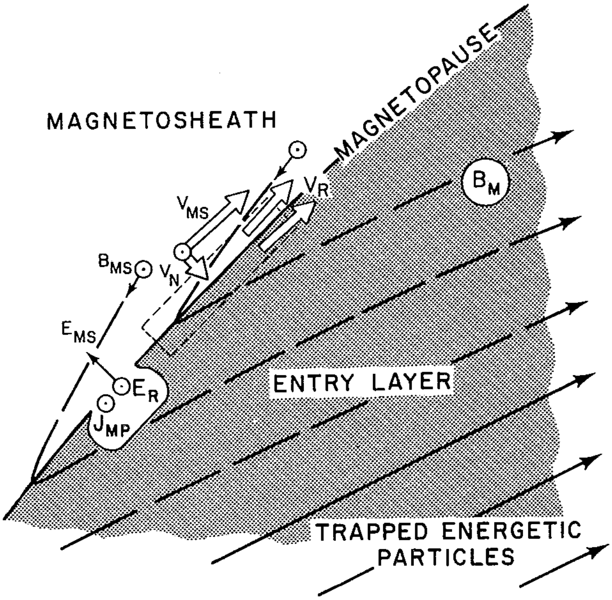

Figure 6. Cross-section of a small part of the northern dayside magnetopause, such as sampled by the HEOS-2 satellite. In the presence of the reconnection electric field E_R, tangential to the dayside magnetopause, the large surface current would dissipate electromagnetic energy. According to reconnection theory, this should show up at least partly in an enhanced outflow V_R. Neither the enhanced flow nor the particle energization has been observed.

If these plasma particles were to pick up the dissipated energy, then the energy gain per particle would be

$$\epsilon = w/f = B_{MS} \Delta B/\mu_0 N_{MS}$$

Fortunately the electric field drops out of this relationship, because both the energy dissipation and the normal flux of plasma particles are proportional to it. This means that the model itself, rather than the strength of the electric field, is under test. The flux and particle energy of this beam is large enough to be easily detected by the HEOS-2 instruments. However, in none of the 41 passes has it been seen.

Let us look again at Figure 3 showing the data reported by PASCHMANN *et al.*, [23]. The observed density and change in magnetic field should produce a bulk velocity V_R corresponding to a few keV energy, but that is not seen.

If the beam had been dispersed it should show up as a temperature or density

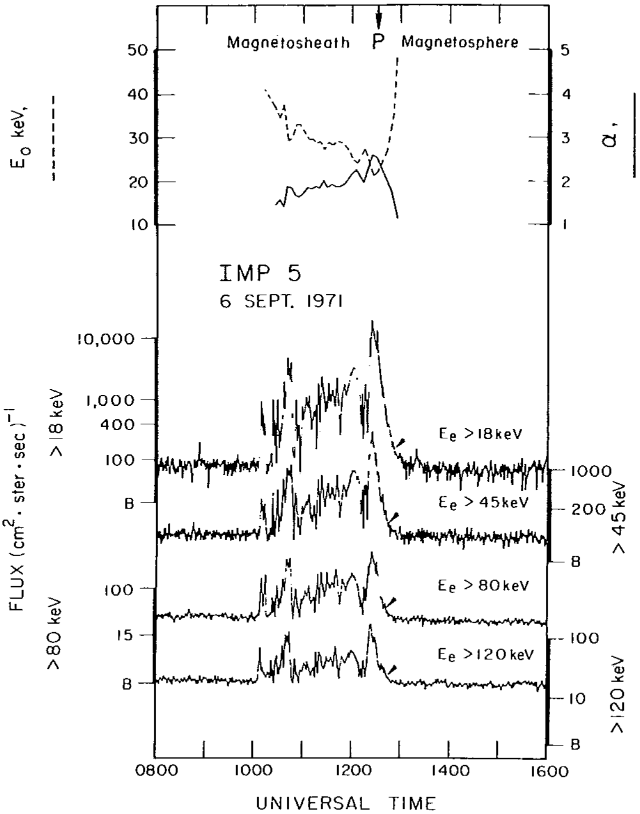

Figure 7. Energetic electron observations for an IMP5 inbound pass of September 6, 1971 (MENG and ANDERSON, [21]). Only a flux of 10^4 particles/sec is seen, but 10^7 is required to explain the expected energy dissipation.

increase, but none is seen here. In the results reported by HANSEN *et al.*, [11], there is also no evidence of this large energy conversion.

As has already been said, the total energy conversion should be of the order of $10^{11} - 10^{12}$ W, which is much more than is dissipated on the nightside. It would indeed be surprising if some of this dissipation would not show up in electromagnetic radiation of some kind, but very little of that has been observed (GURNETT, [6]; ALEXANDER and KAISER, [1, 2]). On the nightside about 1 % of the total auroral dissipation appears as kilometric radiation, but on the dayside the total radiation is two or three orders of magnitude less, even though the dissipation on the basis of the reconnection model should be greater.

It should me mentioned that MENG and ANDERSON, [21]; BAKER and STONE,

[3] and Domingo *et al.,* [4] have discovered energetic electron beams at the magnetopause. However, the energy flux is at least three orders of magnitude too low to explain the expected dissipation. Heikkila [13] estimated that a flux of these energetic particles should be of the order of 10^7 cm^{-2} ster^{-1} sec^{-1}, but only 10^4 is seen in Figure 7. Also, the particle energies are too high (up to several 100 keV) so that these particles must be produced by some other process not involving the cross tail potential difference of some 50 kV.

It must be concluded that there is no reconnection electric field on the day-side. The magnetopause must be essentially an equipotential surface. The extremely large power dissipation associated with reconnection just could not have escaped detection.

Let us now turn to the boundary layer. That is shown in Figure 8 (Heikkila, [15]) which is a cut along the equatorial plane. The flow in the boundary is away

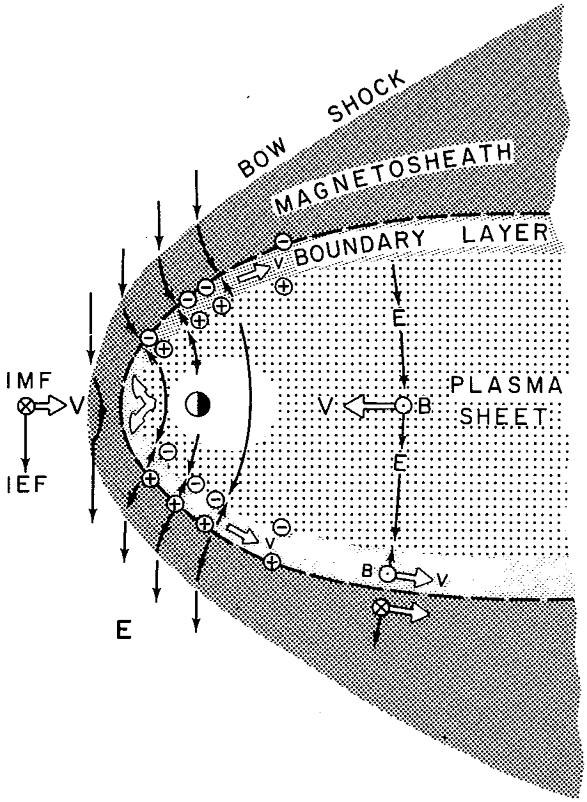

Figure 8. With an equipotential magnetopause, an electric field inside the magnetosphere can exist only if separate sources exist, due to charges placed as shown. The sheet densities need not all be the same; thus the boundary layer plus magnetopause region can be viewed as a combination of a charge sheet and a dipole sheet.

from the sun. Due to the sunward flow in the plasma-sheet the electric field reverses at the inside of the boundary layer. Therefore, the boundary layer must be polarized as shown, making it possible to have a potential drop across the magnetotail while still maintaining an equipotential magnetopause. In this projection the entry layer is on the dayside, joining the boundary layers somewhere in the morning and evening sectors. The properties differ only in that the flow is irregular in the entry layer, and it gradually becomes antisunward in the boundary layers. Thus, there is no sharp transition. The entry layer seems to be the source for the boundary layer flow.

If that is so, there must also be a source for the entry layer plasma. Its spectrum is quite similar to the magnetosheath spectrum, but the density is about a factor 2 lower. (see PASCHMANN *et al.,* [23]; and HANSEN *et al.,* [11]). Accordingly, these authors suggest that the plasma enters from the magnetosheath. However, it cannot enter by $E \times B$ drift, as has been proposed by FORMISANO *et al.,* [7], if the magnetopause is an equipotential. In that part of the entry layer which is on open field lines they may perhaps enter along the field, although SONNERUP [26] has shown that the magnetopause is highly reflective. For access to the closed part there must be some kind of diffusion. That is also consistent with the irregular bulk flow observed by PASCHMANN

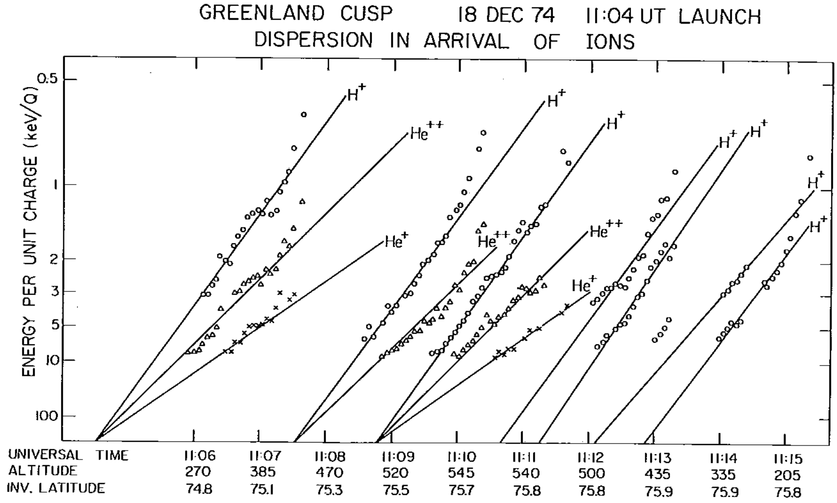

Figure 9. Dispersion curves are deduced from observed ion precipitation on a rocket flight on December 18, 1974 (TORBERT and CARLSON, [27]). The energy is scaled logarithmically, against time. From an assumed ionic composition, it is concluded that the observed time dispersion is consistent with entry at a distance of 12 R_E.

et al., [23] as noted above. A corroboration of this fact is given in Figure 2, showing the HEOS-2 trajectories through the entry layer. The flow directions are indicated by the arrows. At times it is away from the sun, but at other times it is towards the sun.

TORBERT and CARLSON [27] drew the same conclusion from some rocket observations in the cleft. Figure 9 summarizes their results. The abscissa is time, the ordinate is log particle energy per unit charge; from the banded structure on their spectrogram they deduce dispersion curves, which show impulsive injection of particles in agreement with eddy diffusion or some similar process. From the energy dispersion it was concluded that the injection took place about 12 R_E from the rocket, presumably at the magnetopause. The duration of an injection burst was about 20 sec, with repetition period of the order of 100 sec. At times the ion and electron precipitation was anticorrelated, suggesting field-aligned potential drops of the order of 0.5 – 2 kV. Similar results were reported also by WINNINGHAM, *et al.* [28],. where the voltage drop is evaluated along the field line (Fig. 10).

Such parallel potential drops are in fact required in order to reconcile the equipotential magnetopause with the ionospheric convection pattern observed in the cleft region by HEELIS *et al.* [12]. This convection, shown in Figure 11,would imply a reconnection electric field if mapped along the field lines to the magnetopause, but the parallel electric fields invalidate such mapping.

Impulsive injection into the entry layer has earlier been proposed by LEMAIRE and ROTH [18], and LEMAIRE [19], and an eddy diffusion process was proposed by HAERENDEL [10]. Reconnection would prevent such diffusive injection, as the flow should be convected back toward the magnetopause. It should be possible to construct a realistic theory of this diffusion, based on Helmholtz or flute instabilities, taking into account the induced and parallel electric fields, and the essentially equipotential nature of the magnetopause.

Observations in the boundary layer by EASTMAN *et al.* [5] show a decreasing plasma momentum along the cross-field component of the bulk flow velocity. That is consistent with an MHD generator located in that region, as noted by Figure 12 taken from EASTMAN *et al.*, [5]. On that basis they suggest that this generator drives Birkeland currents from the magnetopause towards the cleft region, along the auroral oval, and back to the inner edge of the boundary layer in the afternoon sector. In the morning sector the current is the other way.

These Birkeland currents are of course part of the general Birkeland current system shown in Figure 13, which is taken from a paper by IIJIMA and POTEMRA [17]. The figure is a topside view of the polar cap ionosphere above 60° magnetic

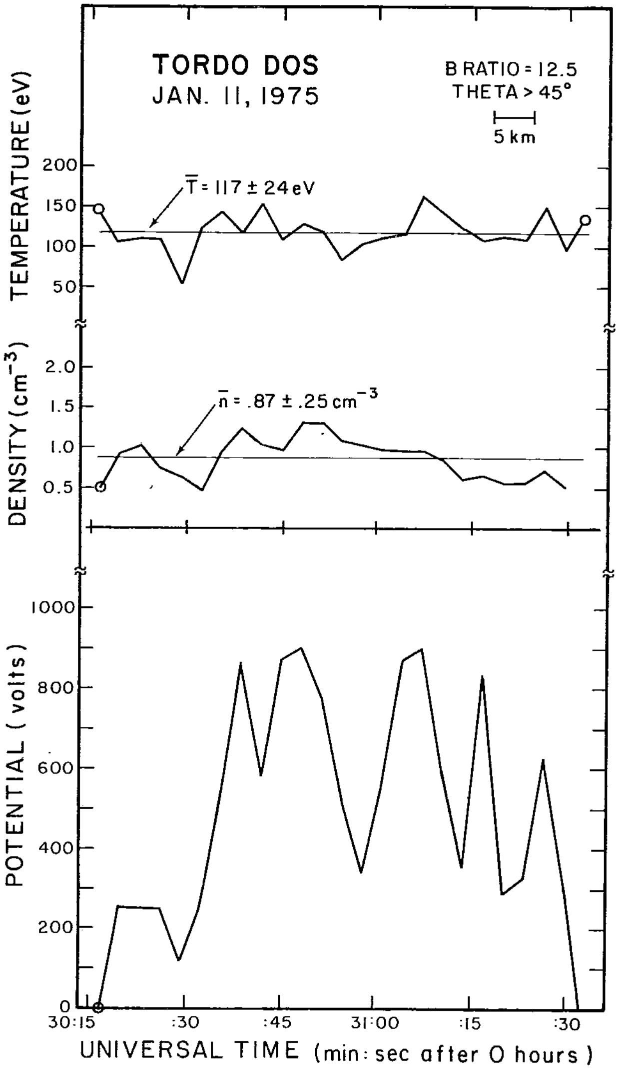

Figure 10. An electron inverted V event was observed in the afternoon cleft region; these results are consistent with a constant density and temperature for an assumed source in the distant cleft, provided that a potential drop exists along magnetic field lines as shown (WINNINGHAM *et al.*, [28]).

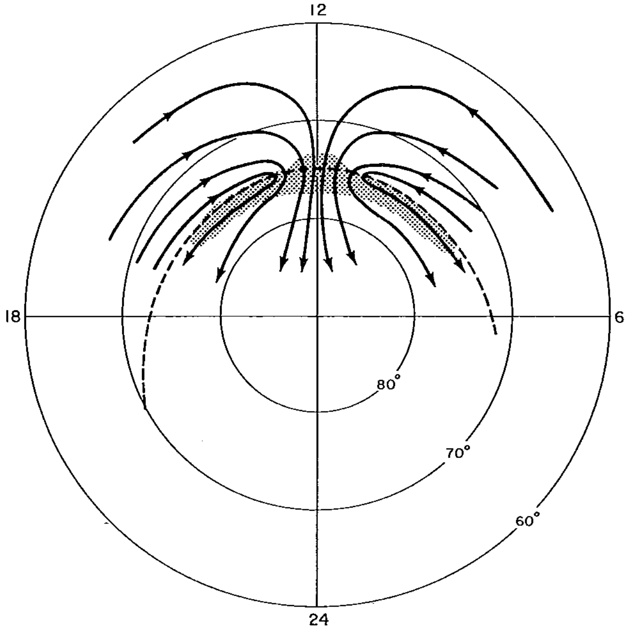

Figure 11. A schematic view of the dayside high-latitude ion flow pattern derived from the AE-C vector ion velocity data (HEELISH *et al.*, [12]). Corotation has been removed from data, and the dashed line indicates the polar cap boundary.

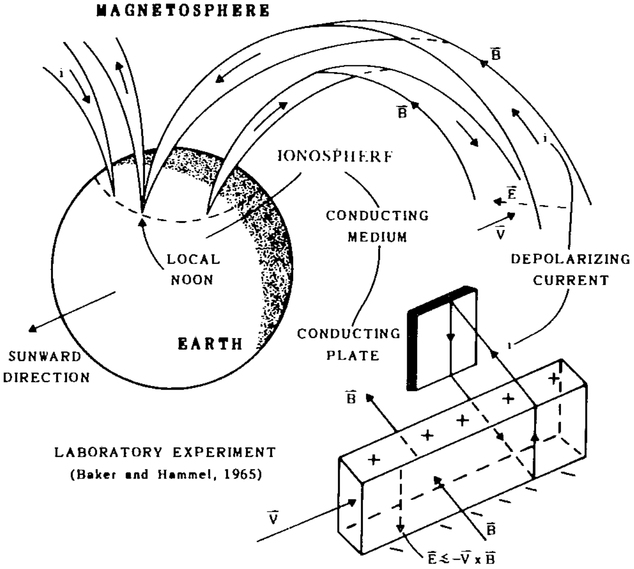

Figure 12. Illustration of polarization electric field, E, and depolarizing currents, i, generated by plasma moving with velocity, V, transverse to a magnetic field, B. Bottom: Laboratory experiment. Top: Earth's magnetosphere. The dotted line at the earth represents a line of constant high latitude. Note that the outermost magnetospheric field lines map to local noon on the earth. Lines deeper in the boundary layer map progressively farther from noon (EASTMAN *et al.*, [5]).

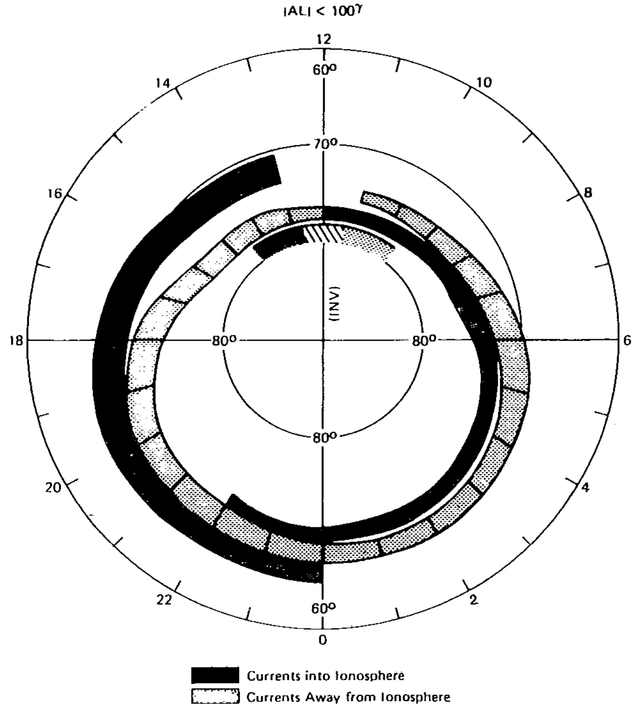

Figure 13. A summary of the distribution and flow directions of largescale field-aligned currents determined from data obtained on 493 passes of Triad during weakly disturbed conditions (|AL| < 100 γ). The 'hatched' area shown between 1130 and 1230 MLT in the polar cusp region indicates that the current flow directions are often confused (IIJIMA and POTEMRA, [17]).

latitude. The black areas indicate regions with downward Birkeland currents, and the grey shows upward currents. These regions correspond to the currents from the magnetopause side of the boundary layers suggested in the previous figure, and also the return currents from the inside of the boundary layers.

Summary

The principal finding of the last two years was the entry layer, at least partly on closed field lines inside the magnetopause. At the magnetopause itself there is no evidence of energy dissipation as would be expected on the basis of merging theories. The central question facing theorists is how the magnetosheath plasma gets into the entry layer. Once it gets in a number of consequences are likely to follow, in particular the creation of Birkeland currents, and even the generation of nightside auroral phenomena.

Acknowledgements: The writing of this review was supported by the Swedish Natural Science Research Council, the U.S. National Science Foundation, and the National Aeronautics and Space Administration.

REFERENCES

1. ALEXANDER, J.K., and M.L. KAISER, 1976: Terrestrial Kilometric Radiation, 1. Spatial Structure Studies, *J. Geophys. Res.*, 81, 5948–5956.
2. –»– , 1977: Terrestrial Kilometric Radiation, 2. Emission From the Magnetospheric Cusp and Dayside Magnetosheath, *Ibid.*, 82, 98–104.
3. BAKER, D.N., and E.C. STONE, 1977: The Magnetopause Electron Layer Along the Distant Magnetotail, *Geophys. Res. Lett.*, 4, p. 133.
4. DOMINGO, V., PAGE, D.E. and K.-P. WENZEL, 1977: Energetic and Relativistic Electrons Near the Polar Magnetopause, *J. Geophys. Res.*, 82, 2327–2336.
5. EASTMAN, T.E., HONES, E.W. Jr., BAME, S.J. and J.R. ASBRIDGE, 1976: The Magnetospheric Boundary Layer: Site of Plasma, Momentum and Energy Transfer from the Magnetosheath into the Magnetosphere, *Geophys. Res. Letters,* 3, p. 685.
6. GURNETT, D.A., 1975: The Earth as a Radio Source: The Nonthermal Continuum, *J. Geophys. Res.*, 80, 2751–2763.
7. FORMISANO, V., DOMINGO, V. and K.-P. WENZEL, 1976: On the Mechanism of Plasma Penetration and Energetic Electron Escape Across the Dayside Magnetopause, *ESLAB preprint 76/08.*
8. FREEMAN, J.W., Jr., WARREN, C.S. and J.J. MAGUIRE, 1968: Plasma Flow Directions at the Magnetopause, January 13 and 14, 1967, *J. Geophys. Res.*, 73, 5719–5731.
9. HAERENDEL, G. and G. PASCHMANN, 1975: Entry of Solar Wind Plasma into the Magnetosphere, p. 23–43 in *Physics of the Hot Plasma in the Magnetosphere,* B. Hultqvist and L. Stenflo, eds. Plenum Press.
10. –»– , 1976: Microscopic Plasma Processes Related to Reconnection, Submitted to *J. of Atmos. Terr. Phys.*
11. HANSEN, MENCKE A., BAHNSEN, A. and N. D'ANGELO, 1976: The cusp-magnetosphere Interface, *J. Geophys. Res.*, 81,556–561.
12. HEELIS, R.A., HANSON, W.B. and J.L. BURCH, 1976: Ion convection velocity reversals in the dayside cleft, *Ibid.*, 81, 3803–3809.
13. HEIKKILA, W.J., 1975: Is there an electrostatic field tangential to the dayside magnetopause and neutral line?, *Geophys. Res. Lett.*, 2, p. 154.
14. –»– , 1977: Criticism of Reconnection Models of the Magnetosphere, Accepted for publication in *Planet. and Space Sciences.*
15. –»– , 1977: Electric Field Topology Near the Dayside Magnetopause, Accepted for publication in *J. Geophys. Res.*
16. HONES, E.W., ASBRIDGE, J.R., BAME, S.J., MONTGOMERY, M.D., SINGER, S. and S.-I. AKASOFU, 1972: Measurements of Magnetotail Plasma Flow Made with Vela 4B, *J. Geophys. Res.*, 77, 5503–5522.

17. IIJIMA, T., and T.A. POTEMRA, 1976: Field-Aligned Currents in the Dayside Cusp Observed by Triad, *Ibid.* 81, 5971–5979.

18. LEMAIRE, J. and M. ROTH, 1976: Penetration of Solar Wind Plasma Elements into the Magnetosphere, *Aeronomica Acta* 166, 1976, to be published in *J. Atmos. and Terr. Physics,* 1977.

19. LEMAIRE, J., 1976: Impulsive penetration of filamentary plasma elements into the magnetospheres of the Earth and Jupiter, *Aeronomica Acta* A177–1976, to be published in *Planet. Space Sci.,* 1977.

20. MCDIARMID, I.B., BURROWS, J.R. and E.E. BUDZINSKI, 1976: Particle Properties in the Day Side Cleft, *J. Geophys. Res.,* 81, 221–226.

21. MENG, C.-I., and K.A. ANDERSON, 1975: Characteristics of the Magnetopause Energetic Electron Layer, *Ibid.,* 80, 4237–4243.

22. PALMER, I.D., HONES, E.W., Jr., BAME, S.J. and J.R. ASBRIDGE, 1977: Characteristics of Energetic Electrons in the Vicinity of the Boundary Layer at Vela Orbit, *Los Alamos preprint, 1977.*

23. PASCHMANN, G., HAERENDEL, G., SCKOPKE, N., ROSENBAUER, H. and P.C. HEDGECOCK, 1976: Plasma and Magnetic Field Characteristics of the Distant polar Cusp near Local Noon: The Entry Layer, *J. Geophys. Res.,* 81, 2883–2899.

24. –»–, *et al.*, 1976: The Entry Layer, Paper presented at the European Geophysical Society Meeting, Amsterdam, August, 1976, to be published in *J. Atm. Terrest. Phys., 1977.*

25. ROSENBAUER, H., GRUNWALDT, H., MONTGOMERY, M.D., PASCHMANN, G. and N. SCKOPKE, 1975: HEOS-2 Plasma Observations in the Distant Polar Magnetosphere: The Plasma Mantle, *J. Geophys. Res.,* 80, 2723–2737.

26. SONNERUP, U.B.O., 1976: *Magnetopause and Boundary Layer, in Physics of Solar-Planetary Environments,* D.J. Williams, ed., American Geophysical Union, p. 541.

27. TORBERT, R.B., and C.W. CARLSON, 1976: Impulsive Ion Injection Into the Polar Cusp, *Magnetospheric Particles and Fields,* B.M. McCormac, ed., p. 47.

28. WINNINGHAM, J.D., SPEISER, T.W., HONES, E.W., Jr., JEFFRIES, R.A., ROACH, W.H., EVANS, D.S. and H.C. STENBAEK-NIELSEN, 1977: Rocket-Borne Measurements of the Dayside Cleft Plasma: The Tordo Experiments, *J. Geophys. Res.,* 82, 1876–1888.

29. YANG, C.-K. and B.U.O. SONNERUP, 1977: Compressible Magnetopause Reconnection, *Ibid.,* 82, 699–703.