Antarctic Science 1 (3): 193–203 (1989)

Review

The polar cusp ionosphere: a window on solar wind–magnetosphere coupling

MARK SAUNDERS

Blackett Laboratory, Imperial College of Science, Technology and Medicine, London SW7 2BZ, UK

Abstract: The polar cusp ionosphere is an important part of near-Earth space which is best monitored by ground-based observations made in the remote polar regions. Antarctica seems certain to play a key role in its future exploration. The region is characterized by the direct entry of solar wind particles along magnetic field lines projecting to the dayside magnetopause (outer boundary of the magnetosphere). Thus the polar cusp ionosphere provides a splendid window for examining processes transferring solar wind mass and momentum to the magnetosphere. The review will emphasize this aspect of polar cusp ionosphere research, an area where the pace of recent work has been rapid. New results highlight the relevance of both the interplanetary magnetic field direction and changes in solar wind pressure for dynamic effects in the polar cusp ionosphere. These phenomena include surges in plasma flow, auroral activity, magnetic impulses and field-aligned (Birkeland) currents. Among the theoretical advances emerging just this past year are ones for the origin of plasma transport in the dayside polar ionosphere and for the source of the dayside Region 1 and cusp Birkeland currents.

Received 6 June 1989, accepted 4 July 1989

Key words: Birkeland currents, flux transfer events, reconnection.

Introduction

The two polar cusps (sometimes called the magnetospheric cusps) are special regions of the magnetosphere found at high magnetic latitudes above the Antarctic and Arctic. They may be visualized as funnel-shaped regions separating geomagnetic field lines projecting to the dayside magnetopause from those which are swept back to form the magnetotail (Fig. 1). The low-altitude extension of each polar cusp, where it meets the ionosphere, is called the *polar cusp ionosphere* and is the topic of this review. These regions possess characteristic plasma properties (Newell & Meng 1988) allowing their ready identification in low-altitude satellite data. They are defined as the areas near noon where the entry of magnetosheath plasma to low altitudes is 'most direct', that is where the fluxes of precipitating particles are highest and their energy spectra closest to magnetosheath values. The polar cusps proper are embedded within larger regions called the polar clefts where magnetosheath particle precipitation also occurs but appears 'less direct'. The polar clefts occupy an area of the ionosphere near noon between roughly 0900 and 1500 hours magnetic local time and between about 76°–80° invariant latitude (this being a form of magnetic latitude based on energetic particle trajectories) and with an altitude extent from about 60 km to 600 km (though see Candidi & Meng (1988) for details on the variability in cleft position). In this review I shall, for simplicity, use the term 'cusp' as referring to both the 'cusp' and 'cleft'.

The polar cusp ionosphere may be studied either *in situ* using experiments flown on low-altitude polar-orbiting satellites or remotely by ground-based observations made in the polar regions. Satellites have provided much useful information, notably on plasma motions, electric fields and field-aligned (Birkeland) currents. However, they suffer from the limitation of only giving 'snapshots' of structure. Observations from the ground, for example through backscatter radars, are necessary for continuous monitoring of the polar cusp ionosphere. As the number of ground-based instruments in the remote polar regions, notably magnetometers, photometers and radars, has grown in recent years, so too has the pace of research. It is certain that the polar cusp ionosphere will be a major topic for research in Earth space plasma physics until at least the launch of the European Space Agency's multi-satellite CLUSTER mission in the mid 1990s.

When a magnetic field line is perturbed or bent, knowledge of that bending travels rapidly along it at the Alfvén speed, the transit time from the subsolar magnetopause to the ionosphere being just two minutes. This speed of communication means that the polar cusp ionosphere is a good window for monitoring events perturbing the outer boundary of the magnetosphere. These include some of the most controversial processes in magnetospheric physics, those involving the transfer of solar wind mass and momentum to

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

the magnetosphere. Hence the recent growth of interest in studying this region.

Among these controversial issues the nature and significance of flux transfer events (FTEs) must surely head the list. These time-dependent reconnection phenomena remain as exciting a topic today as when they were discovered a decade ago (Russell & Elphic 1978). Until 3D measurements from CLUSTER are available, observing the ionospheric signature of FTEs within the polar cusp offers the best hope for deepening our understanding of these complex phenomena. However, there is much debate at present concerning the correct ionospheric signature for an FTE and as to whether such a signature has indeed been observed. The issue is complicated further by the growing view that solar wind dynamic pressure pulses can mimic ionospheric features previously reported as FTEs (Sibeck *et al.* 1989). Other contentious issues involving momentum transfer from the solar wind pertinent to the polar cusp ionosphere are the source of the dayside field-aligned electric current systems and the origin of plasma transport in the dayside ionosphere.

Due to space constraints this review will perforce focus on developments within the last year or so. For a thorough assessment of progress prior to mid-1988, the reader is referred to the paper by Lockwood & Freeman (1989). Brevity also precludes the coverage of other important issues relating to the polar cusp ionosphere. Notable amongst these are:

a. the effect of plasma heating on the chemical composition and motions of the underlying atmosphere,
b. the changes in ionospheric density and conductivity resulting from magnetosheath particle precipitation,
c. cusp ion plasma upflows and their significance for magnetosphere plasma composition,
d. plasma wave processes within the cusp region, and
e. the role of the cusp as a source of non-Maxwellian plasma.

For a discussion on these and other topics, the interested reader is referred to the book edited by Holtet & Egeland (1985) and to the special section on 'Atmospheric Sciences in Antarctica' spanning the 1988 issues of Reviews of Geophysics. A readable introduction to the Antarctic polar ionosphere is given by Rycroft (1985).

The next section provides a framework for the more specialized material by first describing the basic morphology of the magnetosphere, then considering the location of the polar cusp ionosphere in relation to land regions from which it can be monitored, and finally introducing some of the basic physics of the polar cap ionosphere. Four sections then follow focussing on key current issues illustrating the value of the polar cusp ionosphere as a window for studying solar wind-magnetosphere coupling. These are: flux transfer events and their ionospheric signature; the location of momentum input for driving dayside ionospheric motion where I offer fresh insight; the origin of the dayside Region 1 and cusp Birkeland current systems; the effect of solar wind dynamic pressure pulses on polar cusp dynamics. Conclusions and important remaining questions comprise the last section.

Basic concepts

The Earth lies within a vast magnetic cavity called the magnetosphere, some important features of which are depicted in Fig. 1. The outer boundary of the magnetosphere is the magnetopause, a current sheet where the solar wind's forward momentum is balanced by the Earth's magnetic field. Its sunward point occurs about 10 Earth radii (R_E) upstream from our planet ($R_E = 6370$ km is a commonly used distance measurement in magnetospheric research). The Van Allen radiation belts of energetic ions and electrons form a torus surrounding the Earth at altitudes between 1 and 6 R_E. In the centre of the Earth's huge cylindrical magnetotail,which stretches for millions of kilometres into interplanetary space, is the plasma sheet. Here disruptions can occur generating bright auroras at the Earth and propelling vast bodies of hot magnetized gas called plasmoids into the interplanetary medium. About 5 R_E upstream of the magnetospheric cavity a bow shock wave exists, 'standing' in the solar wind flow. This shock wave is analogous to that associated with supersonic aircraft, and occurs because the solar wind flow is supersonic. The two polar cusps are shown marked at high magnetic latitudes and we now examine where their associated polar cusp ionospheres occur in relation to accessible land masses.

Maps for the northern and southern polar regions are shown in Fig. 2. Several of the key stations operational for ionospheric physics research in 1986 are marked together with the geographic pole (GP) and geomagnetic pole (MP). The heavy circle at a magnetic latitude of 76° marks the average locus of the polar cusp ionosphere. The polar cap, the region of open magnetic field lines connecting to interplanetary space, lies poleward of this heavy circle such that the dotted region always lies within the polar cap. The thick dashed circle indicates the equatorward border of the region accessible to daytime auroral observations, that is where the Sun is 10° below the horizon during winter solstice.

Land areas in the Arctic suitable for mounting instruments to study the polar cusp ionosphere are clearly limited: only the Northwest Territories, Greenland and Spitzbergen offer worthwhile opportunities, and of these only Spitzbergen would permit simultaneous auroral observations of the cusp region. Antarctica appears more promising for the polar cusp ionosphere and the region where dayside auroral observations are possible are both over land. However, the observing stations here are widely scattered and many are in the wrong longitude sector. Thus although Antarctica has the geographical advantage of allowing continuous cusp monitoring, it is the Arctic from which more observations are made at present.

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

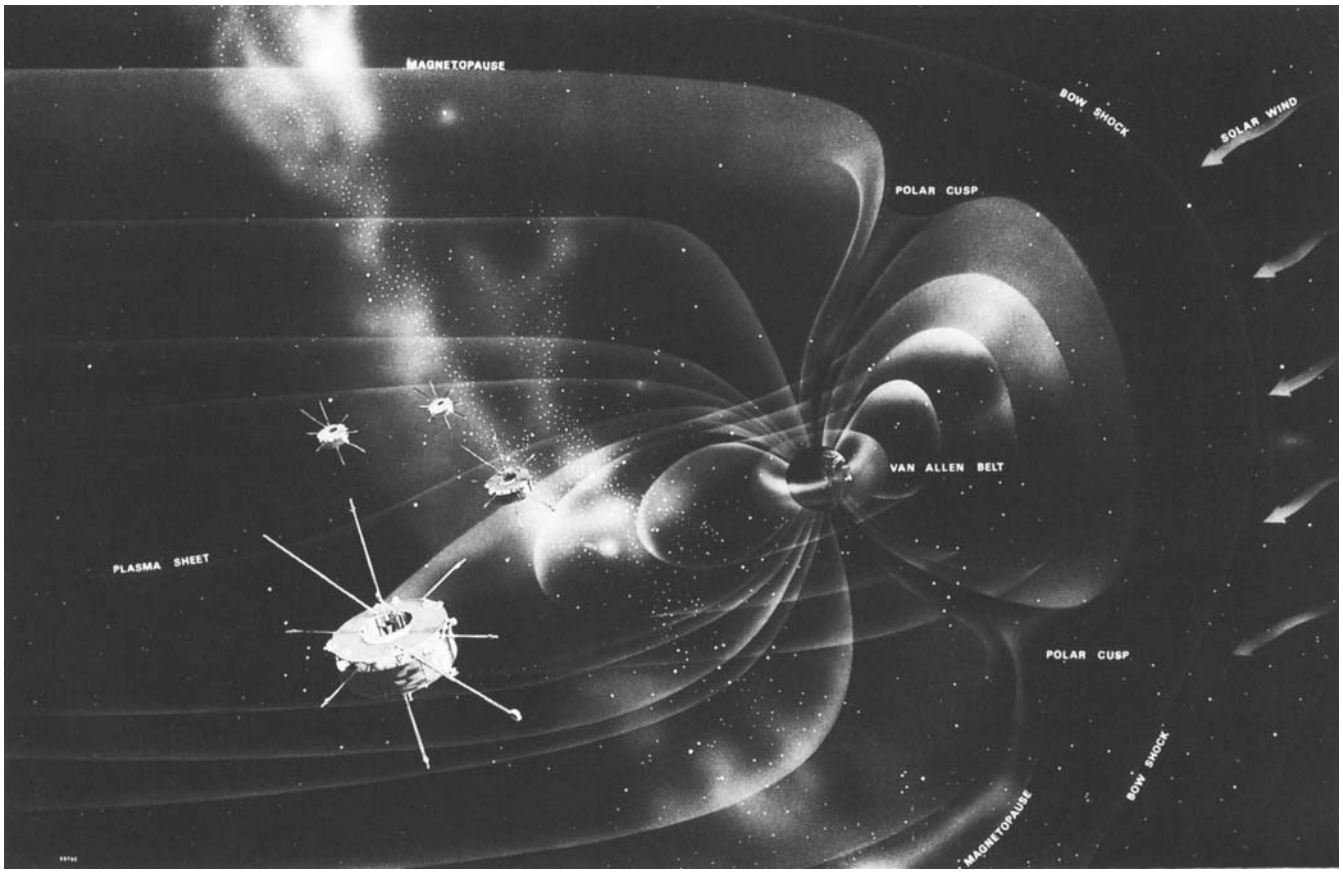


Fig. 1. Important features of the Earth's magnetized space environment (magnetosphere) illustrating the location of the two polar cusps, one of which projects to the ionosphere above Antarctica. Also shown are the four satellites comprising the European Space Agency's CLUSTER mission (from Wenzel *et al.* 1987).

Several ground observational techniques are used to study the polar cusp ionosphere. Magnetometers, which measure fluctuations in the Earth's magnetic field, are the most common type of instrument employed. They are most effective when operated in networks such as the meridian chain along the west coast of Greenland (Friis-Christensen *et al.* 1988). Such networks give useful information on the structure of ionospheric Hall currents. Station separations of at least 100–200 km are required because smaller scale current systems cannot be uniquely resolved from the ground. Observations of the aurora are made by all-sky cameras and photometers. These are able to distinguish important small-scale structures and record the auroral emissions which are sometimes associated with field-aligned currents. Backscatter radars are the third type of ground-based instrument used in studying the polar cusp ionosphere and they are proving a most valuable tool. There are four radars operating in the polar regions at present: the European Incoherent Scatter (EISCAT) system in northern Scandinavia, at Sondre Stromfjord in Greenland, Goose Bay in Labrador and at Halley Bay in Antarctica. The EISCAT system is the most sophisticated and can determine the plasma flow velocity, ion and electron temperatures, and the electron density at altitudes between one hundred and several hundred kilometres. Although EISCAT only monitors the polar cusp rarely, when conditions are disturbed and the polar cap boundary has moved equatorward, it has provided important fresh insight on the origin of plasma motions in the dayside polar ionosphere. As a framework for this and other crucial issues let us first review the basic physics of the polar cap ionosphere.

The diagram in Fig. 3 illustrates the key electromagnetic and plasma features of the northern polar cap ionosphere during southward interplanetary magnetic field (IMF) conditions. It is a magnetic local time/latitude plot looking down on the North Pole with local times of 12 and 24 hours corresponding to noon and midnight respectively and the outer circle corresponding to a magnetic latitude of 60°. The physics of this region arises mainly from the electrodynamic coupling of the Earth's magnetosphere to the solar wind (Dungey 1961). This coupling produces three types of phenomena, the first of which is *plasma transport*. The stresses which the solar wind imposes on the magnetosphere forces its outer regions into convective motion, this motion being communicated along magnetic field lines down to the polar ionosphere. A twin cell plasma flow pattern is established with anti-sunward plasma transport at speeds of

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

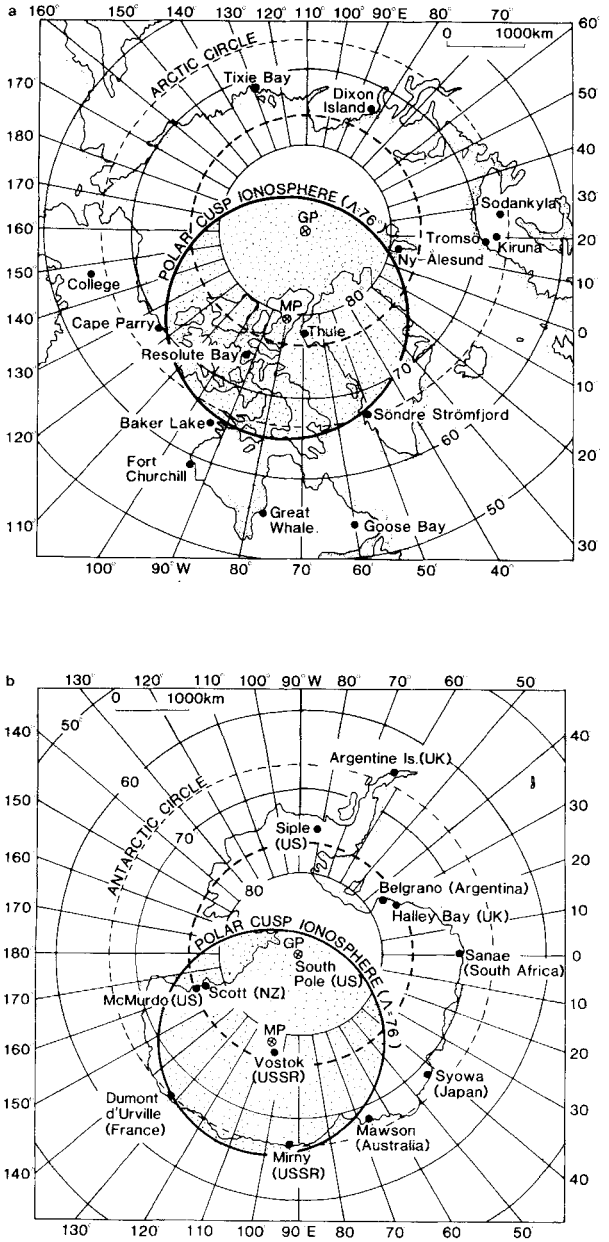


Fig. 2. Maps of the **a.** Arctic and **b.** Antarctic illustrating the locus of the polar cusp ionosphere in relation to land areas and key observing stations.

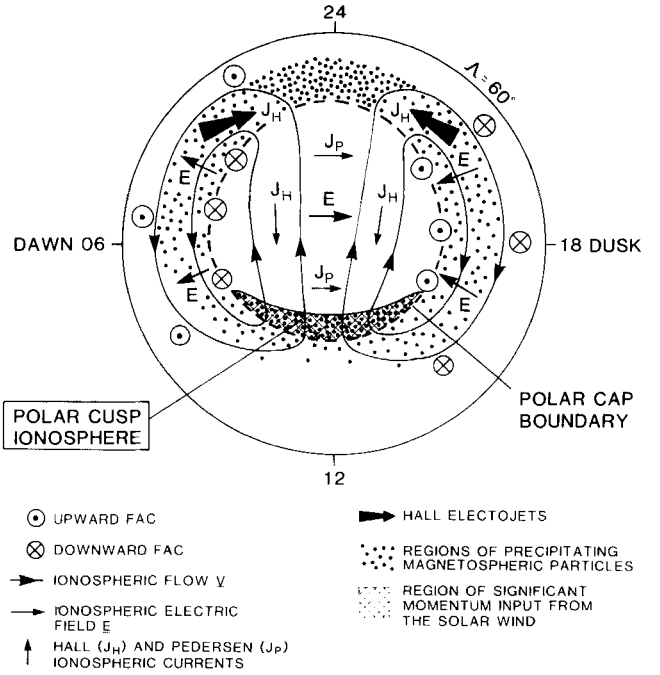


Fig. 3. View looking down on the north geomagnetic pole showing the major electromagnetic and plasma features of the polar cap ionosphere during southward-directed interplanetary magnetic field conditions (based on an unpublished diagram by S.W.H. Cowley).

0.5 km s^{-1} across the polar cap and sunward (return) flow at lower latitudes in the auroral zone. It is this plasma transport which helps to maintain the ionosphere through the polar winter in the absence of solar ionizing radiation.

The second class of phenomena is *ionospheric currents*. There is an electric field E of magnitude $E = -v \times B$ associated with the plasma flow v which drives electric currents, called Hall (J_H) and Pedersen (J_P) currents, in the E- and F-regions of the ionosphere. While J_H is confined to the E-region (altitudes between 100 and 150 km), J_P can maximize higher up in the F-region depending on magnetic latitude, local time and season (see, for example, Rasmussen *et al.* 1988). J_H is directed antiparallel to v and is most intense in two electrojets near midnight. J_P is directed parallel to E and therefore gives rise to Joule heating ($J_P \cdot E$) with a power input of about 10^{11} Watts. J_P is also responsible for the horizontal current closure between field-aligned (Birkeland) current sheets. Two distinct regions of field-aligned current are present in Fig. 3: the Region 1 system at high magnetic latitudes flowing downwards at dawn and upwards at dusk, and a Region 2 system at lower magnetic latitudes which is oppositely-directed to the adjacent Region 1. The Region 1 currents arise from the velocity shear between sunward and anti-sunward flowing plasma in the circulation pattern of magnetospheric motion (Vasyliunas 1979), while the Region 2 system is generally associated with the currents arising from 'charge separation' in plasma convected sunward from the magnetotail (Schield *et al.* 1969).

Precipitating particles are the third type of phenomena. Up to 10^{11} Watts of power are deposited into the auroral ionosphere by precipitating magnetospheric ions and electrons (Fig. 3), with electrons of energy between 200 eV and 20 keV being responsible for most of the energy input. The regions of most intense precipitation are near midnight and noon (Fig. 3), this precipitation giving rise to the so-called 'diffuse aurora', which contrasts with the highly structured 'discrete aurora' produced by electrons of energy 1–10 keV

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

precipitating above regions of upward directed Birkeland current. The ionizing effect of precipitating particles raises the conductivity of the nightside ionosphere by an order of magnitude.

A thin crescent-shaped region near noon is also indicated in Fig. 3. This is where most solar wind momentum is input for dayside ionospheric motion. The significance of this region will be discussed later.

With these basic ideas in mind let us consider some of the crucial issues concerning the polar cusp ionosphere. The one attracting the most attention in recent years is that of flux transfer events.

Flux transfer events and their ionospheric signature

There is little doubt now that magnetic reconnection occurs at the Earth's dayside magnetopause and that it supplies a significant fraction of the mass and the overwhelming amount of the momentum involved in magnetospheric motion (Cowley 1986). However, the rate of reconnection is variable and understanding the reason for its time-dependent character is a major question in magnetospheric physics.

Flux transfer events (FTEs) epitomize the time-dependent nature of reconnection. They were an important discovery near the magnetopause in the early ISEE satellite data (Russell & Elphic 1978) and are usually identified through a characteristic signal in the magnetic field when expressed in boundary normal (*LMN*) co-ordinates. In this orthogonal co-ordinate system N is the estimated outward (positive away from the Earth) normal to the magnetopause. The latter therefore lies in the LM plane with L pointing roughly northward and M westward. The characteristic FTE signal consists of a bipolar perturbation in B_N (positive followed by negative for a northward moving event and vice versa for southward motion). Four examples of FTEs are marked in the left-hand part of Fig. 4, these data coming from Berchem & Russell (1984). These events illustrate the characteristic bipolar signal in B_N together with other significant features such as an increase in field strength and the repetition in event occurrence (every 7 min). It is interesting to note that the two magnetopause encounters at 23.35 and 23.42 UT are also separated by the same 7-min interval.

For a long time most interpretations of FTEs focussed on the original Russell & Elphic (1978) idea of an isolated reconnected flux tube on which reconnection had ceased. However, the evidence slowly accumulated to suggest this model was probably wrong. This prompted Lee & Fu (1985) to suggest an alternative FTE interpretation involving the formation of magnetic islands through multiple X-line reconnection at the magnetopause. Their model has been developed in a series of subsequent papers and has many appealing features. However, there are also difficulties, especially regarding the magnetic topology. Support for the Lee & Fu (1985) idea comes from the recent detailed study of FTE properties by Farrugia *et al.* (1988) which shows that FTEs have a layered structure with the outer layers connecting to a region where reconnection is still occurring.

At about the time that the Farrugia *et al.* (1988) results were announced, a new model for FTEs was proposed independently by Scholer (1988) and by Southwood *et al.* (1988). This model stemmed from the suggestion by Saunders (1983) that FTEs might result from a pulse-like surge in the rate of reconnection. The right-hand part of Fig. 4 shows this effect schematically based on a computer simulation (Scholer 1988). Reconnected magnetic field lines are drawn projected into the noon-midnight meridian plane. The bulges contain extra magnetic flux created by an enhancement, then a decrease, in the reconnection rate. As they move polewards in the direction of the open arrows due to the reconnection flow, these bulges should give rise to FTE signals in the overlying magnetosphere and magnetosheath field regions. For example, ISEE-1 would see a negative/positive bipolar B_N signal similar to those in the left-hand part of Fig. 4. Indeed all the major observational features of FTEs fit qualitatively well with the model, including the presence of

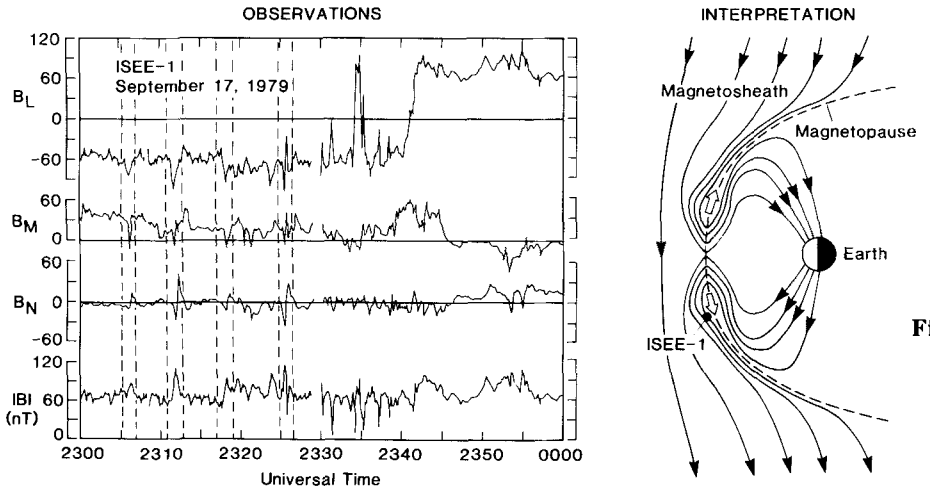


Fig. 4. Flux transfer events: satellite observations from the magnetopause (left — taken from Berchem & Russell 1984) and the present most promising interpretation (right — adapted from Scholer 1988).

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

field twisting within events (Southwood *et al.* 1988). The Scholer-Southwood *et al.* model has emerged as the most promising one for explaining FTEs. However, three-dimensional spatial measurements from CLUSTER will certainly be needed before FTEs can be properly understood at the magnetopause. Hence the value of observations from the polar cusp ionosphere in forwarding our immediate understanding.

The search for the ionospheric signature of FTEs has emerged as one of the most exciting and controversial topics in magnetospheric physics. A large range of experimental data have been published and interpreted in terms of this signature; these include ionospheric plasma flows, auroral observations and ground magnetometer signals (see Sandholt *et al.* (in press) for further details). However, many of these identifications are probably incorrect, with the observations arising from other effects such as solar wind dynamic pressure pulses (see the penultimate section). Since events at the magnetopause are repetitive, recurring on average every 8 min (Rijnbeek *et al.* 1984; also see Fig. 4 (left)) and many of the reported ionospheric identifications consist only of single events, such scepticism is well-founded.

Whatever the detailed ionospheric FTE signature emerges to be, certain basic physical principles must be obeyed when a localized reconnection region maps to the ionosphere and drives plasma motions therein. These principles, which involve the pattern of ionospheric electric currents necessary to drive these flows, are described by Southwood (1987) and are illustrated in Fig. 5. (I focus on this model as it provides a sounder physical explanation for ionospheric plasma motions than the alternative Saunders *et al.* (1984)–Lee (1986) FTE field-aligned current model which is akin to a coaxial cable). The dark oval marks a region of newly-reconnected magnetic flux at a point early in its life when it is near the old polar cap boundary. Field-aligned (Birkeland) current sheets occur at the poleward and equatorward edges of this region driven by the release of magnetic stresses arising from reconnection at the magnetopause. These Birkeland current sheets close in the ionosphere via Pedersen currents J_P such that the $J_P \times B$ force (B is vertically upward in the southern polar regions) provides the momentum input to drive the plasma motions. Twin vortex flows should be generated having tailward flow within the region of newly-opened magnetic flux and sunward return flow outside. The latitudinal extent of the reconnection region should be 100–200 km (Saunders *et al.* 1984) but its longitudinal extent could be much greater and depends on the length of the reconnection X-line at the magnetopause.

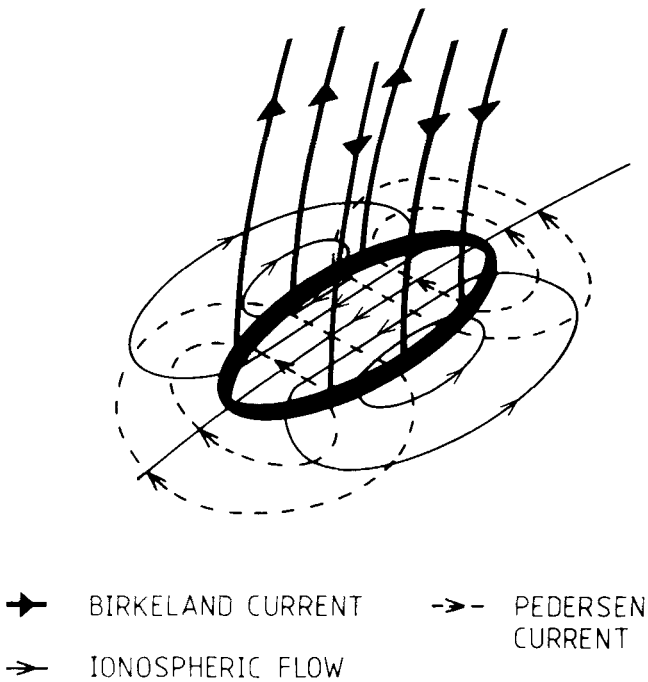


Fig. 5. Diagram illustrating the electric current pattern and ionospheric plasma flows associated with the motion of a newly reconnected bundle of magnetic flux through the Antarctic polar cusp ionosphere (from Southwood 1987).

The most convincing evidence to date purporting to be the ionospheric signature of FTEs comes from recent studies of the 'midday-auroral breakup' phenomenon (Lockwood *et al.* 1989; Sandholt *et al.*, in press). Transient auroral forms are observed having many of the features expected of FTEs: these include occurrence predominantly during southward IMF conditions; east–west motion controlled by the IMF B_Y component; 3–15 min recurrence time; spatial scales of 50–500 km in latitude by 500–2000 km in longitude. Individual features are associated with large electric potentials (25–55 kV) indicating that momentum coupling at the magnetopause is taking place in large bursts. Further studies of the dayside aurora should be productive but definitive identification of the FTE ionospheric signature must surely await simultaneous magnetopause and ground-based observations of the phenomenon. In this connection the recent findings by Freeman *et al.* (in press) appear the most relevant. These authors note that coincident with FTEs being seen near the magnetopause, substantial (20–40% of the background) plasma flow fluctuations are recorded in the polar cusp ionosphere.

Location of momentum input for dayside ionospheric motion

Plasma transport in the dayside polar ionosphere is driven by the coupling of stresses imposed by the solar wind at the magnetopause. Until recently it was widely believed that this momentum input was spread across the polar cap (see, for example, Vasyliunas (1975)). However, new observations by the EISCAT radar in northern Scandinavia (Lockwood & Cowley 1988; Lockwood *et al.*, in press) have brought this view into question. Their key discovery centres on the response of plasma flows in the dayside polar ionosphere to IMF changes impinging on the magnetopause. In particular,

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

following northward turnings of the IMF these plasma flows disappear on timescales of 5–10 min. This rapid decay time implies that only newly-reconnected field lines impart significant momentum to the ionosphere. Thus the region of prime momentum input to the dayside polar ionosphere is limited to a thin crescent-shaped region near noon (Fig. 3). I now offer an interpretation as to why the momentum input region is so localized.

Let us first consider what is required for momentum to be input to the ionosphere. The key physics is illustrated in Fig. 6 which shows a magnetic field line convecting through the magnetosphere at the $E \times B/B^2$ drift speed due to its interaction with the solar wind. Ion-neutral collisions in the ionosphere cause the latter to be 'sticky' to this motion and a perpendicular field perturbation ΔB results above the ionosphere. From the magnetohydrodynamic momentum equation it is easily shown that the flux of perpendicular momentum communicated along B to the ionosphere per unit area is proportional only to ΔB. This momentum flux balances the $J_P \times B$ drag force exerted by the Pedersen currents on the ionosphere (Fig. 6). Momentum input to the dayside polar ionosphere is clearly substantial only where ΔB is significant. Let us consider, therefore, by reference to data, where ΔB does maximize.

Fig. 7 illustrates a typical data swathe through the topside polar cusp ionosphere (taken from Bythrow *et al.* 1988), these measurements coming from the low-altitude (~800 km) polar orbiting DMSP F7 satellite. The pass is from the Northern Hemisphere when the IMF had a southward component. The top panel displays magnetic field vectors along the orbit track plotted on a magnetic latitude/magnetic local time polar dial. Magnetic field and particle data for the cusp crossing are presented in the lower panels. The magnetometer data are transverse components of the perturbation magnetic field. The upper two panels of particle data are line plots of electron and ion energy flux (J_E) and average energy (E_{AVE}), with the lower two panels showing spectrograms of electron (top) and ion (bottom) energy flux versus energy (30 eV–30 keV) and time. The Region 1 (downward) and cusp (upward) Birkeland currents are bracketed by the dashed vertical lines, their identifications being based upon the deflections in B. Associated with these field-aligned currents are large increases in the fluxes of precipitating electrons and ions, these particles having energy and spectra characteristic of magnetosheath particles. This feature indicates that both these dayside Birkeland currents

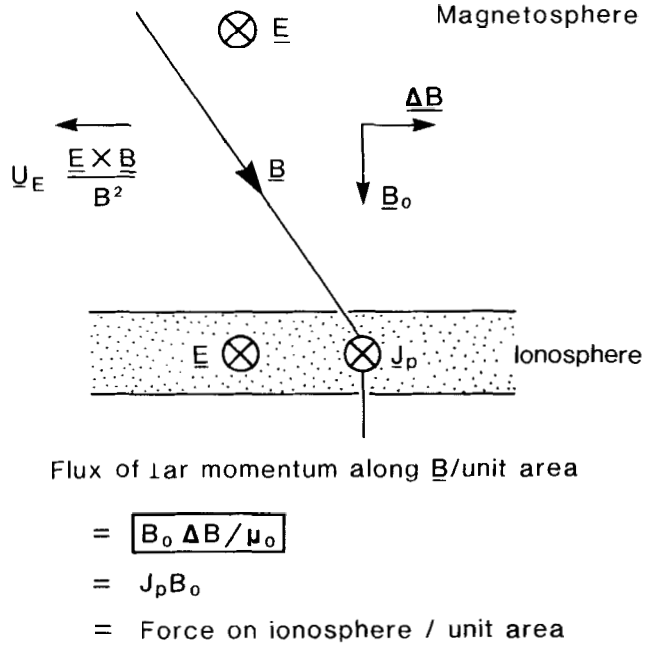


Fig. 6. Simple theoretical scenario illustrating that ΔB is the crucial parameter in determining where magnetospheric momentum is input to the ionosphere (after Southwood & Hughes 1983).

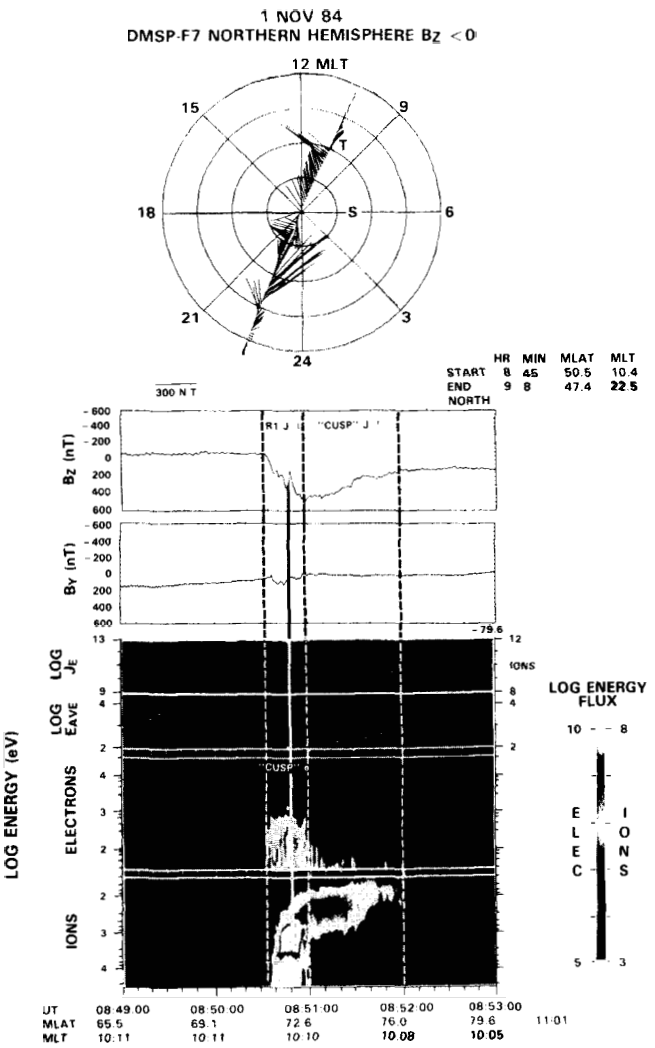


Fig. 7. A typical satellite data sequence through the polar cusp ionosphere during southward IMF conditions (see text for details). These measurements illustrate that momentum input to the polar cusp ionosphere is co-located with the Region 1 and cusp Birkeland current systems (from Bythrow *et al.* 1988).

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

are on reconnected open magnetic field lines and that the polar cap boundary occurs at the equatorward edge of the Region 1 system.

The striking feature of these data is the large ΔB associated with the two Birkeland current systems. From our earlier simple theoretical discussion it is clear that the region of dominant momentum input to the dayside polar ionosphere must correspond to the site of the Region 1 and cusp Birkeland current systems. This is the thin crescent-shaped area near noon referred to by Lockwood *et al.* (in press). It takes roughly 5–10 min for a reconnected field line to shorten and move across this region (Saunders 1989), a timescale agreeing well with the duration of momentum input found experimentally by Lockwood and co-workers. It is this momentum input which initiates plasma convection in the dayside polar ionosphere.

Dayside Birkeland currents arising from reconnection

Having identified the site of momentum input to the polar cusp ionosphere, let us now consider the source of this momentum input, namely the origin of the dayside Region 1 and cusp Birkeland current systems. The characteristics of these field-aligned currents for the northern polar regions are illustrated in Fig. 8 (also see Saunders (1989)). They occupy a crescent-shaped region near noon between roughly 0930 and 1430 magnetic local time and between about 76°–78° invariant latitude (Region 1 currents) and 78°–80° invariant latitude (cusp currents). Their polarities are always oppositely directed and their intensities increase as the IMF southward component increases (the cusp Birkeland current disappears when the IMF is directed northward). Both Birkeland currents lie on open magnetic field lines as evidenced by the Fig. 7 data example. The IMF east–west component B_Y has a strong influence over their directions and associated plasma flow. Indeed the boundary separating upward and downward flowing Birkeland currents shifts either side of noon depending on the polarity of IMF B_Y.

The recent paper by Saunders (1989) offers the most convincing model to date for the origin of these dayside Birkeland currents during southward IMF conditions, previous theories having been sketchy and incomplete. Saunders argues that these currents arise from the field bending accompanying the motion of reconnected open field lines as they shorten and convect over the dayside magnetopause (by 'shortening' I mean the straightening arising from the release of field tension at the sharp hairpin bend where a reconnected field line crosses the magnetopause). Initially these field lines have a significant east–west component to their motion due to the dominant effect of field tension. Later, as the field lines straighten, the magnetosheath flow gains in importance, and the field lines are pulled anti-sunward into the polar cap. Where the field lines change their direction of movement, the magnetic field must tilt and this tilting gives rise to the Region 1 and cusp Birkeland currents. This scenario may be visualised more easily by reference to Fig. 9 which illustrates just how the motion of reconnected field lines maps to the ionosphere.

Fig. 9 is a magnetic local time (MLT) versus invariant latitude (INV. LAT.) display giving the ionospheric plasma flow and Birkeland currents expected from the motion of reconnected field lines at the dayside magnetopause. The Figure is drawn for the Northern Hemisphere and for IMF B_Y positive conditions. There is clearly good agreement with the major reported characteristics shown in Fig. 8. The dotted region is the ionospheric projection of the reconnected field lines which are still shortening, that is, releasing the sharp field curvature created by reconnection. As described above, the net force on these field lines, at the point where they cross the magnetopause, has initially a large east–west component but curves to become anti-sunward where the field lines complete their shortening.

Associated with this plasma flow pattern are field-aligned current sheets which occur where the flow changes its direction of movement because there the magnetic field must tilt. When the change in flow direction (looking down in the Northern Hemisphere) is in a clockwise (anticlockwise) sense, the associated field tilting corresponds to an upward (downward) Birkeland current. Thus Region 1 currents are

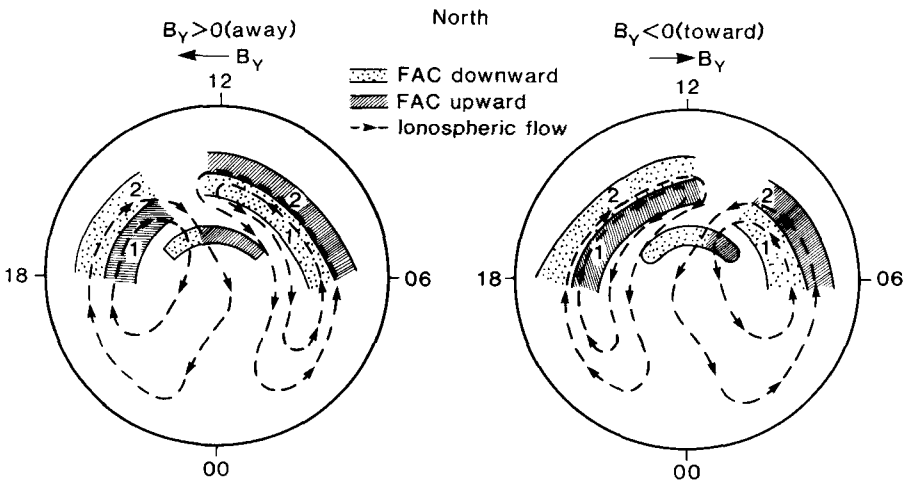


Fig. 8. Diagram showing the field-aligned current (FAC) and inferred average plasma transport patterns in the northern polar regions during intervals of positive and negative IMF B_Y. The cusp Birkeland current region is the area poleward of Regions 1 and 2 (after Potemra & Saflekos 1979).

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

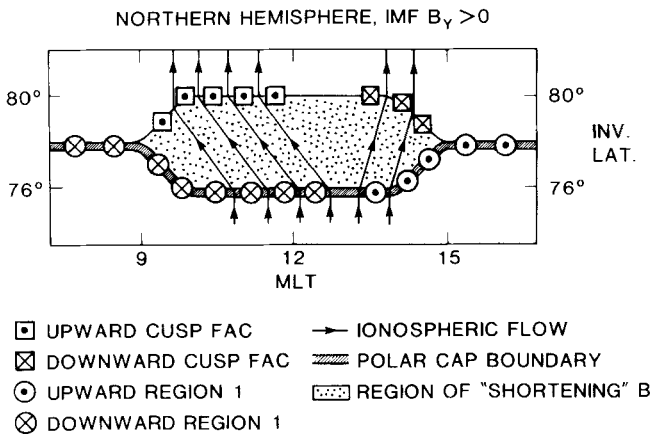


Fig. 9. Plasma flow and Birkeland current pattern in the vicinity of the northern polar cusp ionosphere expected from the motion of reconnected field lines shortening over the dayside magnetopause. Observed properties of the Region 1 and cusp Birkeland currents agree well with this picture (from Saunders 1989).

centred on the polar cap boundary, while the cusp Birkeland currents are found at the poleward edge of the region of shortening reconnected field lines. In practice these currents will be more widely distributed than indicated in Fig. 9 owing to the plasma flow streamlines being curved rather than straight as depicted.

Thus the source of the momentum input for dayside ionospheric plasma transport comes from the motion of reconnected open field lines shortening over the dayside magnetopause. This shortening time is typically 5–10 min. Due to the competing effects of field tension and magnetosheath flow, newly opened field lines bend as they shorten in the correct sense to produce the dayside Region 1 and cusp Birkeland currents.

The effect of solar wind dynamic pressure variations

The solar wind is non-uniform and changes in solar wind dynamic pressure ($P = \rho v_{sw}^2$, where ρ is the mass density and v_{sw} is the solar wind flow speed) occur, for example, accompanying interplanetary shocks. Such changes have been recognized for some time (Kaufmann & Konradi 1969) and are known to compress the magnetosphere and affect it globally but only recently has it become clear that they also produce disturbances in the polar cusp ionosphere (Friis-Christensen *et al.* 1988; Sibeck *et al.* 1989; Farrugia *et al.* 1989). Indeed it is possible that many of the dynamic effects reported to date in the high-latitude ionosphere, such as surges in plasma flow and magnetic impulses, could arise from variations in solar wind dynamic pressure rather than be the signature of transient reconnection (FTEs).

Sibeck *et al.* (1989) report that variations in P are more

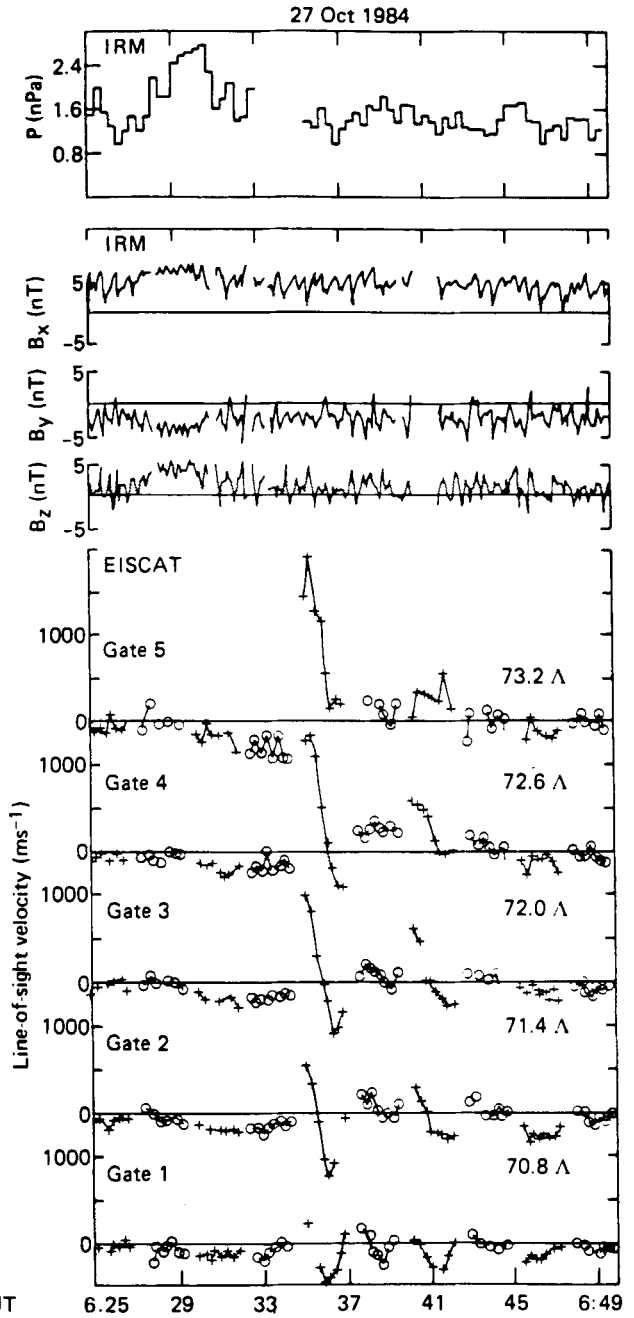


Fig. 10. Comparison of solar wind plasma and magnetometer data from the AMPTE-IRM satellite with simultaneous ionospheric plasma flow measurements from the EISCAT radar recorded at 0900 Local Time. The ionospheric flow surge at 0636 UT seems to be triggered by the solar wind dynamic pressure increase at 0628 UT (from Sibeck *et al.* 1989).

common than just associated with interplanetary shocks. Brief (~100 s), quasi-periodic (5–20 min repetition), large amplitude ($\Delta P/P \sim 1$) solar wind dynamic pressure variations often occur during intervals of near-radial IMF. They can drive bipolar magnetic field perturbations in the north–south

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

component (Sibeck *et al.* 1989; Farrugia *et al.* 1989) and a twin-vortex pattern in the ionospheric plasma flow (Friis-Christensen *et al.* 1988). Both of these are characteristics expected of the Southwood (1987) FTE model. Indeed Sibeck (1989) suggests that pressure pulses can explain many of the ionospheric phenomena previously associated with FTEs.

An example of a polar cusp ionosphere event at first widely interpreted as an FTE but where a solar wind dynamic pressure pulse now appears relevant, is shown in Fig. 10 (from Sibeck *et al.* 1989). This event was reported first by Todd *et al.* (1986) and their EISCAT data form the lower part of the figure. These show line-of-sight ionospheric plasma velocities measured by the Tromsö transmitter at invariant latitudes ranging from 70.8° to 73.2°. There is a striking flow burst at 0636 UT. The upper four panels in Fig. 10 display solar wind data from the AMPTE-IRM satellite. The top panel gives the solar wind dynamic pressure (nPa) and the components of the magnetic field are plotted below in GSE co-ordinates. A brief but clear P increase (50% above background) occurs at 0628 UT. The 8 min time lag between this pressure pulse and the plasma flow surge seen by EISCAT matches the expected time lag. Thus there seems little doubt that the flow surge is associated with the dynamic pressure increase. Further evidence that such flow bursts are probably not of reconnection origin is their similar occurrence probability during northward and southward IMF conditions (M. Lockwood, personal communication 1988).

Conclusions and key remaining questions

The value of the polar cusp ionosphere as a window for monitoring solar wind–magnetosphere coupling at the magnetopause has barely started to be explored. Early results highlight the relevance of magnetic reconnection in producing many of the region's features. These include the origin of the cusp and dayside Region 1 Birkeland current systems and the source of the momentum input which drives anti-sunward plasma transport in the dayside polar ionosphere. Changes in solar wind dynamic pressure also produce dramatic effects in the polar cusp ionosphere. Indeed during southward IMF conditions it seems difficult to distinguish such effects from those expected of time-varying reconnection.

Looking ahead, the polar cusp ionosphere must surely become a major focus for international space plasma research in the pre-CLUSTER era. Ground observations from the polar regions, notably Antarctica with its larger and more suitably located land mass, are certain to play a key role. Among the new experiments and research initiatives already underway or planned are the PACE and Spitzbergen polar cap radars and GEM. PACE (Polar Anglo-American Conjugate Experiment) consists of two coherent radars located at the conjugate sites of Halley Bay in Antarctica and Goose Bay in Labrador. These radars can measure horizontal plasma flows in the F-region ionosphere over the entire polar cusp with 90 s time resolution. The Spitzbergen polar cap radar is a sophisticated international experiment recommended for construction by 1995 to monitor the northern polar ionosphere at magnetic latitudes between 78° and 83°. It will extend the EISCAT viewing area polewards and also provide the high resolution observations necessary to study the dynamic processes I have been describing. GEM (Geospace Environment Modelling) is a major new research initiative due for implementation between 1990–1995, a key component of which will be the use of ground and low altitude observations for monitoring phenomena at the magnetopause. In this regard the conjugate stations of South Pole and Iqaluit (Northwest Territories) offer exciting prospects as they are both under the locus of the polar cusp ionosphere.

An important remaining question concerns the correct ionospheric signature of an FTE. This is crucial for our understanding of reconnection at the magnetopause. Despite much searching over the past four years, a definitive signature has not been found, though the recent auroral observations by Lockwood *et al.* (1989) and Sandholt *et al.* (in press) do appear promising. The quasi-periodicity in FTE occurrence (apparent in Fig. 4) is another outstanding problem whose solution must surely be central to understanding how FTEs are triggered at the magnetopause. Examining magnetosheath or solar wind data for variations in either the plasma β (ratio of the plasma pressure to the magnetic field pressure) or dynamic pressure during FTE occurrence would be a useful first step. The controversy over whether it is time-dependent reconnection (FTEs) or solar wind pressure pulses which are responsible for the plasma flow bursts in the polar cusp ionosphere requires further study. Two methods of distinguishing the relative importance of these two processes are first to quantify the presence of such flow bursts against IMF B_Z, and secondly to examine the simultaneous occurrence of events at the same local time in both hemispheres against IMF B_Y. If dynamic pressure is the primary effect, event occurrence will be independent of the sign of IMF B_Z, and IMF B_Y should exhibit no local time control over the presence of events in opposite hemispheres.

Field-aligned currents are another topic requiring further investigation. Examining statistics on the presence of the cusp Birkeland currents would provide a quantitative check on the occurrence of quasi-steady reconnection at the dayside magnetopause. In addition, information on the length of the reconnection X-line should come from monitoring the local time extent of the cusp Birkeland currents. We also wish to determine the role of ionospheric conductivity in affecting the initiation of dayside polar ionosphere plasma transport. The PACE radar is well situated to examine this question by comparing the timescale for plasma flows to decay following northward turnings of the IMF when one polar region is sunlit and the other is in darkness. Another open topic concerns the evolution of plasma flow bursts as they move through the polar cusp region and into the polar

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press

cap. These are some of the present questions in a fascinating and rapidly progressing subject.

Acknowledgements

This work was performed during the course of a Royal Society 1983 Research Fellowship. I wish to thank M. Lockwood, M.J. Rycroft and, especially, A.S. Rodger for their critical reading of the paper, N. Powell for help in preparing some of the figures and S. Escott for her efficient editorial assistance.

References

Berchem, J. & Russell, C.T. 1984. Flux transfer events on the dayside magnetopause:spatial distribution and controlling factors. *Journal of Geophysical Research*, **89**, 6689–6703.

Bythrow, P.F., Potemra, T.A., Erlandson, R.E., Zanetti, L.J. & Klumpar, D.M. 1988. Birkeland currents and charged particles in the high-latitude pre-noon region: a new interpretation. *Journal of Geophysical Research*, **93**, 9791–9803.

Candidi, M. & Meng, C.-I. 1988. Low-altitude observations of the conjugate polar cusps. *Journal of Geophysical Research*, **93**, 923–931.

Cowley, S.W.H. 1986. The impact of recent observations on theoretical understanding of solar wind-magnetosphere interactions. *Journal of Geomagnetism and Geoelectricity*, **38**, 1223–1256.

Dungey, J.W. 1961. Interplanetary field and the auroral zones. *Physical Review Letters*, **6**, 47–48.

Farrugia, C.J., Rijnbeek, R.P., Saunders, M.A., Southwood, D.J., Rodgers, D.J., Smith, M.F., Chaloner, C.P., Hall, D.S., Christiansen, P.J. & Woolliscroft, L.J.C. 1988. A multi-instrument study of flux transfer event structure. *Journal of Geophysical Research*, **93**, 14465–14478.

Farrugia, C.J., Freeman, M.P., Cowley, S.W.H., Southwood, D.J., Lockwood, M. & Etemadi, A. 1989. Pressure-driven magnetopause motions and attendant response on the ground. *Planetary and Space Science*, **37**, 589–608.

Freeman, M.P., Farrugia, C.J., Cowley, S.W.H. & Etemadi, A. In press. The response of dayside ionospheric convection to the Y component of the magnetosheath magnetic field: a case study. *Planetary and Space Science*.

Friis-Christensen, E., McHenry, M.A., Clauer, C.R. & Vennerstrom, S. 1988. Ionospheric traveling convection vortices observed near the polar cleft: a triggered response to sudden changes in the solar wind. *Geophysical Research Letters*, **15**, 253–256.

Holtet, J.A. & Egeland, A. [Eds] 1985. *The polar cusp*. Dordrecht: D.Reidel Publishing Company, 422 pp.

Kaufmann, R.L. & Konradi, A. 1969. Explorer 12 magnetopause observations: large-scale non-uniform motion. *Journal of Geophysical Research*, **74**, 3609–3627.

Lee, L.C. 1986. Magnetic flux transfer at the Earth's magnetopause. *In* Kamide, Y. & Slavin, J.A., *eds. Solar wind–magnetosphere coupling*. Tokyo: Terra Scientific, 297 pp.

Lee, L.C. & Fu, Z.F. 1985. A theory of magnetic flux transfer at the Earth's magnetopause. *Geophysical Research Letters*, **12**, 105–108.

Lockwood, M. & Cowley, S.W.H. 1988. Observations at the magnetopause and in the auroral ionosphere of momentum transfer from the solar wind. *Advances in Space Research*, **8** (9), 281–299.

Lockwood, M. & Freeman, M.P. 1989. Recent ionospheric observations relating to solar wind-magnetosphere coupling. *Philosophical Transactions of the Royal Society of London, A*, **328**, 93–105.

Lockwood, M., Sandholt, P.E. & Cowley, S.W.H. 1989. Dayside auroral activity and magnetic flux transfer from the solar wind. *Geophysical Research Letters*, **16**, 33–36.

Lockwood, M., Cowley, S.W.H. & Freeman, M.P. In press. The excitation of plasma convection in the high-latitude ionosphere. *Journal of Geophysical Research*.

Newell, P.T. & Meng, C.-I. 1988. The cusp and the cleft/boundary layer: low-altitude identification and statistical local time variation. *Journal of Geophysical Research*, **93**, 14549–14556.

Potemra, T.A. & Saflekos, N.A. 1979. Birkeland currents and the interplanetary magnetic field. *In* Battrick, B., *ed. Magnetospheric Boundary Layers*, Rep. ESA-148, Noordwijk, Netherlands, 193–198.

Rasmussen, C.E., Schunk, R.W. & Wickwar, V.B. 1988. A photochemical equilibrium model for ionospheric conductivity. *Journal of Geophysical Research*, **93**, 9831–9840.

Rijnbeek, R.P., Cowley, S.W.H., Southwood, D.J. & Russell, C.T. 1984. A survey of dayside flux transfer events observed by the ISEE 1 and 2 magnetometers. *Journal of Geophysical Research*, **89**, 786–800.

Russell, C.T. & Elphic, R.C. 1978. Initial ISEE magnetometer results: magnetopause observations. *Space Science Reviews*, **22**, 681–715.

Rycroft, M.J. 1985. A view of the upper atmosphere from Antarctica. *New Scientist*, **108**, 44–49.

Sandholt, P.E., Lockwood, M., Oguti, T., Cowley, S.W.H., Freeman, K.S.C., Lybekk, B., Egeland, A. & Willis, D.M. In press. Midday auroral breakup events and related energy and momentum transfer from the magnetosheath. *Journal of Geophysical Research*.

Saunders, M.A. 1983. Recent ISEE observations of the magnetopause and low latitude boundary layer: a review. *Journal of Geophysics*, **52**, 190–198.

Saunders, M.A. 1989. Origin of the cusp Birkeland currents. *Geophysical Research Letters*, **16**, 151–154.

Saunders, M.A., Russell, C.T. & Sckopke, N. 1984. Flux transfer events: scale size and interior structure. *Geophysical Research Letters*, **11**, 131–134.

Schield, M.A., Freeman, J.W. & Dessler, A.J. 1969. A source for field-aligned currents at auroral latitudes. *Journal of Geophysical Research*, **74**, 247–256.

Scholer, M. 1988. Magnetic flux transfer at the magnetopause based on single X-line bursty reconnection. *Geophysical Research Letters*, **15**, 291–294.

Sibeck, D.G. 1989. The significance of solar wind pressure pulses for magnetosphere dynamics (abstract). *Annales Geophysicae*, special issue for the XIV European Geophysical Society General Assembly in Barcelona, p. 38.

Sibeck, D.G., Baumjohann, W. & Lopez, R.E. 1989. Solar wind dynamic pressure variations and transient magnetospheric signatures. *Geophysical Research Letters*, **16**, 13–16.

Southwood, D.J. 1987. The ionospheric signature of flux transfer events. *Journal of Geophysical Research*, **92**, 3207–3213.

Southwood, D.J. & Hughes, W.J. 1983. Theory of hydromagnetic waves in the magnetosphere. *Space Science Reviews*, **35**, 301–366.

Southwood, D.J., Farrugia, C.J. & Saunders, M.A. 1988. What are flux transfer events? *Planetary and Space Science*, **36**, 503–508.

Todd, H., Bromage, B.J.I., Cowley, S.W.H., Lockwood, M., van Eyken, A.P. & Willis, D.M. 1986. EISCAT observations of bursts of rapid flow in the high latitude dayside ionosphere. *Geophysical Research Letters*, **13**, 909–912.

Vasyliunas, V.M. 1975. Concepts of magnetospheric convection. *In* Formisano, V., *ed. The magnetospheres of the Earth and Jupiter*. Dordrecht: D. Reidel, 179–185.

Vasyliunas, V.M. 1979. Interaction between the magnetospheric boundary layers and the ionosphere. *In* Battrick, B., *ed. Magnetospheric boundary layers*, Rep. ESA SP-148, Noordwijk, Netherlands: European Space Agency, 387–393.

Wenzel, K.-P., Domingo, V. & Schmidt, R. 1987. The solar-terrestrial science programme. *ESA Bulletin*, No. 50, 8–16.

https://doi.org/10.1017/S0954102089000313 Published online by Cambridge University Press