THE IONOSPHERIC SIGNATURE OF FLUX TRANSFER EVENTS

S.W.H. Cowley[1], M.P. Freeman[1], M. Lockwood[2], and M.F. Smith[3]

[1]Blackett Laboratory, Imperial College; [2]Rutherford Appleton Laboratory; [3]NASA Goddard Space Flight Center

ABSTRACT

We consider the effects at ionospheric heights which take place when transient reconnection events (i.e. flux transfer events (FTEs)) occur at the dayside magnetopause. We discuss the nature of the FTE-related ionospheric flows, the associated current systems, and the plasma precipitation. In particular, we outline the nature of the time-dependent cusp precipitation which occurs in this case, and compare expectations with those based on steady magnetopause reconnection.

Keywords: Flux transfer event, magnetopause, reconnection, cusp.

1. INTRODUCTION

The single most important factor governing the structure and dynamics of the Earth's magnetosphere and its internal plasma populations is the cyclic convective flow which is driven within it by its coupling with the solar wind (Refs. 1,2). A broad range of observations demonstrate that the primary coupling mechanism involved is magnetic reconnection, as originally suggested by Dungey (Ref. 3), with a secondary role being played by other "viscous" processes. The primary evidence consists of indirect inferences based on the dependence of magnetospheric fields and flows on the direction of the interplanetary magnetic field (IMF) (Refs. 4-9), direct *in situ* observations of reconnection-associated phenomena at the magnetopause (Refs. 10-16), and demonstrations of the "openness" of the polar cap magnetic flux via studies of the access of solar energetic particles (Ref. 17). Under some circumstances reconnection appears to occur as a quasi-steady phenomenon, both at the magnetopause and in the geomagnetic tail (Refs. 18-20). For much of the time, however, it occurs in a series of characteristic bursts, for reasons which remain largely unknown. Reconnection bursts in the tail are associated with magnetospheric substorms and their intensifications (Refs. 21-23), while bursts at the low-latitude magnetopause were first identified in HEOS-2 and ISEE-1 and -2 data by Haerendel et al. and Russell and Elphic (Refs. 24-26), and have been termed "flux transfer events" (FTEs). These latter bursts are recognized in *in situ* data from characteristic perturbations lasting 1-2 minutes in the magnetic field components both normal and transverse to the magnetopause on either side of the latter, and from the transport of magnetospheric and magnetosheath plasma populations which takes place across the magnetopause along the open field lines (Refs. 27-31). Statistical surveys show that the occurrence of FTEs at low and medium latitudes at the magnetopause is strongly modulated by the direction of the IMF. When the IMF is directed southward FTEs occur roughly every 8 minutes; they disappear almost entirely when the IMF points northwards (Refs. 32, 33). However, there is strong evidence that under the latter conditions reconnection instead occurs on open tail lobe flux tubes poleward of the cusp (Ref. 34), leading to characteristic "reversed" flows within the polar cap (Refs. 4, 35-40). Recent ground-based observations reported by Sandholt, and to be discussed further below, indicate that this reconnection may also be pulsed, with a repetition period of about 3 minutes (Ref. 41).

The occurrence of transient reconnection at the magnetopause must inevitably lead to related transient effects along the boundary field lines, down to ionospheric heights (Refs. 42, 43). The direct two-spacecraft observations of Saunders et al. show that at the magnetopause the characteristic dimension of the open FTE flux tubes in the direction normal to the magnetopause is several 1000 km (Ref. 44). If it is then assumed that the dimension in the transverse direction (and transverse to the magnetic field) is of similar magnitude, we expect a FTE to produce a roughly circular patch of new open flux, appended to the "old" polar cap, which is of order 100 km in radius at ionospheric heights (Ref. 45) (here we are simply using a ratio of ~ 30 to map lengths, based upon the ratio of field strengths (~ 1000), though we recognize that significant mapping distortions may occur near the magnetopause). The motion of this open tube relative to its surroundings will then generate a small-scale twin-vortical flow in the incompressible ionospheric medium together with an associated ionospheric and field-aligned current (FAC) system, as first discussed by Southwood (Refs. 46-48). The characteristic feature of the perturbation is that the flow and FAC pattern will propagate as a whole at the speed of the flow at the centre of the event (i.e. at the speed of the patch of new open flux). With overall dimensions of a few hundred km and ionospheric propagation speeds of perhaps ~ 2 km s^{-1}, the passage of such a system over a ground station would produce a rather characteristic magnetic field and flow perturbation lasting about 2 minutes. Observations show that short-period field and flow pulses exhibiting twin-vortical form do indeed occur in the

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high-latitude dayside ionosphere, but subsequent analyses have demonstrated that these have characteristics at variance with expectations based on the FTE picture outlined above (Refs. 49-54). Specifically, while the flow near the centre of these events typically has a value of a few hundred m s^{-1} north-south, the vortices themselves propagate mainly east-west at several km s^{-1}. This signature is instead indicative of excitation by rapid dynamic pressure variations in the solar wind (Refs. 55-59). Subsequently, however, it has been suggested by Southwood et al. and Scholer that the scale size of the FTE reconnection region on the magnetopause may be considerably larger than that assumed above (Refs. 60, 61), leading to the production of a patch of new open flux at ionospheric heights which may be of similar latitudinal extent to that considered above (100-200 km), but which is considerably extended in longitude (Ref. 59). Simple considerations indicate that the length of the magnetopause X-line for transient reconnection should be limited to the duration of the event (~ 2 minutes for FTEs) times the magnetopause information propagation speed (few 100 km s^{-1}). On this basis we may thus expect magnetopause X-line dimensions of ~ 5 R_E, corresponding to a longitudinal dimension of ~ 1000 km in the ionosphere. At cusp latitudes (~ 75°) this corresponds to about 2 hours of MLT. The prime purpose of this paper is to outline the ionospheric effects which follow from the formation of such an elongated patch of new open flux. However, in order to provide context, we begin by first outlining the structure of the dayside ionospheric flows, currents and precipitation patterns which will occur under conditions of steady reconnection.

2. THE DAYSIDE IONOSPHERE FOR STEADY RECONNECTION

In Figure (1) we sketch the conditions which occur in the northern high-latitude dayside ionosphere when steady reconnection occurs between closed terrestrial flux tubes and the interplanetary magnetic field. (We also assume a steady balancing nightside reconnection rate such that the open-closed field line boundary is stationary.) Sketch (a) corresponds to the (approximately) symmetrical configuration for a purely southward-directed IMF, while sketch (b) illustrates the dawn-dusk asymmetries introduced by the y-component of the IMF, specifically for IMF B_y positive. The heavy dashed line is the boundary between open and closed magnetic flux; the plasma streamlines (heavy solid lines) cross this boundary in that portion which maps to the dayside reconnection region. (We note, however, that in the more general case where the nightside and dayside reconnection rates are not in balance, the open-closed field line boundary will be in motion as the amount of open flux changes. The plasma streamlines will then cross the boundary at essentially all local times, though the plasma itself will only cross the boundary in those regions mapping to the neutral lines. Elsewhere the boundary moves with the plasma flow, as described in Refs. 62, 82, 84.) Overall the plasma flow is of twin-vortical form, but the flow reversal boundary does not in general coincide with the open-closed field line boundary due to the presence of anti-sunward flowing closed boundary layer flux tubes adjacent to the magnetopause, driven by the "viscous" coupling process. The principal pattern of field-aligned currents (FAC) are shown by the circled symbols, circled dots representing current flow out of the ionosphere, and circled crosses current flow in. For an approximately uniformly-conducting ionosphere the FACs predominantly represent the closure currents of the ionospheric Pedersen system, and are given by the divergence of the latter currents, or equivalently by the curl of the plasma velocity. They are directly associated with the communication of energy and momentum between the magnetosphere and ionosphere

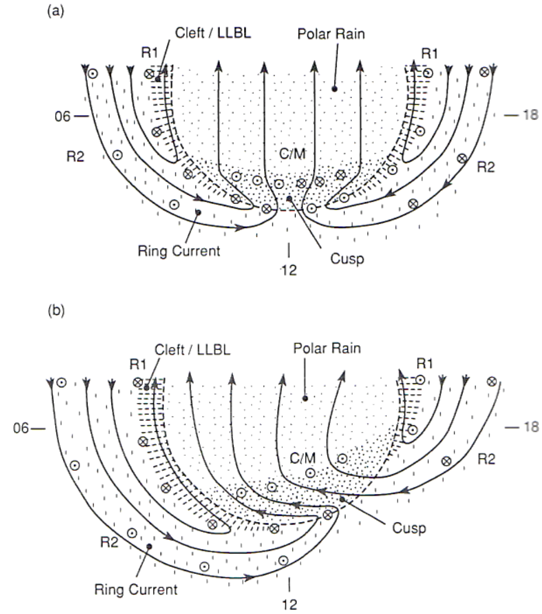

Figure (1): Sketch of the dayside high-latitude ionosphere in the northern hemisphere, showing the flows, FAC and precipitation regions for steady balanced reconnection at the dayside and in the tail. Sketch (a) is for IMF B_z negative and B_y zero, while (b) is for IMF B_z negative and B_y positive. The heavy dashed line shows the open-closed field line boundary, the solid lines the plasma streamlines, the circled dots the upward-directed FAC, and the circled crosses the downward-directed FAC. The vertical dashes indicate precipitation from the ring-current region, the dots magnetosheath precipitation on open field lines (the cusp and polar rain), while the radial dashed lines indicate the "cleft" precipitation from the closed field line boundary layers.

(Ref. 63). Three FAC components are shown (Refs. 64, 65), the "Region 2" (R2) currents lying in the equatorward portion of the closed-field line flow, the "Region 1" (R1) currents centred on the flow reversal boundary, and the "cusp/mantle" (C/M) currents located within the dayside region of open flux, as will be discussed further below. There are also three principal zones of precipitation. The main part of the region of closed field lines at lower latitudes maps to the outer radiation zone or ring current region, and is characterised by the precipitation of particles at ~ 1 to 100 keV energies (vertical dashes in Figure (1)). The additional presence of low energy (~ 100 eV to ~ 1 keV) plasma precipitating in the anti-sunward flowing closed field line boundary layers adjacent to the magnetopause is indicated by the dashed lines drawn radially equatorward from the open-closed field line boundary. This plasma, termed the "cleft" precipitation, is of magnetosheath origin, but has a somewhat higher temperature and lower density than that of the "cusp" precipitation on open field lines (dots), reflecting a similar property of the plasma in the low-latitude boundary layer (Ref. 66). We have shown no cleft precipitation in the region equatorward of the open-closed field line boundary which maps to the reconnection region (where the streamlines cross the boundary). Particles could in principle be scattered onto adjacent closed field lines in this region from the reconnection-associated boundary layers of magnetosheath plasma inside the magnetosphere, but they would subsequently be rapidly swept back into the boundary by the reconnection-associated convection. Magnetosheath plasma also precipitates into the region of open field lines, as shown by the dots in the figure. This precipitation is at its most intense in a latitudinally narrow strip just poleward of the dayside open-closed field line boundary (the "cusp"), before continuously declining to a weak structureless drizzle of low-energy plasma precipitation in the central polar cap termed the "polar rain". We will now discuss the behaviour of the flow, currents and precipitation in this region in more detail.

Following reconnection at the low-latitude magnetopause, the evolution of an open flux tube over the dayside magnetopause and into the tail, although in principle continuous, can be divided into two main phases. The first corresponds to its evolution over the dayside magnetopause when the magnetopause intersection point lies sunward of the magnetopause cusp. During this phase the distended loops of open flux contract north-south away from the reconnection site under the influence of the field tension and the north-south flow of the magnetosheath away from the subsolar region, liberating energy to the magnetosheath plasma that crosses the magnetopause as they do so. However, the open field lines are also pulled azimuthally around the dayside boundary by the combined action of the field tension and the east-west component of the magnetosheath flow (Refs. 15, 67, 68), leading to similar azimuthal motions in the ionosphere just poleward of the mapped reconnection site (i.e. in the cusp). The "sideways" pull on the newly opened flux tubes is communicated to the ionosphere by an Alfvenic disturbance which propagates from the magnetopause, and which carries the cusp "Region 1" FAC. (A similar disturbance is also propagated out into the magnetosheath). In the case of a purely southward-directed IMF, the azimuthal flow is related only to the flow of the magnetosheath plasma, so that the open tubes are carried approximately symmetrically away from noon as shown in Figure (1a). When IMF B_y is present, however, the east-west field tension effect (Refs. 69-70) dominates near to noon where the magnetosheath flow is sub-Alfvenic, carrying the open flux tubes predominantly towards either dawn or dusk depending on the sense of B_y (to dawn in Figure (1b) for the northern hemisphere with B_y positive). However, once the open tubes move past the magnetopause cusp they start to become stretched out down the tail (now decelerating the magnetosheath as they do so), so that the azimuthal motion in the ionosphere gives way to a predominant antisunward flow over the polar cap. This change is also communicated to the ionosphere by an Alfvenic disturbance propagating from the magnetopause, which now carries the "cusp/mantle" FAC as first discussed by Saunders (Ref. 71). With this physical interpretation, the term "cusp/mantle" (C/M) FAC is appropriate because these currents lie at the boundary between those open field lines which map to the dayside magnetopause sunwards of the magnetopause cusp, and those which map to the tail i.e. the mantle (ignoring for simplicity the ~ 1 minute shift due to the finite Alfven-wave propagation time from the cusp magnetopause to the ionosphere). For a purely southward-directed IMF these C/M FAC will thus be approximately antisymmetric about noon with an opposite sense to the adjacent R1 currents at a lower latitude (Figure (1a)), while in the presence of IMF B_y they will have a predominant sign (Figure (1b)), which may, however, reverse for weak B_y due to the action of the magnetosheath flow (not shown in the figure). This qualitative picture is in good agreement with observations (Ref. 65).

The system of flows and currents on newly opened dayside flux tubes is also directly related to the magnetosheath plasma precipitation characteristics. Once a field line becomes open due to reconnection at the magnetopause it provides a direct magnetic pathway for the access of magnetosheath plasma to the ionosphere, though the plasma properties will in general be somewhat modified as it crosses the magnetopause due to the action of the field tension and scattering in the current layer. On the dayside the plasma which crosses the magnetopause flows along the reconnected field lines towards the ionosphere and precipitates in the cusp region. However, due to the finite time-of-flight of the precipitating particles those with higher field-aligned speeds will reach the ionosphere before those of lower speed, leading to velocity dispersion along the cusp streamlines with higher energies being found closer to the open-closed field line boundary (Ref. 72). More precisely, there will exist a pitch-angle dependent lower cut-off to the precipitating particle distributions, with the cut-off falling in energy with distance along the streamlines from the boundary. Above the cut-off the particle distribution function will represent that of the transmitted magnetosheath source, though this will be somewhat complicated by the changing source conditions as the open tubes evolve over the magnetopause, due both to the changing properties of the magnetosheath plasma itself and the changing magnetopause current sheet configuration. The cut-off also depends on pitch angle, being at the lowest energy for field-aligned particles, and increasing with increasing pitch angle. This effect is not important at low altitudes, but gives rise to a characteristic "V" signature in particle spectrograms from the mid-altitude cusp as a detector scans in pitch-angle through the field-aligned direction (Ref. 73, 74). However, the point we wish to emphasize here is that once the open flux tubes move past the magnetopause cusp into the tail the supply of magnetosheath plasma to the ionosphere is largely shut off. Magnetosheath plasma will still cross the magnetopause current sheet onto open field lines, but will then continue to move down-tail away from the Earth forming a contribution to the plasma mantle population. Only Earthward-moving ions will move towards the ionosphere from this region, and since the flow is strongly supersonic their numbers are very few indeed. Consequently, poleward of the cusp the precipitation declines continuously but rapidly to a weak drizzle (the "polar rain"). This decline should be colocated with the C/M currents, since both are associated with the evolution of the open flux tubes from the dayside magnetopause into the tail.

The final point we wish to make here concerns the dawn-dusk IMF B_y-associated asymmetries shown in Figure (1b). We have already mentioned above the flow asymmetry which occurs in the cusp region in this case, due to the field tension effect on open flux tubes. However, additional asymmetries also occur which involve both open and closed field lines. The first is the shift in the local time of flow entry into the polar cap, which together with the flow asymmetry on open cusp field lines gives rise to further local time and latitudinal asymmetries in cusp precipitation (Refs. 75, 76). The second is the dawn-dusk shift of the open-closed field line boundary, to dawn in the case shown (northern hemisphere for B_y positive) (Ref. 77). These effects are associated with a distortion of the magnetospheric magnetic field, caused by the stresses exterted upon it by its connection to the IMF, which in effect allow a partial penetration of the IMF B_y component into the open and the closed field line region (Refs. 78-81).

3. EFFECTS OF TRANSIENT RECONNECTION

With the above discussion forming an extended introduction, we can now turn to the case of transient reconnection at the magnetopause, and compare expectations with those based on steady-state considerations. Initially we will take the opposite extreme condition to the above, and will consider the case of an instantaneous reconnection impulse (i.e. an instantaneous FTE). An appropriate theoretical framework for this discussion has been introduced by Cowley and Lockwood (Ref. 82), following earlier related work by Freeman and Southwood (Ref. 83). Cowley and Lockwood begin by considering the possibility of a zero-flow (apart from corotation), zero precipitation magnetosphere which nevertheless contains a finite (arbitrary) quantity of open magnetic flux. This state would be that achieved if all tangential drag at the magnetopause and all reconnection in the tail were switched off for a long time. In this state the magnetosphere is held in equilibrium by the normal stress exerted by the solar wind, with an open tail stretching essentially to infinity. We emphasize that this state represents an idealization which is never achieved in practice (due e.g. to viscous magnetopause drag, magnetopause reconnection occurring at some point on the boundary under essentially all conditions, low-level continuous tail reconnection needed to maintain the cross-tail current etc.), but it is an important theoretical concept since it represents an equilibrium system which we can perturb by a reconnection impulse to excite flow, and to which the system will then subsequently decay, but with a changed amount of open flux.

We illustrate the point by reference to Figure (2). This figure shows idealized views of the high-latitude ionosphere, with sketch (a) showing the initial zero-flow equilibrium with open flux F. A dayside reconnection impulse then instantaneously creates new open flux dF, which is initially appended to the noon border of the pre-existing region of open flux, as shown in sketch (b). The new equilibrium boundary for flux F+dF is

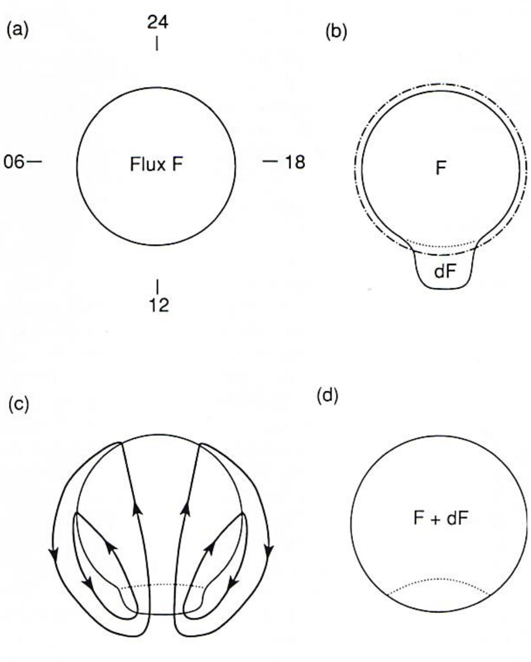

Figure (2): Sketch illustrating the response to an impulse of dayside reconnection: (a) initial zero-flow equilibrium with open flux F; (b) perturbed boundary (solid line) following the impulse, together with the new zero-flow equilibrium boundary (dot-dash line) which contains the same amount of open flux F+dF; (c) form of the flow which takes the perturbed system towards the new zero equilibrium configuration; (d) new zero-flow equilibrium with flux F+dF, the dotted line indicates the location of the open flux created during the impulse.

shown by the dot-dash line in sketch (b), and the displacement between the actual open boundary (solid line) and the equilibrium boundary for the same amount of open flux represents the potential which is in the system for flow. The flow which then occurs is shown in sketch (c), which takes the actual boundary towards the new equilibrium configuration (here we are assuming a southward-directed IMF, with no B_y effect). When that is achieved the flow will then stop until a further reconnection event occurs at the dayside (or in the tail). The new open flux will then be located in the polar cap just poleward of the position where it was created, as shown by the dotted line in sketch (d).

The picture presented here emphasizes the point that it is not the existence of open flux, as such, that excites flow in the magnetosphere, but rather the creation of open flux at the magnetopause or the destruction of open flux in the tail. These processes alter the magnetospheric boundary conditions (i.e. the amount and distribution of open and closed magnetic flux in the system) and excite flow until a new equilibrium is achieved. The flow produced by the dayside impulse shown in Figure (2c) is essentially similar to that for steady unbalanced dayside reconnection presented previously by Siscoe and Huang (Ref. 84), but here generalized to the time-dependent case. The time-scale for the excitation and decay of the flow depends upon two factors. The first is the time scale for the boundary conditions to fully change following the reconnection impulse i.e. the evolution time of open flux tubes from the dayside magnetopause to a few 10's of R_E down-tail (the subsequent further evolution of the flux tubes down the tail does not alter the near-Earth field configuration and is consequently not germane to the excitation of near-Earth flow). This time scale is ~ 10 minutes. The second factor is the time taken by the near-Earth system to respond to the change in those boundary conditions, involving e.g. information propagation throughout the near-Earth system at speeds of order a few hundred km s^{-1}. This time scale (largely concurrent with that above) is again around 10 minutes. Thus, overall, we expect the flow to be excited and to decay on time scales of ~ 10-15 minutes. The flow shown in Figure (2c) represents the fully developed pattern at its peak. Initially, of course, we would expect the flow pattern to be localized near the patch of new open flux, and from thence to expand outwards over the polar cap as the effect of the reconnection impulse is communicated through the system. Indeed, the initial motion of the patch may be to extend in azimuth around the boundary away from noon (and simultaneously to narrow in latitude), due to the flow of the magnetosheath plasma away from noon, as discussed previously in relation to Figure (1a). This will be discussed further below. Overall, the phase speed of the expansion of the flow pattern in the ionosphere is readily estimated by dividing the size of the overall flow system (~ 3000 km at ionospheric heights), by the ~ 10 minute development time. This speed is ~ 5 km s^{-1}.

We may also discuss the structure of the cusp precipitation which occurs in this case, following the earlier discussions in Refs. 74, 85-90. Since we are assuming that the patch of new open flux is created in an instant of time, no spatial velocity dispersion of the precipitating cusp plasma will occur across the patch, in contrast to the steady-state case discussed above. Instead the lower cut-off energy of the precipitating particles will continuously decrease with time uniformly over the patch. The magnetosheath source then switches off when the open flux tubes pass into the tail, after which the flow will also begin to decay. The evolution of the precipitation will thus roughly follow the evolution of the flow, with the precipitating flux falling to background levels by the time that the flow has died away. We also note that the formation of the new open patch

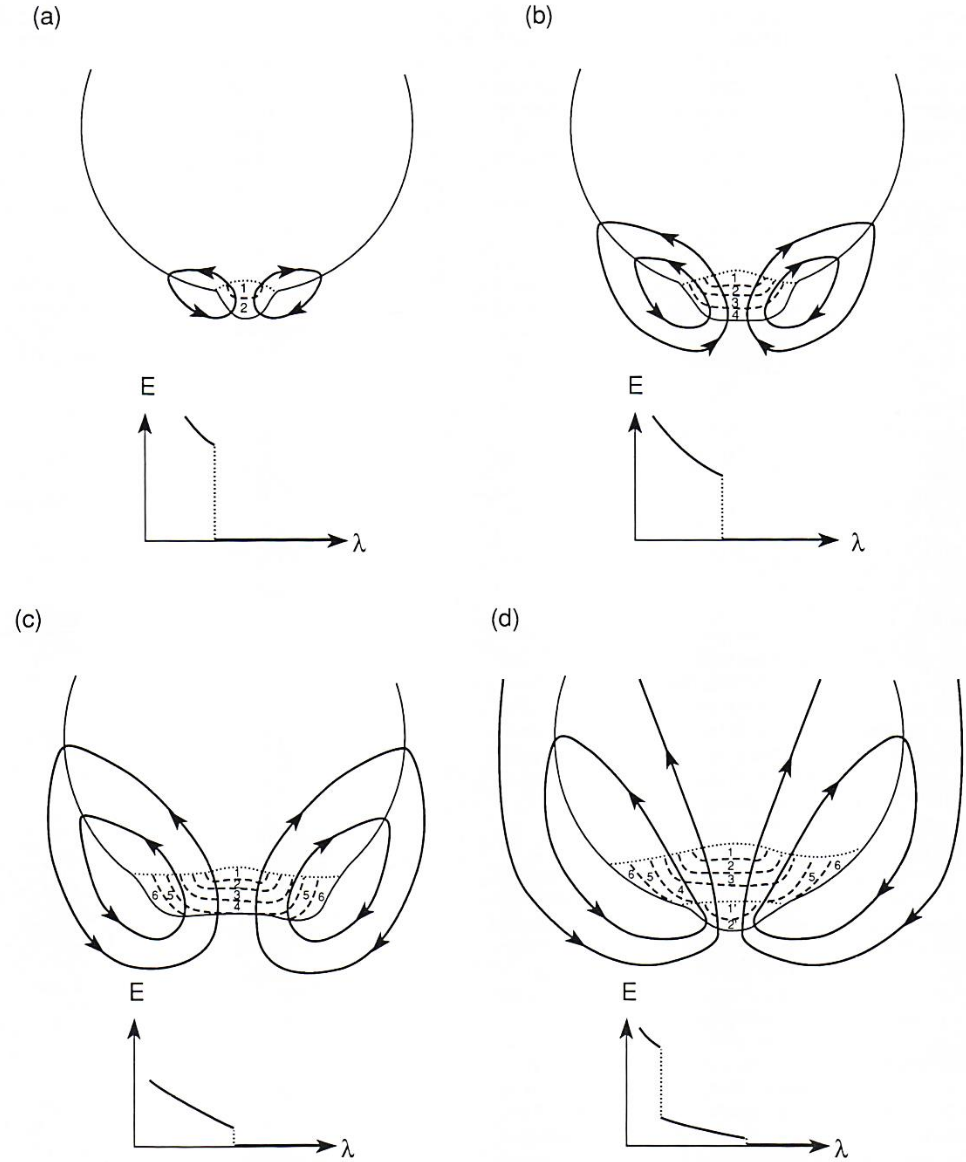

Figure (3): Sketches (a) to (c) show the evolution of a FTE-produced patch of open flux and its associated flow, starting from a zero-flow equilibrium and for IMF B_y zero. The dashed lines indicate field lines reconnected at the same instant (separated by roughly 30 s) and which thus possess similar cusp precipitation dispersion characteristics (for approximately equal field line lengths to the magnetopause). The graphs below each diagram show schematically the cusp lower cut-off energy versus latitude along the noon meridian. Sketch (d) shows the fully developed flow ~ 8 minutes after sketch (a), together with a second FTE patch forming near noon, giving rise to a characteristic "stepped" cusp.

will locally erode or destroy any pre-existing cleft precipitation layer which lies adjacent to the formation region, though the cleft may subsequently re-form equatorward of the patch after the reconnection has ceased.

The assumption of an instantaneous reconnection impulse is, of course, an idealization. Observations discussed in Section (1) indicate that for a FTE the burst of reconnection takes place over an interval of ~ 2 minutes, and is followed typically by a ~ 6 minute period in which reconnection is much reduced or absent. It is notable, however, that both these intervals are significantly less than the 10-15 minute time scale for the excitation and decay of flow which is produced by the impulse, as discussed above. In Figure (3a) to (3c) we show the development of the patch of open flux produced by the FTE over the first few minutes, together with the associated flow. We assume that we start from an initial zero-flow equilibrium, and that the IMF is directed southward with no B_y. We further assume that the FTE reconnection starts near to noon and expands in local time over the magnetopause, before declining after a couple of minutes, again first at noon and then expanding over the magnetopause. The ionospheric effect of this assumed behaviour is indicated in the sketch by the series of numbered dashed lines which show the locus of field lines reconnected at the same time, roughly 30 s apart. As indicated in the introduction, the patch is expected to grow to a longitudinal length of ~ 1000 km and a latitudinal width of ~ 200 km during the interval shown. The corresponding east-west expansion speed of the patch is ~ 3 km s^{-1}, comparable with the expansion phase speed of the flow pattern as a whole, as indicated in the sketch. During this early interval we also expect that the flow within the patch will exhibit a strong longitudinal component away from noon caused by the magnetosheath flow, as previously discussed. This effect will also cause the patch to elongate around the boundary away from noon.

The graph beneath each of Figures (3a) to (3c) then shows schematically the variation with latitude of the zero-degree pitch angle low-energy cut-off of the cusp precipitation along the noon meridian. In this case the cut-off falls with increasing latitude across the patch while also falling in time at a given position within the patch. The spatial dispersion across the patch results solely from the finite time over which the reconnection which formed the patch took place, and to a first approximation is independent of the motion of the patch in the ionosphere.

Figure (3d) then shows the situation after a further ~ 6 minutes. The flow excited by the above FTE is now at its maximum epoch and extends over essentially the whole of the polar cap. At the same time a new FTE is forming near to noon and is affecting the flow in its vicinity. The cusp precipitation correspondingly shows a distinctive "stepped" appearance, reflecting the history of reconnection over the previous ~ 10 minute period (Ref. 90). An observed cusp which exhibits just such properties, and which was previously interpreted as a FTE, may be found in the work of Lockwood and Smith (Ref. 85). (Note, however, that if reconnection remains small but non-zero between FTEs, the dotted "steps" in the figure would be resolved into steeply falling ramps.) After a further ~ 10 minutes the first FTE will be inactive in exciting flow (the open tubes at the magnetopause will be approximately at the lunar distance), while the flow excited by the second will be starting to decline from its maximum epoch, and a third FTE will typically be forming. We thus resolve an apparent contradiction between observations at the magnetopause, which show that for southward IMF reconnection often occurs in ~ 2 minute pulses every ~ 8 minutes, and observations in the ionosphere, which show an essentially continuous flow which appears to be strongly and directly modulated by the north-south component of the IMF (Refs. 9, 91). The key point is that each FTE excites flow for a significantly longer interval (10-15 minutes) than the mean time between FTEs (~ 8 minutes). Thus at any one time the flow will be maintained by one or two "active" FTEs. We would nevertheless expect that the dayside flow should contain ~ 8 minute fluctuations which reflect its FTE origin. Similarly, the magnetosheath cusp precipitation from a given FTE will also last for intervals somewhat greater than the mean repetition time, such that a cusp will always be present on open dayside flux tubes (for southward IMF). Thus the continuous existence of the cusp is not incompatible with a FTE origin, as recently suggested by Smith and Lockwood (Refs. 89, 90). Nevertheless, it should often exhibit one or two dispersion "steps" as shown in Figure (3), reflecting the pulsed nature of the reconnection formation process.

In Figure (4) we sketch the evolution of the flow which takes place for an isolated reconnection impulse in the more general case in which the IMF has a significant B_y component; we take B_y to be positive and sketch the effects in the northern hemisphere. Sketch (a) shows the initial phase during and after the formation of the patch of new open flux, in which the open tubes map to the dayside magnetopause. We have shown the patch to be formed in the post-noon sector even though the reconnection at the magnetopause is assumed to be centred at noon; this results from the distortion of the interior magnetic field which occurs under these conditions as discussed previously in relation to Figure (1b). The most significant dynamical effect during this period is the "sideways" pull on the open tubes resulting from the B_y component, such that in the northern hemisphere they move predominantly westwards (for IMF B_y positive). This motion may last typically for ~ 8 minutes from the initiation of the FTE, so that with east-west ionospheric flow speeds of ~ 3 km s^{-1} (Refs. 96-98) the patch will move in longitude a distance comparable with its length during this period. The flow excited in the incompressible ionospheric medium will be of twin-vortical form as shown, a flow which is qualitatively similar to, but

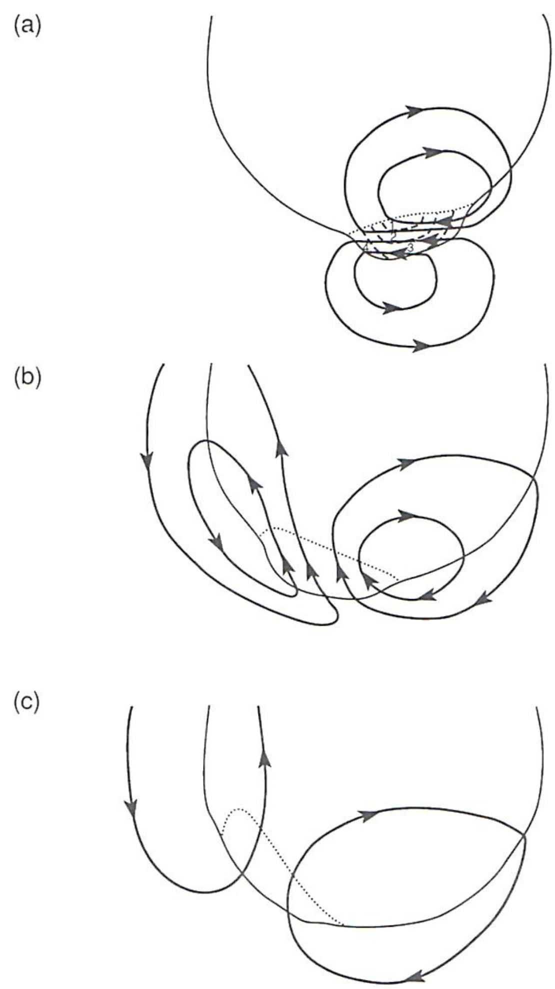

Figure (4): Sketches showing the evolution of the northern hemisphere flow for a reconnection impulse (FTE) when B_y is positive. Sketch (a) shows the initial phase with a predominant azimuthal motion of the patch of new open flux around the polar cap boundary, depending on the sense of B_y, the dashed lines indicate field lines reconnected at the same time and hence also the sense of the cusp velocity dispersion; sketch (b) shows the second phase when the flow within the patch becomes predominantly poleward, and (c) shows the decay phase.

quantitatively different from, that suggested by Southwood (Ref. 47). The point is that the main "return" flows excited around the FTE patch will be spread over a transverse distance comparable with the length of the patch in its direction of motion (Refs. 59, 92). For a circular patch, therefore, the exterior flows will be comparable with those within the patch itself, while for an elongated patch moving along its length, as shown, the exterior flow will be considerably weaker than that in the interior, approximately by the ratio of its width to its length. The principle effect during this phase, therefore, will be the formation of an "electrojet" flow near the polar cap boundary whose direction is determined by IMF B_y, and which moves around the boundary poleward of the pre-existing cleft precipitation (see Figure (1b)), though again the cleft will be locally eroded or destroyed in the FTE formation region. Spatially and temporally dispersed cusp precipitation will occur within the patch itself. The patch will also be associated with sheets of FAC along its northern and southern borders, the sense of which will be the same as for the steady-state case under similar IMF conditions (Figure (1b)). The FAC at the northern border corresponds to the steady-state "cusp/mantle" current, while that at the southern border corresponds to the "region 1" current (Ref. 89).

After ~ 8 minutes all the "new" open field lines have evolved into the tail and the predominant east-west flow declines to become mainly poleward, as shown in Figure (4b). At essentially the same time the magnetosheath source for the cusp precipitation is largely switched off, so that the precipitation declines over the next several minutes. Figure (4c) shows the patch and the flow during a late phase of the decay (after ~ 15 minutes), when the system has almost returned to its equilibrium configuration and the cusp precipitation has ceased. However, as we pointed out above, if the IMF remains southwards during this interval we would instead expect a new patch to start to form in the east well before this happens (essentially concurrently with sketch (b)). In this case, therefore, the overall flow would not decay away as shown, but would instead be maintained in a configuration which is not dissimilar to the steady-state case shown in Figure (1b) (see also section (4) of Ref. 93).

Finally, we noted in the introduction the possibility that pulsed reconnection may also occur between a northward-directed IMF and the open tail lobe flux, based on the observations of Sandholt (Ref. 41). Such a process does not involve a change in the amount of open flux in the system (if only one lobe is involved in the reconnection), but the overall effect is to "stir" the open flux around in the polar cap in a sense dependent on B_y. Figure (5) shows a sketch of the northern hemisphere flow which will occur in this case, in the presence of a positive IMF B_y. In the initial phase shown in sketch (a) the reconnected tubes are pulled azimuthally by the tension associated with B_y, while also being pulled sunwards. The flow is not dissimilar to that shown in Figure (4a) for the initial phase of reconnection with a southward IMF and the same sense of B_y, except that the sense of north-south motion is reversed. The spatial dispersion of the cusp plasma across the newly reconnected patch is also reversed, as indicated by the numbered dashed lines. The low-energy cut-off is at higher energies at the poleward edge of the patch, and falls towards the equator. In addition, the pre-existing cleft precipitation will not be eroded or destroyed in the process, but will instead be displaced with the motion of the patch. The decay phase of the motion is shown in sketch (b), where the newly-reconnected tubes are being carried down-tail once more, so that the ionospheric patch moves back poleward towards the equilibrium configuration.

4. RELEVANT IONOSPHERIC OBSERVATIONS

Although, as indicated in the introduction, there have been many attempts to identify FTE signatures in ionospheric data, the only observed phenomenon described to date which clearly relates to the above theoretical discussion is the "dayside auroral breakup" which has been discussed by Sandholt and co-workers (Refs. 94-99). In these "breakup" events a new patch of cusp precipitation is formed which is elongated in local time around the boundary. This patch then moves in azimuth along the boundary in a sense dependent on IMF B_y, before moving poleward and then fading. Radar data have shown that these auroral motions do indeed reflect the simultaneous motion of the ionospheric plasma (Refs. 59, 96). The relationship between such a sequence of events and the sketches in Figures (3) and (4) should be obvious. Furthermore, these features are typical of intervals of southward IMF, and recur on ~ 8 minute time scales under such conditions (Refs. 97, 99).

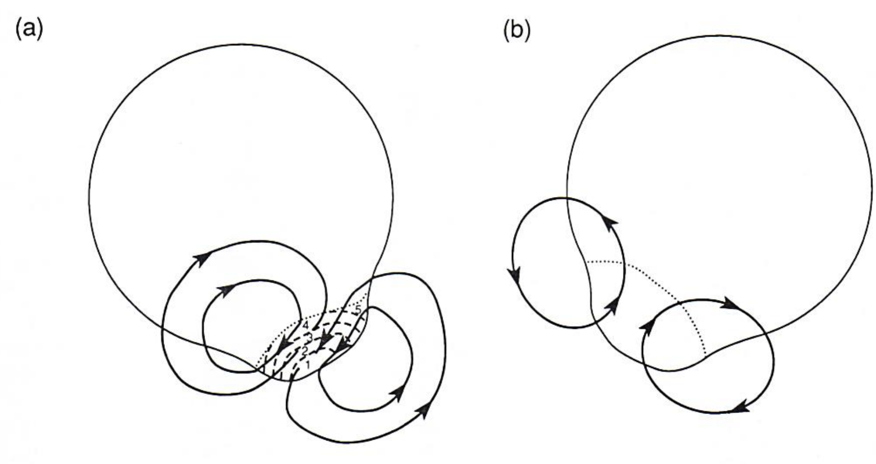

Figure (5): Sketch showing the development of flow in the northern hemisphere for lobe reconnection with a northward IMF and B_y positive. Sketch (a) shows the initial phase, where the dashed lines show field lines reconnected at the same time and hence the sense of the velocity dispersion (the sense is opposite to that in Figure (4a)). Sketch (b) illustrates the decay phase of the flow.

To date, however, there has been only one reported simultaneous observation of dayside auroral breakups in the ionosphere and flux transfer events at the magnetopause, by Elphic and co-workers (Ref. 100). Figure (6) provides an overview of part of the data set, obtained by the ISEE-2 spacecraft and the EISCAT radar. The top panel shows the ISEE-2 magnetic field data over a 1.5 hour period on 1 Dec 1986. The spacecraft was inbound in the northern hemisphere in the post-noon sector, and crossed into the magnetosphere at 0926 UT where B_L (the northward field component tangential to the magnetopause) changed from negative in the magnetosheath to positive in the magnetosphere. Two clear magnetosheath FTEs are observed in B_N (the outward field normal to the magnetopause) at 0845 and 0904 UT. The northward and eastward components of the radar velocities are shown in the bottom panel, determined by beam-swinging. The local time of the observations is near noon (UT plus 2.5 hours), and span the latitude range from 71^o (gate 1) to 73^o (gate 4). It can be seen that the two FTEs are accompanied by a ~ 10 minute burst of westward flow in the ionosphere (magnetosheath B_y is positive throughout), followed by a period of enhanced northward flow. These events are also accompanied by a "breakup" in the dayside cusp aurora (not shown). To date this data represents the best available observational evidence for FTEs at the magnetopause and simultaneous perturbations in flow and precipitation at ionospheric heights.

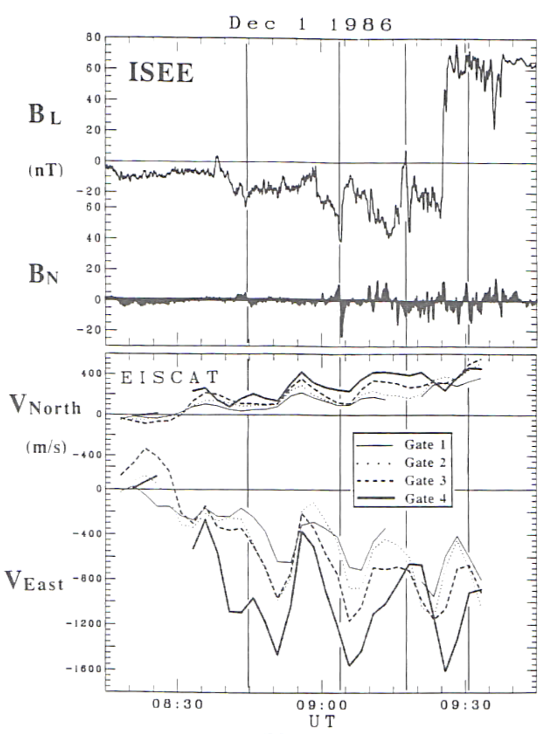

Figure (6): Simultaneous magnetic field data from the ISEE-2 spacecraft near the magnetopause and cusp ionosphere flow observations by the EISCAT radar, showing the simultaneous presence of FTEs and bursts of ionospheric flow. [From Elphic et al., 1990].

Although promising, these data clearly represent only a start on the experimental study of the ionospheric consequences of magnetopause reconnection-associated coupling phenomena. Further progress must await an extended and properly coordinated programme of space- and ground-based observations such as the Cluster spacecraft and the EISCAT Svalbard Radar will provide. One lesson is, however, very clear. In order to study these phenomena the radar experiment cycle times must be short. The signatures of FTEs in the ionosphere begin and end within ~ 10 minutes; thus to study them the resolution of the radar data must be better than a minute or two.

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