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THE PULSATING CUSP

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Abstract. Recent observations at the magnetopause and of the high-latitude ionosphere, suggest that the cusp may be pulsed in nature. Specifically ground-based observations in the dayside auroral oval reveal transient optical features accompanied by bursts of enhanced plasma flow. Also, recent interpretation has shown cusp satellite data to be consistent with a burst of enhanced reconnection. In this paper we use these observations to produce a scenario in which both the satellite and ground-based observations can be fitted. The scenario we develop is based on the flux transfer event (FTE) models of Southwood et al. and Scholer and shows that the signatures, at both low and high altitudes, can be interpreted in terms of FTEs.

Introduction

Since the initial observations and interpretation of FTEs in ISEE magnetopause data by Russell and Elphic [1978], many ideas have been proposed to explain FTE signatures. Recently, Southwood et al. [1988] and Scholer [1988a,b; 1989] (hereinafter S/S) put forward two similar pictures of FTEs and their formation. These models predict plasma bubbles through which loops of newly opened magnetic field exist, the bubbles being formed by a pulse of increased reconnection rate. The importance of these models is that they allow an extended bubble region along the reconnection line leading to greater flux transfer across the magnetopause per event. Figure 1a illustrates the cylindrical bubbles in the dayside magnetopause caused by a burst of enhanced reconnection at the elongated X-line in the equatorial magnetopause (solid line). These bubbles are threaded by the newly opened field lines and move away from the X-line towards higher latitudes. In the ionosphere the bubble will form an elongated bulge on the equatorward edge of the polar cap boundary (Figure 1b) but will otherwise be similar to previous models of FTE ionospheric signatures [e.g., Southwood, 1987]; the flow and field-aligned current signatures for the elongated FTE flux tubes have been predicted by Lockwood [1990] and Wei and Lee [1990]. The ionospheric signature of these bubbles will initially have oppositely directed field-aligned currents on the equatorward and poleward edges and will move, depending on the sign of B_y, either duskward or dawnward under the tension force due to the unbending of the reconnected field lines. Subsequently this motion will decay as the tube unbends and the dominant motion will be poleward, because the flux tube is being moved antisunward by the magnetosheath flow. This zonal then poleward pattern of motion of ionospheric FTE signatures was suggested by Lockwood and Freeman [1989] and used by Saunders [1989] in his explanation of cusp currents.

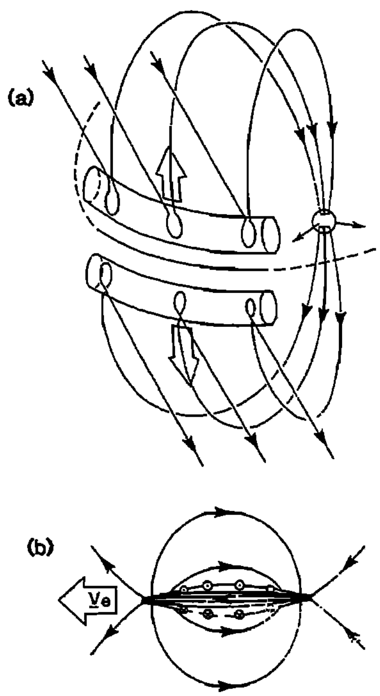

Fig. 1. (a) Three-dimensional view of the dayside magnetosphere showing the newly opened field lines looped through the cylindrical plasma bubbles of the S/S FTE model. (b) The predicted ionospheric flow signature for early in the event when the motion (with event velocity V_e), under magnetic tension, is around the polar cap boundary.

Ground-based observations by radars and optical imagers have revealed transient features occurring in the cusp /cleft region (see reviews by Lockwood et al. [1990a] and Lockwood [1990]). These observations show an initial enhancement in the 630.0 nm emission at the cusp equatorward edge, followed by a strong 557.7 nm transient emission. These emissions first move around the polar cap boundary before entering the polar cap and moving anti-

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sunward and have been termed dayside auroral breakups [Sandholt et al., 1989]. At the same time, radar observations reveal enhanced flows and electric fields which when integrated over the radar field-of-view give voltages of up to 55 kV. Both the radar and optical data show these features occurring repetitively with timescales of the order of 8–10 minutes when the IMF is continuously southward, typical of the time between FTEs at the magnetopause. In addition, the data show that the motion is in the appropriate direction for the IMF B_y component for newly opened flux tubes, and that the drifts are first eastward/westward and then poleward. Optical data also show these regions to be extended along the polar cap boundary and to have scale-sizes consistent with the S/S model of FTEs. Thus these signatures have been interpreted as the ionospheric signature of FTEs.

Carlson and Torbert [1980] showed cusp particle signatures, as seen by sounding rockets, were consistent with injection events of magnetosheath ions into the dayside morning auroral oval. Menietti and Burch [1988] discussed how cusp observations of "V"-shaped patterns in DE-1 energy-time spectrograms, along with a characteristic dispersion in energy, can be interpreted as the signature of ion injection. The DE-1 data were used to infer a plasma injection region size of about 1 R_E, with a radial injection distance of about 6 R_E. As FTEs have a typical boundary-normal dimension of 1 R_E [Saunders et al., 1984], Menietti and Burch [1988] speculated that these injections may be caused by FTEs. However, a problem with this interpretation has been that the distance, measured along the field line that the injections appeared to come from did not map back to the subsolar magnetopause. Rather, the injections mapped to middle latitudes, and thus a problem exists in explaining how the dispersion signatures can be generated by FTEs, which are generally found to originate from reconnection at the equatorial subsolar magnetopause [e.g. Saunders et al., 1986]. We will address this problem.

Due to the problem of spatial/temporal ambiguity and the relatively short time low-altitude spacecraft spend in the cusp, ionospheric satellite observations of transient events is difficult. However, Lockwood and Smith [1989; 1990] have shown that an injection event observed by the low-altitude DE-2 spacecraft can be interpreted in terms of an expanding reconnected FTE flux tube, with a structure and motion like that predicted by the S/S model. Specifically, the event shows the correct motion, plasma flows, field-aligned currents and particle structure for the ionospheric signature to be an FTE. As this event showed typical features of the cusp and occurred in the predicted cusp location, it led Lockwood and Smith [1990] to propose that the cusp shows transient variations over a background level: a transient enhancement of the cusp (in latitudinal width and possibly particle flux and longitudinal width) would then be one ionospheric signature of an FTE.

The aim of the present paper is to show how both the observations at the magnetopause and those in the ionosphere can be reconciled. To do this we use the S/S model. We conclude that all observations can be explained by one phenomenon, namely, time-varying reconnection at the dayside magnetopause.

Ionospheric FTE Signatures

A major problem in predicting ionospheric FTE signatures is that the mapping of dayside magnetopause field lines into the auroral ionosphere is not well known. Crooker [1990] and Crooker and Siscoe [1990] have considered the dimensions of the ionospheric footprints of FTE newly opened flux regions. For a circular FTE flux tube, as in the Russell and Elphic [1978] model, appended to an otherwise fully closed magnetosphere, this footprint is elongated in the east-west dimension. However, a more realistic approach is to append the FTE to a pre-existing, open, polar cap. In this case, Crooker [1990] finds that the Russell and Elphic footprint is nearly circular with a typical radius of 100 km. However, the extended X-line S/S model gives footprint dimensions of typically 200 km north-south and over 1000 km east-west. Lockwood [1990] has predicted the ionospheric flow signatures for elliptical FTE-tubes of these dimensions and shown them to be broadly consistent with ionospheric flows observed by the EISCAT radar during dayside auroral breakups.

This east-west elongation means that FTEs have longitudinal widths similar to the width of the cusp [see Newell, 1990]. Thus FTE signatures should not be viewed as small patches embedded within the cusp but as variations in the cusp as a whole, as suggested by Lockwood and Smith [1990]. Figure 2 illustrates the evolution of such an elongated FTE footprint. The motion is shown for an IMF $B_y > 0$ in the northern hemisphere. Initially, the event moves towards dawn under the action of magnetic tension, before slowing and being moved anti-sunward by magnetosheath flow, as discussed earlier. This pattern of motion is also that observed in dayside auroral breakup events and associated flow signatures. The event is shown as remaining dawn-dusk aligned, consistent with the behaviour of the transient aurora. Wei and Lee [1990] have

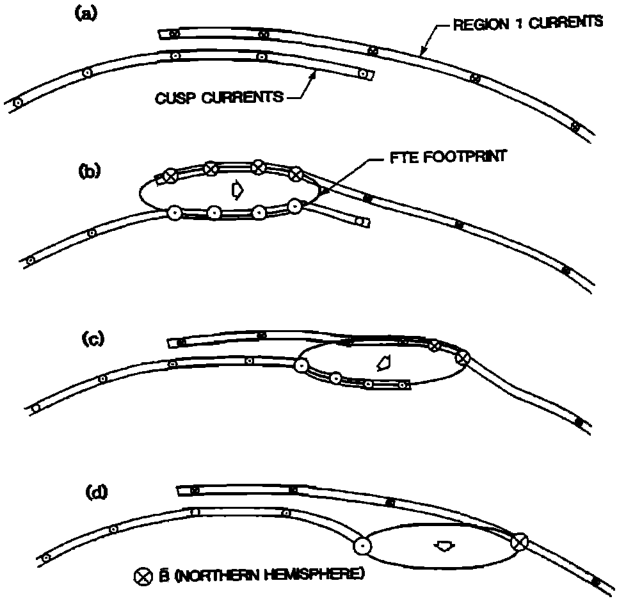

Fig. 2. Travelling, transient intensification of the region 1/cusp field-aligned currents due to an elliptical FTE.

predicted the distribution of field-aligned currents around such a tube. In the initial westward-moving phase these are small sheets (or elongated filaments) on the poleward and equatorward edges of the event. These currents are shown in Figure 2 by the larger field-aligned current symbols superposed on the weaker background cusp and region 1 currents (smaller symbols), which are seen in isolation before the event onset (panel a). In panels (c) and (d) the event motion evolves to poleward; however, the filamentary current densities remain roughly constant as the increase in current density with angle between the ellipse major axis and direction of motion, as calculated by Wei and Lee, is largely cancelled by the event speed reduction, as predicted for and observed in dayside auroral breakup events. At later times the newly opened tube is subsumed into the polar cap flow. This is consistent with recent findings that newly opened flux tubes only excite convection for a period of ~10 minutes before returning to the background level shown in Figure 2a [Lockwood, 1990]. Figure 2 demonstrates Lockwood and Smith's [1990] idea that the filamentary field-aligned currents of the FTE are "transient and travelling intensifications of the cusp/region 1 currents."

In this view, enhanced 630 nm emissions observed inside the FTE footprint are caused by magnetosheath plasma injected during the reconnection burst, while the 557.7 nm emissions are due to transient acceleration in the region of transient, upward field-aligned current, as observed in dayside auroral breakups. The latitudinal width of the 630 nm emission region (i.e. "the cusp") may be roughly 3 times larger during the transient event than in the periods before and after [Lockwood et al., 1990b]. Note that Figure 2 shows the evolution of an isolated FTE. Lockwood [1990] has considered the dayside convection pattern which results from a sequence of FTEs occuring every 8 minutes (the mean FTE repetition rate).

Magnetopause FTE Observations and the Point of Particle Injection

Figure 3 shows a series of snapshots through the noon-midnight meridian; this sequence of events is based on the S/S model. Panel (a) shows the newly formed FTE. The shaded area represents the plasma bubble, which is extended in the dawn-dusk direction (out of the plane of the figure). As Scholer [1989] points out, the bubble moves at about 70% of the magnetosheath Alfvén speed but the plasma flow within the bubble and magnetopause current layer is super-Alfvénic and hence a fast-mode shock must form at the bubble's leading edge as it moves through the background plasma. Also on either side of the loop in the magnetic field are magnetic mirrors which will act to contain the plasma within the bubble (i.e. the bubble is a "magnetic bottle"). Plasma entering the magnetosphere on newly opened flux tubes is thus prevented from moving along the magnetopause at a speed greater than the bubble velocity by the shock and the magnetic mirrors. In other words, the plasma injected across the magnetopause in the bubble (where field lines thread the boundary), as predicted by S/S, is prevented from dispersing along these field lines.

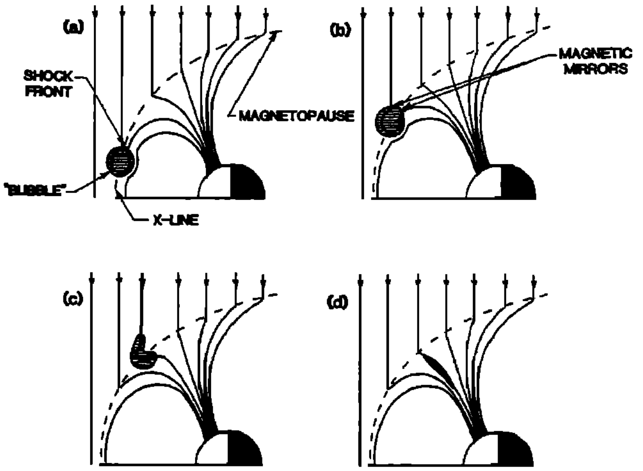

Fig. 3. The evolution of an FTE plasma bubble into dispersed particle precipitation in the cusp.

While the plasma speed (i.e. the FTE speed, typically 100–200 km s^{-1}) exceeds the local Alfvén speed, the shock will exist and hence no dispersion of the plasma in the bubble will occur. However, if the Alfvén speed should increase sufficiently in the region into which the shock is propagating and/or the FTE speed should decrease, then the shock will dissipate and the FTE will "break up" (i.e. particles will disperse according to their energy and no longer move as a coherent structure). Such an Alfvén speed increase could be caused either by a rise in the magnetic field or a decrease in the plasma density within the current layer. Scholer [1988b] has suggested such a rise in the magnetic field as the looped field lines sweep up any pre-existing magnetopause field. In addition, the magnetic mirrors on either side of the loop will be lost as the field lines straighten. Either of these mechanisms will cause the plasma bubble to "burst" and subsequently the particles precipitate into the ionosphere and are dispersed according to energy (Figure 3c and d). At this time the dominant force on the plasma bubble will be that exerted by field line tension and hence, the first motion in the ionosphere will be around the polar cap boundary. Because Lockwood and Smith [1989] deduced an equatorward expansion in their DE-2 data, and Lockwood et al. [1990b] saw equatorward motion of the equatorward cusp/cleft boundary in dayside breakup events, we suggest that the bubble may release particles first from its center, as shown in Figure 3b. Thus the observations of Menietti and Burch map to the bursting point of this plasma bubble and not the formation of the FTE.

Menietti and Burch find a typical spread of injection latitudes of about 25° to 50° [J. D. Menietti, private communication, 1990]. The latitudinal occurrence of FTE signatures is not well-known above about 50°, as spacecraft have not sampled this part of the magnetopause in any great detail. However, Saunders et al. [1986] find that the occurrence frequency increases with latitude in the range from 0° to 50°. In the scenario presented here, we may have expected the occurrence frquency to decrease with higher latitudes. However, the bursting of the bubble will not cause the FTE to disappear immediately and hence signatures will still be observed at higher latitudes than the point of onset of particle injection. Also, observations made at the magnetopause show that FTEs expand during their lifetime and will thus be easier to observe at higher latitudes. This increase in size with latitude is normally attributed to the decrease in the magnitude of the exterior magnetic field. However, in our picture the size would also increase due to the plasma dispersion following the bursting of the bubble. Lockwood and Smith [1989] estimated that the injection event lasts for some 200 s if the injection point is assumed to be fixed. In the scenario presented here, the injection region is moving towards the ionospheric cusp (at the speed of the FTE bubble). Hence, we would expect that the rate of FTE occurrence will decrease at a latitude given by the first point of particle injection, say 25–50°, plus the distance the FTE travels while injecting the plasma (200 s times the typical velocity). This turns out to be a latitude in excess of about 55° or so.

Summary

We have used the S/S model to show how the generation of FTEs at the dayside magnetopause can produce ion dispersion, flow, and field-aligned current signatures in the polar cusp. Thus the observations from high and low altitude satellites and from ground-based instruments are consistent with the theory that the manifestation of time-dependent reconnection at the magnetopause, i.e. FTEs, is indeed a pulsating cusp signature.

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References

Carlson, C. W. and R. B. Torbert, Solar wind ion injections in the morning auroral oval, *J. Geophys. Res.*, *85*, 2903, 1980.

Crooker, N. U., Flux transfer event footprint patterns and implications for convection, *J. Geophys. Res.*, in press, 1990.

Crooker, N. U., and G. L. Siscoe, On mapping flux transfer events to the ionosphere, *J. Geophys. Res.*, *95*, 3795, 1990.

Lockwood, M., The excitation of ionospheric convection, *J. Atmos. Terr. Phys.*, in press, 1990.

Lockwood, M., and M. P. Freeman, Recent ionospheric observations relating to solar wind-magnetosphere coupling, *Phil. Trans. Roy. Soc., A*, *328*, 93, 1989.

Lockwood, M., and M. F. Smith, Low altitude signatures of the cusp and flux transfer events, *Geophys. Res. Lett.*, *16*, 879, 1989.

Lockwood, M., and M. F. Smith, Reply to comments by P. T. Newell, *Geophys. Res. Lett.*, *17*, 305, 1990.

Lockwood M., S. W. H. Cowley and P. E. Sandholt, Transient reconnection – search for ionospheric signatures, *EOS Trans. AGU*, *71*, 709, 1990a.

Lockwood M., et al., Auroral and plasma flow transients at magnetic noon, *Planet. Space Sci.*, in press, 1990b.

Menietti, J. D., and J. L. Burch, Spatial extent of the plasma injection region in the cusp-magnetosheath interface, *J. Geophys. Res.*, *93*, 105, 1988.

Newell P.T., Comment on "Low-altitude signatures of the cusp and flux transfer events" by Lockwood and Smith, *Geophys. Res. Lett.*, *17*, 303, 1990.

Russell C. T., and R. C. Elphic, Initial ISEE magnetometer results: magnetopause observations, *Space Sci. Rev.*, *22*, 681, 1978.

Sandholt P. E., B. Lybekk, A. Egeland, R. Nakamura, and T. Oguti, Midday auroral breakup, *J. Geomag. Geoelectr.*, *41*, 371 , 1989.

Saunders, M. A., The origin of cusp Birkeland currents, *Geophys. Res. Lett.*, *16*, 151, 1989.

Saunders, M. A., C. T. Russell, and N. Sckopke, Flux transfer events: scale size and interior structure, *Geophys. Res. Lett.*, *11*, 131, 1984.

Saunders, M. A., et al., Detection of FTEs by the AMPTE-UKS magnetometer, *Adv. Space Res.*, *6*, 123, 1986.

Scholer M., Magnetic flux transfer at the magnetopause based on single X-line bursty reconnection, *Geophys. Res. Lett.*, *15*, 291, 1988a.

Scholer M., Strong core magnetic fields in magnetopause flux transfer events, *Geophys. Res. Lett.*, *15*, 748. 1988b.

Scholer M., Asymmetric time-dependent and stationary magnetic reconnection at the dayside magnetopause, *J. Geophys. Res.*, *94*, 15099, 1989.

Southwood, D. J., The ionospheric signature of flux transfer events, *J. Geophys. Res.*, *92*, 3207, 1987.

Southwood D. J., C. J. Farrugia, and M. A. Saunders, What are flux transfer events?, *Planet. Space Sci.*, *36*, 503, 1988.

Wei, C. Q., and L. C. Lee, Ground magnetic signatures of moving elongated plasma clouds, *J. Geophys. Res.*, in press, 1990.

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