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THE STATISTICAL CUSP: A FLUX TRANSFER EVENT MODEL

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Abstract—Traditionally, the cusp has been described in terms of a time-stationary feature of the magnetosphere which allows access of magnetosheath-like plasma to low altitudes. Statistical surveys of data from low-altitude spacecraft have shown the average characteristics and position of the cusp. Recently, however, it has been suggested that the ionospheric footprint of flux transfer events (FTEs) may be identified as variations of the "cusp" on timescales of a few minutes. In this model, the cusp can vary in form between a steady-state feature in one limit and a series of discrete ionospheric FTE signatures in the other limit. If this time-dependent cusp scenario is correct, then the signatures of the transient reconnection events must be able, on average, to reproduce the statistical cusp occurrence previously determined from the satellite observations. In this paper, we predict the precipitation signatures which are associated with transient magnetopause reconnection, following recent observations of the dependence of dayside ionospheric convection on the orientation of the IMF. We then employ a simple model of the longitudinal motion of FTE signatures to show how such events can easily reproduce the local time distribution of cusp occurrence probabilities, as observed by low-altitude satellites. This is true even in the limit where the cusp is a series of discrete events. Furthermore, we investigate the existence of double cusp patches predicted by the simple model and show how these events may be identified in the data.

1. INTRODUCTION

Since dayside nulls in the geomagnetic field were sketched by Chapman and Ferraro (1931), the spatial structure of these magnetic cusps has been widely investigated (see, for example, Siscoe, 1987). However, the term "cusp" has been loosely and often indiscriminately used. Indeed, until recently there had been no quantitative definitions of the cusp. For a closed magnetosphere, the magnetic cusp is that point at which all the magnetic field lines that make up the magnetopause surface in that hemisphere meet. Observationally, it is clear that some mechanism allows magnetosheath plasma to penetrate into the ionosphere in the vicinity of the magnetic cusps (e.g. Heikkila and Winningham, 1971; Shelley *et al.*, 1976; Reiff *et al.*, 1977). This plasma entry is termed cusp particle injection and is accompanied by the cusp current system revealed by Iijima and Potemra's (1976) work, showing the presence of field-aligned currents poleward of the dayside region 1 current system.

More recently, Newell and Meng (1988) and Newell *et al.* (1989) have, for the first time, quantified the distinction between the cusp and surrounding precipitation regimes using DMSP data. In particular, these authors have provided definitions which distinguish the "cusp" from the "cleft" precipitation. The latter is found equatorward of the cusp (and never poleward of it), and is thought to be the ionospheric signature of the low-latitude boundary layer (LLBL). They defined the "cusp" as the region in which the magnetosheath plasma has the "most direct entry" and identified it (distinguishing it from the cleft/LLBL) by the lower average energy of the ions, and found that the number flux was greater than in the cleft. In addition, these authors distinguish between the cusp and "mantle" precipitation, the latter being found poleward of the cusp and at its dawn and dusk flanks. This distinction is based upon the ion energy and the electron precipitation flux. For southward

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IMF, the poleward convection of plasma through the cusp region gives rise to the characteristic "velocity-filter" effect, whereby cusp ions are dispersed in latitude according to their energy. It is significant that the ion energy usually falls with latitude continuously across the boundary between the cusp and mantle, as defined by Newell and Meng (1988) (see, for example, their Fig. 1a). It is highly unlikely that two separate processes could contrive to produce the same ion energy at the cusp/mantle boundary and hence this fact strongly suggests that cusp and mantle ions undergo the same injection and transport processes.

Both the Newell *et al.* (1989) and the Iijima and Potemra (1976) studies have viewed the cusp characteristics using large, statistical surveys. These surveys, by virtue of their statistical nature, express time-stationary average concepts. Indeed, the rapid motion of low- and mid-altitude spacecraft through the cusp and the along-track nature of the data do not allow for temporal/spatial ambiguities to be resolved. Based on these, and many other observations, a myriad of cartoons have been drawn representing the observational features (e.g. Haerendel *et al.*, 1978). All these cartoons allow the penetration of plasma to low altitudes within the cusp and generally consist of a funnel-shaped region into which the plasma may penetrate. However, they are all intrinsically quasi-steady states and deal with spatial, not temporal, structure.

Recently, using ground-based instrumentation, it has become clear that the cusp/cleft region exhibits rapid (i.e. on time scales of a few minutes) temporal variations when the IMF has a southward (negative B_z) component. This is true of both particle precipitation, as viewed using ground-based optical instruments (Sandholt, 1988; Sandholt *et al.*, 1990a), and the field-aligned currents, as inferred from the F-region plasma flows and their equivalent E-region currents (Lockwood *et al.*, 1989a, b, 1990a–c; Sandholt *et al.*, 1990b). The optical data do not allow the distinction between the cusp and cleft to be made, but the plasma flow and the motion of the auroral transient events can only be explained in terms of newly-opened flux tubes, on which the cusp particles are mainly found (Reiff *et al.*, 1977). Both transient aurorae and associated flow bursts show a quasi-periodic variation, with a mean repetition period of about 8 min (Lockwood *et al.*, 1989b). This is similar to the behaviour of magnetopause flux transfer events (FTEs) as reported by Berchem and Russell (1984) and Rijnbeek *et al.* (1984). This similarity, along with the observed IMF B_y dependence of the sense of their zonal motion, has led to an interpretation of the cusp in terms of transient reconnection (e.g. Lockwood and Smith, 1989). Indeed, prior to this Menietti and Burch (1988) had suggested a link between cusp ion injection and FTEs, from calculations of the size of the injection region.

Smith and Lockwood (1990) have suggested that the cusp could be a series of FTE footprints, generally (but not necessarily) superposed on a background cusp. The background cusp would result from reconnection taking place at the same X-line between the bursts, but at a reduced rate, as postulated by the Southwood *et al.* (1988)/Scholer (1988) model of FTEs. Hence, Smith and Lockwood showed how the Southwood *et al.*/Scholer model of reconnection may produce the observed ion injection and low-altitude cusp signatures normally associated with the "cusp". As discussed by Lockwood and Smith (1989), a patch of newly-opened flux grows with time as a burst of dayside reconnection proceeds. Thus, the field lines at the poleward edge of the cusp have been open for longer than those at the equatorward edge, so that the time-of-flight of the precipitating ions is longer, i.e. their energy is lower. Hence ion energy decreases with latitude across the patch. This will remain the case at all stages of the evolution of the patch, although all ion energies within the patch will fall with time. The sense of the dispersion is thus independent of the direction of satellite motion and of the direction of convection of the patch: for southward IMF, ion energy will always fall with latitude. Because it is produced by a burst of dayside reconnection, each patch is, by definition, an ionospheric signature of a flux transfer event (FTE). However, because of its particle precipitation characteristics, Lockwood and Smith contend that the patch would also be classed as the "cusp" when intersected by a low-altitude satellite.

This picture of a time-dependent cusp, driven by time-varying reconnection of the interplanetary and geomagnetic fields, is considerably different from the traditional spatial view. However, in the limit of steady continuous reconnection, it yields the usually adopted spatial concept of the cusp. The generalized "pulsating cusp" concept is based on observational evidence, which, because of its remote-sensing nature (from the ground), can distinguish temporal and spatial variations of the low-altitude cusp.

Although it has been shown how, for a single low-altitude pass, this transient picture may be reconciled with spacecraft data (Lockwood and Smith, 1989), it is also necessary for the FTE model to be able to reproduce the statistically averaged cusp features already published. It is the aim of this paper to show how low- and mid-altitude satellites would observe time-varying FTE footprints and generate the "time-averaged" cusp behaviour. We will do this (in Section 4) by using a simple analytical model of an FTE footprint, without any background cusp (i.e. the limit of the cusp model, where the cusp is a series of discrete events). The purpose is to show that even this "discrete event" limit can model the cusp statistics equally as well as the steady cusp limit. From this model, we make predictions about "double cusps" and discuss their form in satellite data for both the discrete event limit and more general cases (Section 5). However, before this can be done we must first consider the nature and motion of the ionospheric signatures of FTEs. This is done in Section 2, using recent observational and theoretical work on how dayside ionospheric convection is excited, and in Section 3 where the particle precipitation characteristics in FTE signatures are discussed.

2. THE IONOSPHERIC SIGNATURE OF FLUX TRANSFER EVENTS

Early discussions of the ionospheric flow signatures of FTEs were made by Cowley (1984), van Eyken *et al.* (1984), Goertz *et al.* (1985), Southwood (1985, 1987) and Lee (1986). These considerations were all based upon the then current model of FTEs, due to Russell and Elphic (1978). In this model, the magnetopause signatures were caused by the passage nearby of a tube of newly-opened flux of nearly circular cross-section, this having previously been produced by a burst of reconnection at a localized X-line. More recently, a new model of FTEs has been put forward, initially by Saunders (1983), but subsequently developed by Southwood *et al.* (1988) and Scholer (1988), as mentioned above. In this model, the magnetopause FTE signatures are produced by a burst of reconnection, but at an X-line which need not be spatially localized. An important piece of evidence for this model is that, unlike the Russell and Elphic model, it can explain the streaming electrons which are frequently observed on the edges of the FTEs (Scudder *et al.*, 1984; Farrugia *et al.*, 1988). Lockwood *et al.* (1990b) and Wei and Lee (1990) have generalized the predictions of the ionospheric signatures of FTEs to allow for newly-reconnected flux tubes which are more extended in local time. These predictions were, in principle, the same as those by Southwood (1985, 1987), only differing in the generalization of the shape of the flux tubes, the local time extent being increased to that of the postulated elongated X-line. Lockwood *et al.* have shown how these elongated signatures are broadly consistent with dayside auroral transients detected by optical and radar observations (Lockwood *et al.*, 1990a–c; Lockwood, 1991a; Elphic *et al.*, 1990).

The important difference between the Russell and Elphic and the Southwood *et al.*/Scholer models of FTEs is that the former predicts a small signature in the ionosphere (a few hundred km for both North–South and East–West dimensions), while the latter model predicts that the signature could be several thousand km in East–West extent. Hence Smith and Lockwood (1990) have suggested that FTE signatures may not be small features embedded within the cusp, rather they are temporal variations of the cusp as a whole. All of these models involve newly-opened flux tubes driving a twin vortical flow pattern as they move through the incompressible ionosphere. In their model of cusp precipitation in FTEs, Lockwood and Smith (1989) pointed out that the region of newly-opened flux will grow as the reconnection proceeds, and this will complicate the flow patterns. In addition, Cowley *et al.* (1991a) have recently re-evaluated the signature of FTEs, based on observations of the response of ionospheric convection to changes in the IMF. The remainder of this section discusses this new understanding of FTE signatures.

The EISCAT–AMPTE observations of the response of ionospheric flows to changes in the IMF (see review by Lockwood *et al.*, 1990c), showed that dayside convection responds on very short time scales to the North–South (B_z) component of the IMF, thus confirming equivalent observations of the response of the directly-driven current systems in the dayside auroral ionosphere (Nishida, 1968a,b). [These observed response times following the onset or cessation of reconnection are as short as those for changes in IMF B_y orientation (Greenwald *et al.*, 1990), which act because of the tension force on the newly-reconnected field lines.] The observations have a very important implication, namely that it is not the existence of open flux which excites ionospheric convection, rather it is its generation and destruction by reconnection (at the dayside magnetopause and in the tail neutral sheet, respectively). As a result, Cowley and Lockwood (1992) have introduced the concept of zero-flow equilibrium configurations of the magnetosphere. This model is demonstrated in Fig. 1 for IMF $B_y \approx 0$ conditions. In Fig. 1(a), we show an equilibrium situation, with the magnetosphere containing an open flux F in each hemisphere. In the ionosphere, that open flux forms a polar cap, which is shown here as being circular in its equilibrium configuration, for simplicity. In part (b) we add some newly-opened flux, dF, to the dayside polar cap boundary. In this idealized case, the flux is produced by an instantaneous burst of reconnection in an FTE. We will generalize to allow for a finite reconnection rate later. Note that, for clarity, Fig. 1 exaggerates the amount of newly-opened flux produced by the reconnection

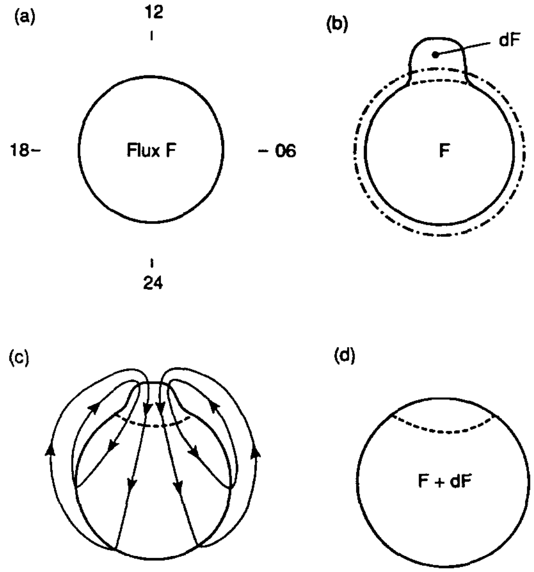

FIG. 1. A SEQUENCE OF SKETCHES ILLUSTRATING THE RESPONSE OF IONOSPHERIC FLOWS TO A BURST OF DAYSIDE RECONNECTION WITH IMF $B_y \approx 0$.
In this simplified case, a magnetic flux of dF has been instantaneously appended to the dayside of the pre-existing polar cap (flux F) by dayside reconnection. Flows are excited for 10–15 min, until the equilibrium configuration for the new open flux of (F+dF) is achieved (from Cowley and Lockwood, 1992).

burst: Lockwood *et al.* (1990b) estimate from the ground-based optical and radar measurements of dayside transients that dF/F is typically 0.03.

The dot-dashed line in part (b) shows the equilibrium configuration of the polar cap for the new amount of open flux (F+dF) (again, this is shown as circular for simplicity). The dotted line denotes the boundary between the "old" open flux (F) and the newly-opened flux (dF). Ionospheric flow will be excited until the new equilibrium is achieved. Because this will involve the poleward motion of the boundary at the local times where the newly-opened flux was appended, and the equatorward motion at all other local times, ionospheric flow of the type shown in Fig. 1(c) will be excited. Generalization of the shapes of the equilibrium configurations will alter the exact form of the flows, but will not alter the principles involved. It should be noted that this flow (and the associated poleward motion of the patch of newly-opened flux) has been produced purely by the burst of dayside reconnection, with no nightside reconnection taking place. [Eventually, of course, the continued addition of open flux into the tail lobe will result in a burst of reconnection in the tail neutral sheet and this will drive flows, but at a later time, the strongest flows being on the nightside (Lockwood *et al.*, 1990c; Cowley and Lockwood, 1992).] In part (d), the new equilibrium configuration has been attained and hence the flow has ceased. The dotted line denotes the final boundary of the region of newly-opened flux. The observed responses of dayside flows to IMF changes indicate that the new equilibrium configuration (and flow stagnation) is achieved in a period of the order of 10–15 min following the reconnection burst.

This theory of the excitation of convection, by Cowley and Lockwood (1992), thus predicts that a burst of dayside reconnection will produce a twin vortical flow pattern, but on a global scale, not on the localized scale of the Southwood (1985, 1987) FTE model (or even of its more extended versions by Lockwood *et al.*, 1990b and Wei and Lee, 1990). The important difference in the context of the cusp is that the newly-opened flux tubes produced in the reconnection burst do not, at least in this case with $B_y \approx 0$, overtake any "older" open flux (i.e. open flux which was produced by reconnection at earlier times). This should be contrasted with all the other models, for which the exact nature of the flow outside the region of newly-opened flux was not discussed. As a result, in the previous models the newly-opened flux could "overtake" some older open flux, which is moved from in front of the event to behind it, as part of the twin vortical flow pattern. Indeed, for the most commonly-used description of the flow, namely that equivalent to the flow around a cylinder of circular or elliptical cross-section, this does occur (see discussion by Lockwood *et al.*, 1988). As a result, sucessive FTE signatures become separated by regions of older open flux tubes which have been overtaken by the leading event (see Lockwood, 1991a). The theory by Cowley and Lockwood (1992) is substantially different in this respect. Because no older open flux is overtaken by the FTE footprint, any subsequent FTE signature is appended immediately equatorward of the one that preceded it.

Figure 2 generalizes the sketches of Fig. 1 with allowance for a non-zero reconnection time (i.e. a finite reconnection rate) and considering a sequence of reconnection bursts. Magnetopause observations indicate that FTEs are formed by reconnection bursts which are typically of 2 min duration and recur every 8 min on average (Berchem and Russell, 1984; Rijnbeek *et al.*, 1984; Saunders *et al.*, 1984). During the periods between the bursts, reconnection is either absent or takes place at a much lower rate. Because this interval is somewhat lower (by a factor of about 2) than the 10–15 min taken to re-establish an equilibrium, such a sequence of events will continuously drive flows, but those flows will show some variations

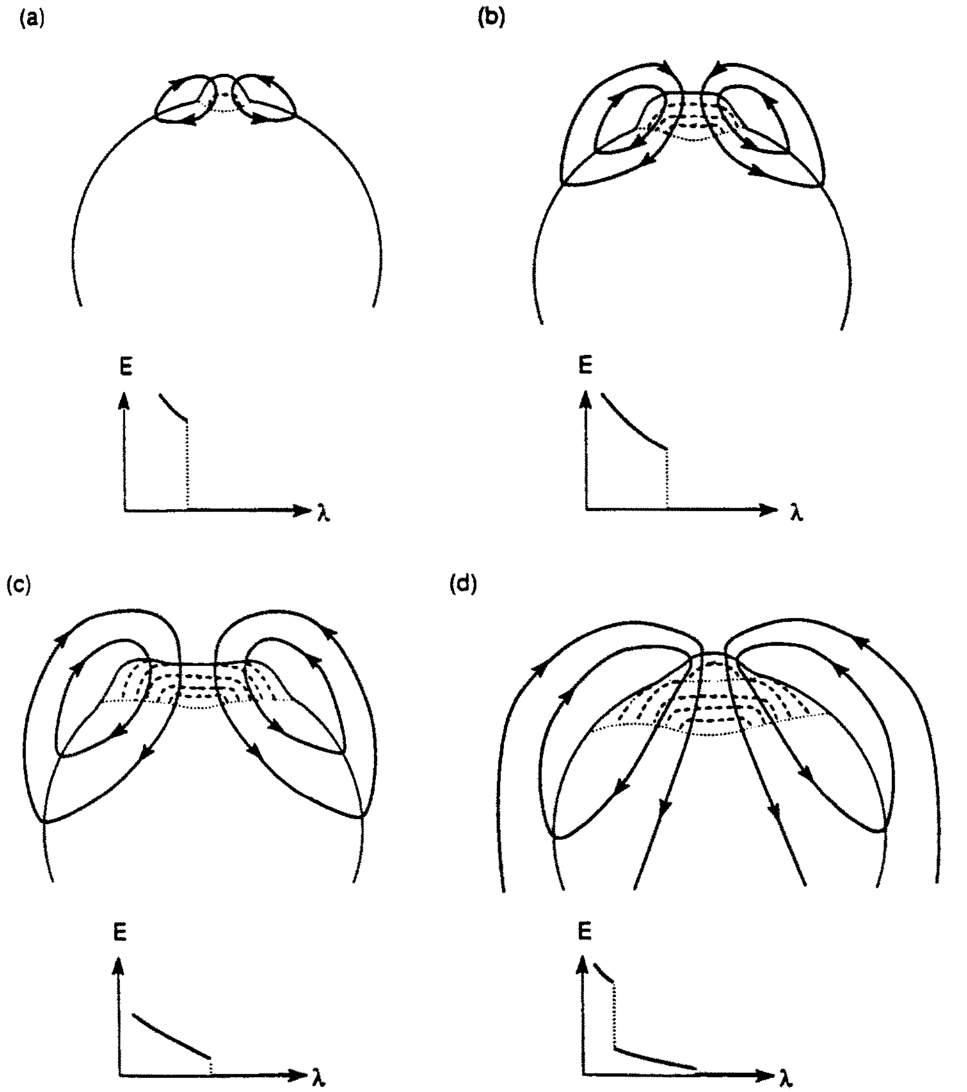

FIG. 2. THE EVOLUTION OF PATCHES OF NEWLY-OPENED FLUX IN FTEs.
The dashed lines connect field lines reconnected at one instant of time (taken here to be 30 s apart), and the solid lines are the flow equipotentials. Sketches are shown for times: (a) $t = 1$ min; (b) $t = 2$ min; (c) $t = 3$ min and (d) $t = 9$ min. In part (d) a second burst is forming immediately equatorward of the first. As in Fig. 1, noon is at the top of the figure, dawn to the right. Beneath each sketch of the flows is a plot of the lower cut-off energy of the cusp ion precipitation as a function of latitude for each instant of time (from Cowley *et al.*, 1991a).

with the same repetition period as the reconnection bursts. One should note that there is considerable spread of the distribution of FTE recurrence periods about the mean value of 8 min. Lockwood and Wild (1992) have recently shown that the decile values of the distribution are 1.5 and 18 min. Hence there could be up to about 10 effective events at any one time, or there could be brief periods when no event was active. Only on average will two events be producing flows at any one time. Even in the cases for which the FTE bursts are separated by exceptionally long periods, the dayside flows (and associated field-aligned currents) may not decay to zero 15 min after the reconnection burst. This could be because the Southwood *et* *al.*/Scholer FTE model allows reconnection to continue at a lower level between the bursts, or because the two-source convection model (Lockwood *et al.*, 1990c; Cowley and Lockwood, 1992) shows that a low level of flow on the dayside will be driven by any reconnection taking place in the tail. Hence periods of complete stagnation in the cusp region when the IMF is southward will be very rare and brief.

Figure 2 considers the ionospheric signatures of the onset of a sequence of FTEs, starting from a zero-flow equilibrium configuration, for IMF $B_y \approx 0$. In Fig. 2(a)–(c) we show the development of a region of newly-opened flux. In this case, the reconnection is taken to start near noon and expand in local time over the magnetopause. After about 2 min the reconnection rate decays, again commencing at noon. The dashed lines in Fig. 2 join magnetic field lines which were reconnected at the same time, those times being 30 s apart. Part (d) of Fig. 2 is for a time 8 min after (a) and a second region of newly-opened flux can be seen forming near noon, due to a second burst of reconnection. As discussed above, the patch of newly-opened flux formed by the second reconnection burst lies immediately equatorward of that produced by the first. The lower panel of each part of Fig. 2 will be discussed in the next section.

Thus far we have only considered the case for IMF $B_y \approx 0$. Figure 3 considers the flows which would result in the Northern Hemisphere from a single burst of reconnection with an IMF which has a strong duskward component ($B_y > 0$). In this case, the tension force on the newly-opened flux acts to move the point where it threads the magnetopause westward as well as poleward. As the flux tubes move away from the X-line, this tension force decays as the field lines straighten, but the influence of the increasing magnetosheath flow speed becomes greater. In the ionosphere, the footprint moves westward initially before moving poleward as the magnetospheric system returns toward an equilibrium configuration, as discussed above. This two-phase motion was used by Saunders (1989) to explain the cusp field-aligned currents. Consequently, the patches of newly-opened flux produced by reconnection bursts tend to move around the polar cap boundary before they are subsumed into it. This is exactly the behaviour of the transient aurora/flow bursts observed from the ground and which were discussed in the introduction (Sandholt, 1988; Lockwood *et al.*, 1989a, b; Sandholt *et al.*, 1990a, b). Note that while the flux tubes are moving zonally around the boundary, a flow pattern of the type predicted by Southwood (1985, 1987) is formed. In fact, because of the elongation of the events, the pattern is more likely to be of the form described by

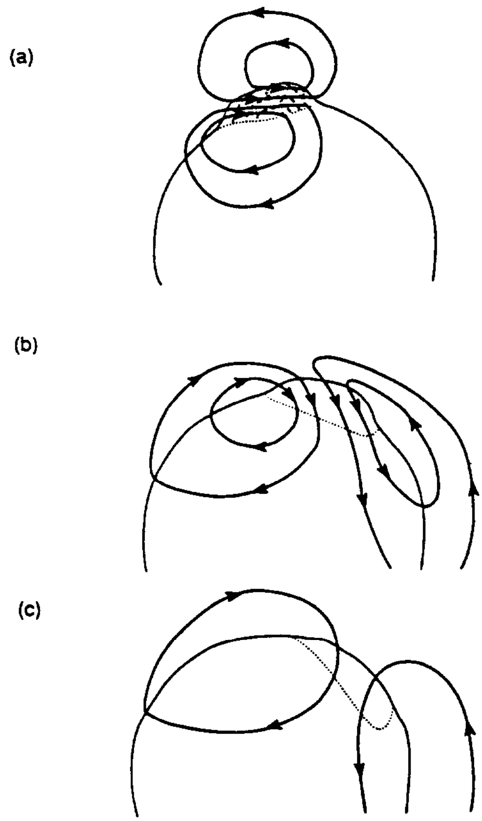

FIG. 3. THE EVOLUTION OF A REGION OF NEWLY-OPENED FLUX, AND ASSOCIATED FLOWS, IN THE NORTHERN HEMISPHERE FOR A SHORT-LIVED BURST OF RECONNECTION WITH AN IMF WITH $B_y > 0$.
As for Fig. 1, noon is at the top of the figure and dawn is to the right (from Cowley *et al.*, 1991a).

Lockwood *et al.* (1990b) and Wei and Lee (1990), with the event motion aligned with its major axis. If the newly-opened flux patch moves initially only around the boundary, with no poleward motion at all, it will "overtake" closed field lines and the flow pattern will be dominated by a single vortex immediately equatorward of the polar cap boundary. In Fig. 4(a), however, the patch is shown as moving slightly poleward as it moves westward, in which case, it will also "overtake" some older open field lines. If the event moves East or West (i.e. to greater or smaller M.L.T., respectively) by more than its East–West extent, a subsequent event formed at the same M.L.T. will not initially be contiguous with the first and the two will be separated by older open flux. This is the case in Fig. 3. This should be compared with the $B_y \approx 0$ case depicted in Fig. 2, for which the ionospheric signatures of subsequent events are spatially contiguous at all times.

Lastly, in passing, we comment on another difference between the "moving cloud" models of FTE signatures (Southwood, 1987; Lockwood *et al.*, 1990b; Wei and Lee, 1990) and the "pulsating cusp" model advocated by Smith and Lockwood (1990) and Cowley *et al.* (1991a). In the "moving-cloud" models the flow inside the cloud (i.e. the region of newly-opened flux) is uniform. However for the pulsating cusp model, the flow at the ionospheric foot of a field line depends upon the time elapsed since it was reconnected and hence varies with latitude across the cloud. Those flux tubes opened at the start of the burst of reconnection (which are located at the poleward edge of the cloud) will have a higher poleward and a lower longitudinal speed than those reconnected later in the burst (i.e. located at lower latitudes within the cloud). Hence the flow streamlines generally curve polewards within the cloud for the pulsating cusp model, instead of being straight, as for the moving cloud models. The distribution of magnetopause FTE durations indicates that reconnection bursts can last for between about 0.5 and 5 min (Elphic, 1990). For the short-lived bursts the difference in reconnection times across the cloud is short compared to the 10–15 min evolution times of the flows and this difference between the two models is not significant. However, this could be a significant difference for the events caused by the longer bursts. In Fig. 3(b), the flow streamlines within the cloud have been drawn as curving only slightly poleward—i.e. the event was formed by a relatively short-lived reconnection burst.

3. PARTICLE PRECIPITATION IN FTES

The cusp model of Smith and Lockwood (1990) is based on the concept that the same particle population is injected onto each newly-opened field line as it is reconnected and then transferred into the tail by the magnetosheath flow. This is true irrespective of the reconnection rate. In an FTE, it is simply the rate at which field lines undergo this process which varies.

By definition, reconnection at the dayside magnetopause produces magnetic field lines which thread the magnetopause and hence magnetosheath particles gain access to the magnetosphere by flowing along those field lines. Observations show that this is the primary source of cusp ions (Hill, 1979; Hill and Reiff, 1977; Reiff *et al.*, 1977). Each field line is then moved (under the joint action of magnetic tension and then magnetosheath flow) away from the stagnation region where the reconnection occurred and after about 10–15 min is appended to the tail lobe (it becomes "older open flux" in the terminology used in the previous section). In this section, we consider the particle precipitation which results from bursts of sub-solar reconnection during southward IMF, by considering the evolution of the newly-opened field line.

After reconnection at the subsolar magnetopause, magnetosheath particles have access to the magnetosphere, and can subsequently precipitate into the ionosphere. As these particles cross the rotational field reversal at the magnetopause, they will be accelerated or decelerated. Cowley (1982) has discussed the resulting populations of ions by considering conservation of energy in the de-Hoffmann–Teller reference frame (in which there is no convection electric field). As the newly-opened field line evolves over the dayside magnetopause, particles continue to cross the magnetopause, but the spectrum of particles injected to low altitudes will alter. This may, in part, be because the spectrum of magnetosheath particles may vary with distance along the magnetopause away from the stagnation region. However, a more likely cause is the decrease in the magnetopause acceleration as the curvature of the field line decreases. Equatorward of the magnetic cusp, where the Chapman–Ferraro current $\mathbf{J}$ and the magnetopause electric field $\mathbf{E}$ are such that $\mathbf{J}\cdot\mathbf{E} > 0$, the curvature is such that the particles are accelerated as they cross the magnetopause: poleward of the magnetic cusp, where $\mathbf{J}\cdot\mathbf{E} < 0$, they are decelerated (e.g. Hill, 1979). Cowley (1982) predicted "D-shaped" distributions of magnetosheath ions injected and accelerated in this way, and these have recently been observed (Smith and Rodgers, 1991; Fuselier *et al.*, 1991).

However, not all ions which cross the magnetopause in this way will precipitate into the ionosphere. Once the field line is tailward of the magnetic cusp, the plasma ions will be flowing away from the Earth at speeds which exceed their thermal speed. Hence they mainly move away from the Earth and into the tail lobe. These ions hence form the high-latitude boundary layer or "mantle". Only ions in the high-energy tail of the spectrum, with a large thermal velocity directed towards the Earth, have sufficient field-aligned velocity to precipitate toward the Earth.

As a result of these two mechanisms (the deceleration as they cross the boundary and the anti-sunward flow) very little of the magnetosheath ion distribution will precipitate into the ionosphere after crossing the magnetopause at latitudes above the magnetic cusp (Cowley *et al.*, 1991a). Such ions take a considerable time to precipitate into the ionosphere where they have a low flux and a much lower energy (in the Earth's frame of reference). By this time the field-line is well within the polar cap and poleward of the ionospheric particle cusp.

With these effects in mind, we now consider the variations in the particles which would be seen at the foot of a newly-opened field line as it evolves over the dayside magnetopause and into the tail. The mirroring effect of the converging field lines means that only particles which have very small pitch angles at great altitudes will reach the ionosphere. Hence we here only consider field-aligned particles—more general characteristics of the mid-altitude cusp can be predicted by similar considerations of the full pitch angle distribution. In general, the distributions will also be altered by pitch-angle scattering and possible acceleration processes between the magnetopause and the ionosphere. However, the overall cusp characteristics can be qualitatively explained in terms of adiabatic particle motion.

The first ions observed in the ionosphere would be the highest energy ions injected near the X-line, immediately after reconnection. Because of the acceleration on crossing the magnetopause, these ions will have energies which are a factor of about 2 or 3 higher than in the source (subsolar) magnetopause. Subsequently, lower energy ions, also injected immediately after the field line was reconnected, will arrive at the same time as more energetic ions which have been injected at later times (and hence from higher magnetic latitudes as the field line moves over the magnetopause). Hence the lowest energy of the observed ions falls with time. Initially, the temporal variation of the highest energy of the precipitation is uncertain because of any variation of the source magnetosheath population with latitude and the decay of the acceleration (as the field line straightens). However, as the point where the field line threads the boundary passes from the dayside toward the lobe, the magnetosheath flow and temperature become more constant, while the acceleration on crossing the boundary continues to decrease (and turns negative poleward of the cusp), causing a continuous reduction of the upper energy and total flux of the precipitating particle spectrum. This decay is observed as the foot of the field line moves poleward through the regions which have been termed cusp, mantle and polar cap.

The precipitation characteristics (the lower and higher cut-off energies, the mean energy, the energy flux and the number flux) at the foot of a field line at any instant of time will all depend only upon the time elapsed since the field line was reconnected. Hence, in Fig. 2, the dashed lines would join points where the precipitation characteristics are the same. Note that these dashed lines are largely L-shell aligned, so the ion dispersion is predominantly with latitude (this will be true even if the IMF has a large B_y component)—as is generally observed to be the case (P. T. Newell, private communication, 1992). At the bottom of each part of Fig. 2 is a plot of the variation of the lower cut-off energy with latitude. In part (a) only the highest energy ions associated with field-lines which are recently reconnected are observed. At the poleward edge of the region of newly-opened flux is a discontinuous drop in the energy, poleward of which there is only the weak, low-energy polar ion precipitation on "old" open field lines. In parts (b–d) this cut-off moves to higher latitudes as the first-reconnected field lines move poleward, as part of the convection excited by the burst of reconnection. In (c) the energy observed at the low-latitude edge of the cusp has decreased because reconnection has ceased and hence the most recently reconnected field lines are "ageing". In part (d), the second reconnection burst has produced a second region of newly-opened flux, on which higher energy ions are found. The boundary between the two regions is marked by a discrete jump in ion energy, reflecting the different reconnection times of the field lines. The nature of these jumps will be discussed in Section 5.

4. A SIMPLE TIME-DEPENDENT MODEL OF THE LOCAL-TIME OCCURRENCE OF THE CUSP

The pulsating cusp model (Lockwood and Smith, 1989; Smith and Lockwood, 1990; hereinafter referred to as the LS model) predicts that the cusp is the particle precipitation signature of reconnection events (FTEs). The model is a generalization of that discussed by Reiff et al. (1977), in that the reconnection rate is not, in general, considered to be steady. However, it is known that the cusp is seen with varying probability throughout most of the region from 9 to 15 M.L.T. (Newell and Meng, 1988; Newell et al., 1989). This is demonstrated by Fig. 4, which shows

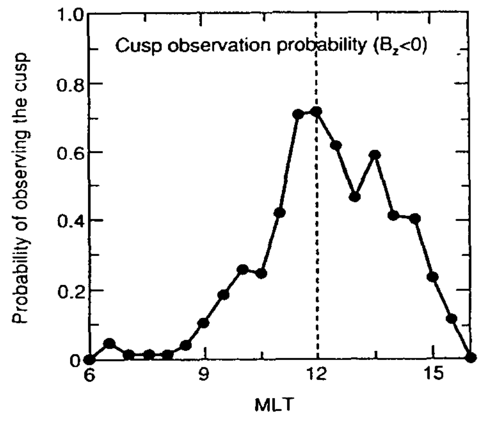

FIG. 4. PROBABILITY OF OBSERVING THE CUSP AS DERIVED FROM DMSP MEASUREMENTS FOR $B_z < 0$ BY NEWELL et al. (1989).

the results of Newell *et al.* (1989) for the probability of an observing satellite intersecting the cusp as a function of M.L.T. for $B_z < 0$. In this section we investigate the implications for the LS pulsating cusp model of these cusp occurrence statistics during southward IMF.

4.1. *The model*

In the LS model, the cusp is found on the "newly opened" flux produced by reconnection, as described above. If the rate of reconnection remains constant there are no magnetopause FTEs (i.e. there is just "quasi-steady" reconnection) and the LS model predicts a steady-state cusp. However, this is only one limit of a general range of behaviour. The other limit occurs when reconnection proceeds as a series of pulses with no reconnection between them. In this limit, the LS model predicts a series of isolated and evolving cusp patches, each being a FTE footprint. If these patches persist for longer than the interval between reconnection bursts, a cusp will always be present at some M.L.T. It should be noted that in general the variation of the reconnection rate may be such as to produce a behaviour anywhere between the "steady" and "discrete event" limits. Previously, the cusp occurrence statistics have been interpreted in terms of the steady-state limit. In this section, we illustrate how the discrete event limit can equally well reproduce the time-averaged cusp statistics.

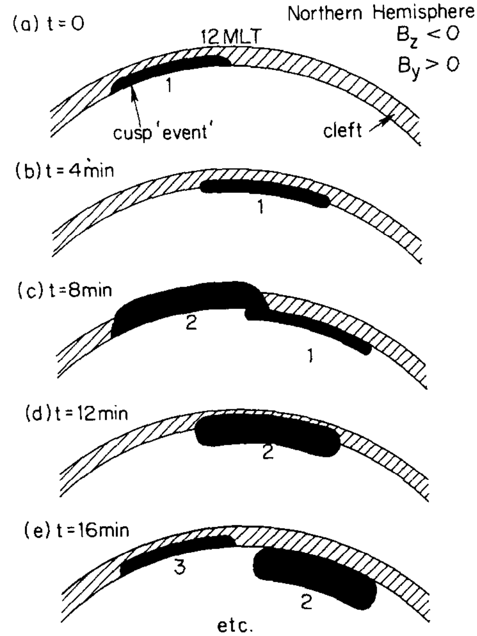

FIG. 5. SCHEMATIC SHOWING THE MOTION OF FTE FOOTPRINTS IN THE IONOSPHERE FOR $B_z < 0$, AS PREDICTED BY THE PULSATING CUSP MODEL.
The hatched area is the cleft/LLBL. Events 1, 2 and 3 are described in the text.

Figure 5 shows the motion of the FTE signatures (i.e. the cusp patches in the LS model) in the Northern Hemisphere for IMF $B_z < 0$ and $B_y > 0$. The patches are reconnected in the order 1, 2, 3 and subsequently move in the manner predicted in Fig. 3. The hatched region is the cleft/LLBL, taken here to be on closed field lines. The areas shaded black denote the newly-opened flux tube regions which are the FTE footprints. From the response time of ionospheric flows to IMF changes, Lockwood and Cowley (1988) predict that each FTE flow signature lasts about 10–15 min before being subsumed into the polar cap: this is consistent with recent observations (Lockwood *et al.*, 1990a–c). If the FTE repetition period has its average value of about 8 min (Rijnbeek *et al.*, 1984; Berchem and Russell, 1984), then at least one "active" FTE footprint will exist at all times. As described in the previous section, the precipitation in each of these patches varies with the time elapsed since it was reconnected. An event is not shown after about 15 min, when the ion precipitation has decayed to the low-flux, low-energy polar cap spectrum. Thus the cusp patches "fade" when they have moved poleward by approximately their own latitudinal width. This is exactly the behaviour of the 630 nm transient aurorae observed from the ground (Sandholt, 1988; Sandholt *et al.*, 1990a,b).

For illustrative purposes, in Fig. 5, we show two reconnection bursts (those which produce the patches labelled 1 and 3) which do not erode the LLBL completely, whereas the other (that giving rise to patch 2) does. How much a closed LLBL is eroded by the newly opened flux region depends upon the magnetopause reconnection rate. The North–South extent of the open flux tube region can be any size and is dependent on the size of the enhancement in the magnetopause reconnection rate and the duration of that enhancement. Thus a low-altitude spacecraft may traverse a cusp signature either with or without an accompanying cleft/LLBL signature on the equatorward edge. Both these possibilities are indeed observed by DMSP (Newell *et al.*, 1989).

Ground-based measurements show (at least for the relatively few events observed thus far) that the FTE footprint is typically about 1500 km in the East–West direction and about 300 km North–South (Lockwood *et al.*, 1990). Thus, for a typical North–South pass of a low-altitude satellite, each footprint would be crossed in about 45 s. Furthermore, the optical data show that only the larger events have been detected by the EISCAT radar. Hence, the mean latitudinal widths are likely to be lower, with values of 100–200 km (consistent with the mean cusp width for $B_z < 0$). The FTE footprint moves East–West with a speed below about 3 km s^{-1}. Thus, in the time taken for the spacecraft to cross the patch, the FTE footprint will move East–West by about 100 km at most, i.e. by typically less than 10% of its length. Thus, to first order, the FTE is stationary with respect to a polar orbiting spacecraft. Thus we may assume that the probability of the spacecraft detecting the cusp on a specific pass is directly related to the probability distribution of the FTE footprints. In other words, if we can calculate the probability of an FTE signature being at a specific M.L.T. we will, for the LS model in the discrete event limit, obtain the likelihood that the cusp will be observed by a spacecraft crossing the boundary region at that M.L.T.

In the simple calculation presented here, we start by choosing an M.L.T. range at which the FTE is formed. Because our simple model does not allow for any evolution in the longitudinal extent of the events, the extent of this X-line projection (merging gap) is the same as the longitudinal extent of the events it generates. The M.L.T. about which this merging gap is centred is treated as a free parameter. In the following, we calculate the probability distribution of event occurrence as a function of M.L.T. by using a number of assumptions and inputs, based on experimental results. These are:

(1) that the initial East/West component of the event motion is the same for each event;

(2) this component subsequently decreases at a constant rate during each event's lifetime;

(3) that all events have the same longitudinal extent;

(4) that events repeat every 8 min for continuously southward IMF, but on average occur every 11 min during an hour for which the average IMF B_z is negative.

These assumptions are discussed in the following section. The M.L.T. of the X-line centre is then varied, so that the distribution best fits the occurrence distribution observed by Newell *et al.* (1989). This best fit therefore defines the location of the projection of the reconnection X-line required by the model.

4.2. *Inputs to the model*

Newell *et al.* (1989) present cusp occurrence statistics for intervals when the B_z component of the IMF is negative and when the B_y component exceeds 3 nT in magnitude (i.e. $B_y > +3$ nT and $B_y < -3$ nT). The data presented by Lockwood *et al.* (1989b) indicate that for such conditions 630 nm transient events initially move with an eastward/westward component (depending on the sense of B_y) of typically 3 km s^{-1}. These events have a lifetime of about 15 min, at the end of which the zonal component of the event velocity has fallen to zero. We thus allow the zonal speed of the events to decelerate at a constant rate from 3 km s^{-1} to zero over an event lifetime of 15 min (i.e. the acceleration is -3.125 m s^{-2}). For any time in the lifetime, we can therefore compute the M.L.T. position of the FTE signature, converting distances into M.L.T. differences for a constant cusp latitude of 75°. Using the event repetition time of 8 min found by Lockwood *et al.* [consistent with the FTE repetition rate at the magnetopause determined by Berchem and Russell (1984) and Rijnbeek *et al.* (1984)], the probability distribution with M.L.T. can then be calculated. The events are here taken to have a (constant) longitudinal extent of 1500 km. This is an average of the values deduced by Lockwood *et al.* (1990b).

However, we must also take into account that the probabilities given by Newell *et al.* (1989) were based upon a statistical survey using hourly averaged IMF data. Lockwood (1991b) has shown that the polarity of IMF B_z is stable for periods of one hour or more only 40% of the time. Thus in the hourly averaged data used in Newell *et al.*'s statistical survey, some of each hour with mean $B_z < 0$ would, on average, have $B_z > 0$. From the data set used by Lockwood (1991b) we can estimate that in any one-hour period with mean southward IMF, the field will, on average, be positive instead of negative for approximately 25% of the time. To account for this, we have reduced the probability predicted by the model by 25%. Effectively, the mean time between FTEs in hourly periods of mean southward IMF is taken to be $8/0.75 = 11$ min. This reduction effectively assumes that the probability of observing the cusp for northward IMF is zero, which for steady-state conditions is incorrect. However, one has to ask what happens to the cusp during a change of IMF. For a change from southward to northward IMF, the time between the cessation of southward reconnection at the nose of the magnetopause and the start of northward reconnection in the lobes is of the order of 5 min (the travel time between the nose and the lobes). However, there is no reason to believe that reconnection starts immediately, hence there may be a further delay of a few minutes before a lobe FTE (and hence, for the model presented here, the northward IMF cusp) forms. The 15 min of northward IMF (during the typical hour for which the IMF is southward) is generally not contiguous but is most likely to occur in two or three separate periods. Hence, for simplicity, we assume that each hour has periods of northward

IMF during which no event is seen. Note that this does not mean that the probability of observing the cusp during a period of steady northward IMF is zero. For the reverse transition, i.e. from northward to southward IMF, magnetopause reconnection will occur at the lobes and at the subsolar point at the same time. This will not change the cusp observation probability but will affect the plasma characteristics. The pulsating cusp model would predict almost simultaneous injection events both from the dayside and the tail lobe into the low-altitude cusp. The footprint of the southward IMF (dayside magnetopause) FTE would give ion energy falling with latitude (as discussed earlier). This would be immediately equatorward of the northward IMF (lobe) footprint for which ion energy would conversely rise with latitude. Hence, the resulting signature would be a "bowl"-shaped ion signature in energy–time spectrograms, with ion energy falling with latitude to a minimum and then increasing again up to a sharp poleward boundary. This is a feature which is indeed sometimes observed in satellite data. Note that this is a rather different signature from the purely southward IMF "double" cusps and cusp patches, discussed in Section 3 above and further in Section 5.

4.3. *Model results*

In Fig. 6 we show the results for $B_y > 3$ nT and compare them to the Newell *et al.* (1989) results (the points joined by a solid line). The solid line gives the modelled probability of observing just one FTE signature, P_1, the dashed line shows the probability of observing two or more events, P_2, and the dot-dash line is the sum of these two probabilities ($P_1 + P_2$). The model values are given as a function of the difference in M.L.T. from the eastern edge of the X-line projection, Δ M.L.T. The observational results are given as a function of M.L.T. The two scales have been adjusted to give best agreement, for which the X-line projection is at the M.L.T. given by the horizontal bar. Similarly, Fig. 7 shows the results for $B_y < -3$ nT, which for the model prediction is a reflection of Fig. 6 about noon.

Figure 5 shows that a number of satellite passes will intersect two regions of newly-opened flux or "cusp patches" and the dashed curves marked P_2 in Figs 6

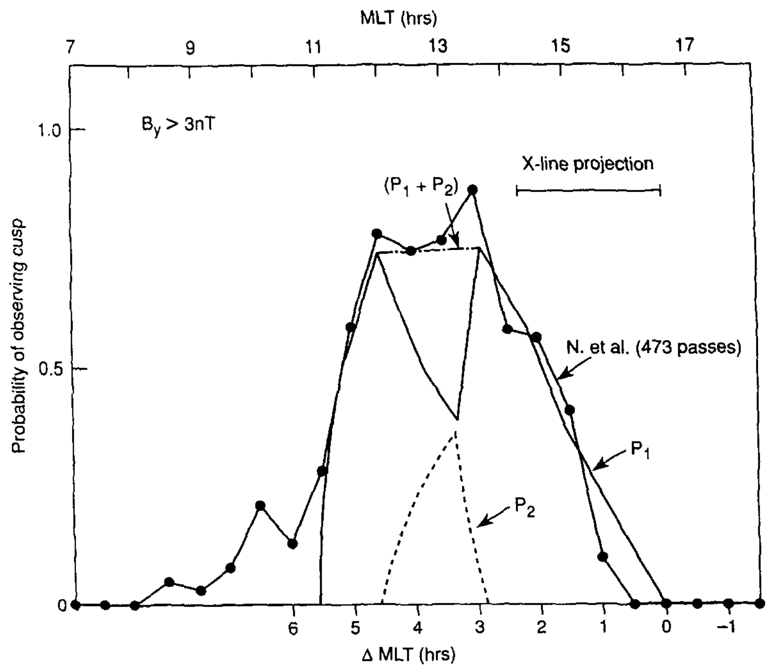

FIG. 6. RESULTS FROM THE SIMPLE FTE MODEL SHOWING THE PROBABILITY OF OBSERVING AN FTE IONOSPHERIC FOOTPRINT AS A FUNCTION OF MLT FOR $B_y > 3$ nT COMPARED TO THE RESULTS OF NEWELL *et al.* (1989). The solid curve labelled P_1 is the probability of observing a single cusp patch, while the dashed line gives P_2, the probability of observing more than one cusp patch. The dot–dashed line is the sum of the two. The reconnection X-line projection used in the model was moved to the position shown to get the best fit with observations.

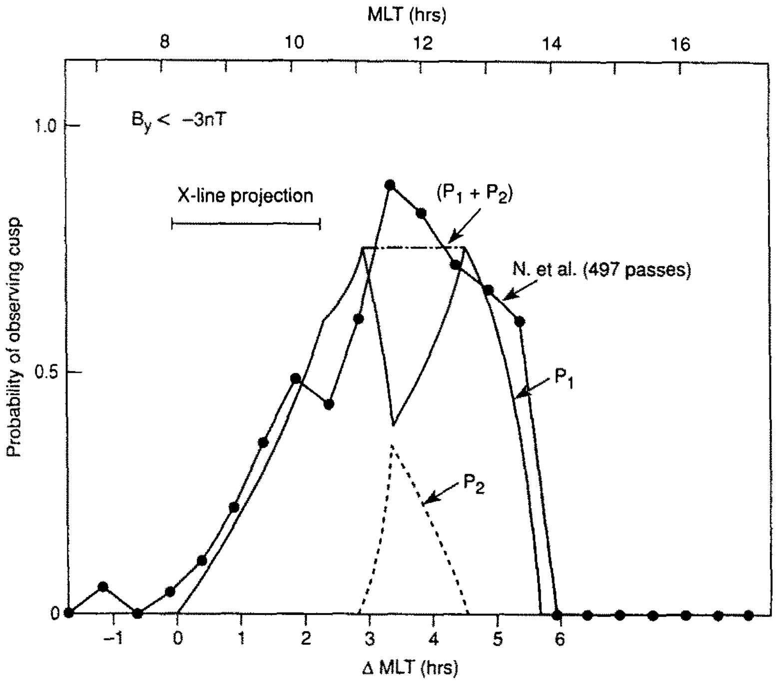

FIG. 7. SAME AS FIG. 3 EXCEPT FOR $B_y < -3$ nT.

and 7 show the probability of this occurring for our simple model. For $B_y < -3$ nT, the maximum in P_2 of 0.35 is at an M.L.T. of 11:00 hours, whereas for $B_y > 3$ nT, it is at 13:00 M.L.T. The analysis of Newell *et al.* (1989) excluded a small number of passes containing "double cusps", i.e. two cusps which were separated in latitude by $>0.5°$, thus they do not affect the statistics. However, if the gap was smaller than this, Newell *et al.* would have identified crossings through two almost contiguous cusp regions as a normal "single" cusp. Hence, the dot-dashed line should be compared to the Newell *et al.* statistics. It can be seen that the agreement is rather good, with the peak, width and asymmetry of the observed distribution all well reproduced.

Lastly, we note that to get a good fit to the Newell *et al.* cusp observations, the X-line projection is at 08:10–10:20 M.L.T. for $B_y < -3$ nT (i.e. in the morning sector), whereas it is at 14:15–16:30 M.L.T. for $B_y > 3$ nT (in the afternoon sector). This shift in merging gap position is consistent with recent theoretical considerations by Cowley *et al.* (1991b). These authors discuss how the stresses exerted on the magnetospheric field by its connection to an IMF with a non-zero B_y component allow, in effect, a partial penetration of the IMF B_y into the magnetosphere and hence cause a B_y-dependent East/West shift of the M.L.T. of the ionospheric footprint of the nose of the magnetosphere. In addition, the magnetopause FTE occurrence determined by Daly *et al.* (1984) suggests that they may be preferentially formed at the afternoon sector equatorial magnetopause for magnetosheath $B_m < 0$ and, if true, this is also consistent with the shift in the ionospheric X-line projection in the Northern Hemisphere for IMF $B_y > 0$, shown in Fig. 7. The corresponding plot by Daly *et al.* for $B_m > 0$ (broadly equivalent to $B_y < 0$) does not clearly define a source region. Any shift in the M.L.T. of the equatorial X-line itself may occur in addition to the mapping asymmetry discussed by Cowley *et al.* However, there is an important difference between these two causes of asymmetry. For the field line mapping change described by Cowley *et al.*, the simultaneous shift in opposite hemispheres will have the opposite sense; however, for a shift in the M.L.T. of the X-line location, the shift would have the same sense in the two hemispheres. The statistics of Newell *et al.* are dominated by Northern Hemisphere data, but Southern Hemisphere data were included, however these were reflected in M.L.T. about noon. This implies that the asymmetry evident in Figs 6 and 7 is actually due to the effects described by Cowley *et al.* and not due to a motion of the X-line in M.L.T. We also note that Crooker (1979) used the anti-parallel field-merging hypothesis to predict a B_y-dependent shift, of opposite sense in the two hemispheres, similar to that predicted by Cowley *et al.* However, this model also predicts that reconnection will occur at high latitudes near noon for large B_y: this is not consistent with magnetopause observations which always indicate that the reconnection is close to the equatorial plane (e.g. Daly *et al.*, 1984; Gosling *et al.*, 1990).

Several points should be noted about the simple analysis presented here. Firstly, if our estimate that the IMF is northward for, on average, 25% of the time for a southward hourly average is too great, all the probabilities presented here will be underestimates. In general, movements of the "merging gap" would broaden the distributions whilst reducing the peak values. Furthermore, the event sizes and zonal speeds are based on EISCAT radar observations and may only apply to the larger events which were most easily resolved. All probabilities would be reduced if the mean longitudinal extent of the events used here is an overestimate. Hence, the fit may be improved further with more accurate input to the model. However, the calculations presented here do serve to show that the pulsating cusp model, even in its "continual discrete events" limit, could explain the observed cusp occurrence statistics and hence the large occurrence probabilities of the cusp in satellite data does not argue against an event cusp model.

5. DISCONTINUITIES IN CUSP DISPERSION CHARACTERISTICS AND DOUBLE CUSPS

The probability of observing a pair of cusp patches (P_2 in Figs 6 and 7) appears to be rather high, if we consider that double cusps have not been extensively reported in the literature. One example is given by Burch *et al.* (1986), where a distinct gap appears between regions of cusp precipitation. The gap between the two cusp regions would have to be larger than 0.5° for Newell *et al.* (1989) to identify the events as a double cusp (P. Newell, private communication, 1991). In this section we point out that an intersection of two (or more) cusp events (probability P_2) would not have been classed as a "double cusp" by Newell *et al.*

The formation of a gap between regions of cusp precipitation, formed by sequential bursts of magnetopause reconnection, is a feature of the FTE signatures where the newly-opened flux can "overtake" older open tubes. This is a feature of many FTE flow signature models (e.g. Southwood 1985, 1987; Goertz *et al.*, 1985; Lockwood *et al.*, 1988, 1990b; Wei and Lee, 1990), if the signature persists for a long enough period. However, careful reading of the relevant publications reveals an important difference between the original Southwood and Goertz *et al.* models—in that Southwood points out that the signature will not move poleward for long enough for it to move into the old polar cap—i.e. it will not overtake the "older" open field lines.

The model of FTE signatures put forward by Cowley *et al.* (1991a) and in Section 2 of this paper is different from the previous models in this important respect. This is because it prescribes both the form of the flows outside the region of newly-opened flux and when the flows cease, such that no "overtaking" occurs. A new FTE will append itself directly equatorward of the old one without any region of "older" open flux between them. Hence with this model, Newell *et al.* (1989) would not have identified the two events as a double cusp. As discussed in Section 3, the only signature that a particle detector on a spacecraft would observe is a jump in ion energy as the spacecraft crossed from one event into the other, as shown for the lower cut-off energies in Fig. 2. For large IMF B_y, the two FTEs may separate in longitude due to the large tension force exerted by the bent reconnected field lines, as demonstrated in Fig. 3. Indeed for this case two separated cusps would be observed only for dawn–dusk orbits as the spacecraft skims the polar cap boundary region. Hence the model of FTE signatures proposed here predicts double, separated cusps would be seen most often for dawn–dusk satellite orbits through the cusp region when the magnitude of the IMF B_y component is large.

The jump in ion energy between the two FTE signatures (cusp patches) can be predicted if we assume adiabatic ion precipitation from a specified ion injection point. In this respect, it is simplest to consider the lower energy cut-off of the ions because, for any one time of observation, these ions will have had the longest time of flight and hence were the first to be injected into the magnetosphere. This is useful because the injection of such lowest energy ions will be close to the X-line and hence we need only consider one injection point. For any other ions we would have to bear in mind that ions are injected continuously as the flux tube evolves over the dayside magnetopause.

The question arises as to where this injection point is. Smith and Lockwood (1990) have proposed that even for subsolar reconnection, the particles may not effectively be injected until the mid-altitude cusp of the magnetic field. In this suggestion, the mixture of magnetosheath and magnetospheric plasma moves as a coherent bubble (a magnetopause FTE) from the X-line to the magnetic cusp. This was proposed for two reasons: firstly, ion dispersion is not observed in magnetopause FTEs (such that ion energy falls with latitude) and secondly, pitch-angle energy dispersion indicates that the particles move adiabatically from the mid-latitude cusp (Menietti and Burch, 1988). We here comment that this "bubble" mechanism may not be needed. If particles continuously stream across the magnetopause while the newly-opened flux tube is on the dayside, then roughly the same energy spectrum will always be found on the looped, newly-opened field lines of the magnetopause FTE (irrespective of its latitude). Concerning the injection point measurements, it is interesting to note that the energy–latitude dispersion yields injection points close to the subsolar magnetopause: indeed, this was the chief piece of evidence used by Reiff et al. (1977) to show that the cusp particle injection was caused by reconnection. The pitch-angle/energy mapping of Menietti and Burch relies upon a simple model for the magnetic field strength at all points on the evolving newly opened field line, from the injection point to the satellite. This may well cause the estimated injection point to be closer than for the energy/time dispersion, which employs the particle dispersion and convection velocity along the satellite track, but does not rely on a magnetic field model.

In the light of this discussion, we here use an initial injection point at the subsolar magnetopause, i.e. at the X-line. Where appropriate we will note the implications of the "bubble confinement" concept of Smith and Lockwood. Were this to act, it would effectively reduce the injection distance. From these assumptions we can calculate the decay in the lower cut-off energy at the equatorward edge of an "older" patch and the same value for the poleward edge of a "newer" patch and hence investigate the magnitude of the discontinuity in the lower cut-off ion energy across the join between two adjacent patches. The probability of observing such a discontinuity is P_2.

The top panel of Fig. 8 shows the probability P_2 of observing two cusp patches as a function of Δ M.L.T., the M.L.T. relative to the merging gap position, for IMF $B_y < -3$ nT (as was previously shown in Fig. 7). Note that if IMF B_y has a small magnitude P_2 will increase until for $B_y \approx 0$ there is no zonal motion of the patches and P_2 becomes equal to unity at all M.L.T. where the cusp is observed, provided the event lifetime always exceeds the event repetition period.

The lower panel of Fig. 8 predicts the variation with Δ M.L.T. of the lower cut-off energies of the precipitating ions for the "older" and "newer" cusp patches. In these plots it has been assumed that there is a continuous spectrum of ions injected onto each newly-opened field line at the subsolar magnetopause from a few eV up to a maximum energy of 5 keV. Because we are here considering only the low-energy

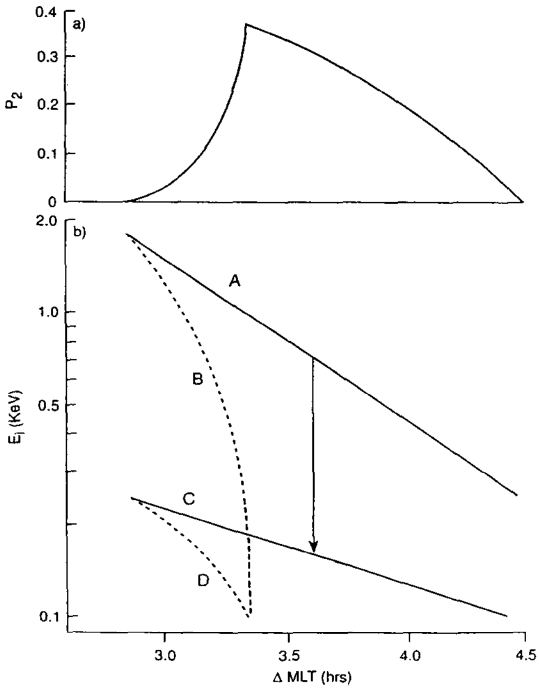

FIG. 8. PANEL (a) SHOWS THE OCCURRENCE PROBABILITY (FROM FIG. 7) OF SEEING A DOUBLE CUSP PATCH FOR $B_y <$ -3 nT.
(b) Shows the variation with M.L.T. (relative to the merging gap position) of the lower cut-off energy of injected ions at low altitudes. The figure is fully described in the text and can be used to predict the jump in ion energy detected when a spacecraft crosses from one FTE signature into an adjacent one (e.g. solid arrow).

cut-off of the precipitating spectrum, we assume adiabatic motion from an injection point at a distance of 1.2×10^8 m (corresponding to injection and any acceleration taking place close to the subsolar X-line). At times after the arrival of the lowest energy ions from the subsolar magnetosheath, ions of greater energy will continue to precipitate, these having been injected across the magnetopause at higher latitudes and at later times while the field line moves over the dayside magnetopause.

We must allow for the duration of the reconnection burst: magnetopause observations indicate that this is about 2 min on average (Elphic, 1990). For the average repetition period of FTEs of 8 min, this gives a total time-of-flight difference of 6 min between the most recently injected ions of the older event (i.e. at its equatorward edge) and the first injected ions of the newer event (i.e. at its poleward edge). All other parameters are identical to those used to produce Figs 6 and 7.

The uppermost curves (A and B) are for the "newer" FTE, the lower ones (C and D) are for the "older" FTE. The solid lines are the lower cut-off energies of the precipitating ions as a function of Δ M.L.T. for the instant at which two ionospheric cusp patches are first present at that M.L.T. The dashed lines (B and D) are similar to the solid lines except they are the lower cut-off ion energies at the last instant when two patches are present at that M.L.T. Once formed, a double patch will disappear for one of two reasons, depending on the Δ M.L.T. For Δ M.L.T. less than 03:35 h (i.e. at the peak of P_2), when the double patch (and hence the energy jump) disappears, it is because one or both of the patches move to a greater Δ M.L.T. For Δ M.L.T. greater than 03:35 h, the disappearance of the double patch is because cusp/mantle ions are no longer observed on the older of the two patches. The energy drop for a specific Δ M.L.T. can be calculated from this figure. For example, the vertical arrow shows the maximum jump (decrease) in the lower cut-off energy observed by a satellite as it crosses from the newer cusp patch into the older patch for the first moment when both are present at Δ M.L.T. of 3.6 h. For this example, this is a drop of 550 eV. At later times the drop decays to zero as both patches evolve. Thus, depending on the time of observation, the magnitude of the energy jump will be between 550 eV and zero at this Δ M.L.T.

Notice that for small Δ M.L.T.s there can be a large jump in energy (>1.5 keV) within the cusp precipitation region, yet the probability of seeing this is low, as given in Fig. 8(a). Examination of Fig. 8 shows that for most cases the jump in the lower cut-off energy will be below 1 keV and for a large subset the jump will be less than a few hundred eV. It is thus not likely that these jumps have elicited much attention when the data have been inspected. However, inspection of cusp spectra frequently reveals jumps in ion energy of precisely the kind predicted here (e.g. Newell and Meng, 1991; Baker *et al.*, 1990). Indeed, the DE2 cusp crossing interpreted as an FTE signature by Lockwood and Smith (1989) shows jumps at both edges of the region that these authors interpret as the newly-opened flux region of the FTE.

Figure 8 aims to simulate the situation for large IMF B_y, when events have a large zonal motion and we must consider the relatively low probability of these jumps (P_2). However, for $B_y \approx 0$ we should expect the probability P_2 to be higher because there will be little or no zonal motion. Indeed, it will be possible to have two jumps present at the same time, even for the 8 min repetition period of FTEs (in practice, this period can be smaller than the average of 8 min, and hence even more than two jumps could be present). The lack of zonal motion means that the maximum size of jumps could be even larger than in Fig. 8. However, if FTEs repeat more frequently than the average of once every 8 min, the magnitude of the jumps will be correspondingly smaller.

At this point we should also consider the implications of the "bubble" hypothesis of Smith and Lockwood (1990). In effect this reduces the injection distance of the ions and hence the differences in the time-of-flight. As a result, the magnitude of the jumps would be smaller than predicted by Fig. 8 which is for a larger injection distance.

Lastly, we must stress that we have here chosen to model the discrete limit of the LS cusp model. However, generalization to the Southwood *et al.*/Scholer FTE model (of bursts of enhanced reconnection over a background level) is straightforward. For a continuous but time-varying reconnection rate there will be a non-zero reconnection rate between the bursts. The energy jumps would then no longer be instantaneous. Instead there will be a ramp down in energy, the slope of the ramp being dependent on the reconnection rate during the intervals between the bursts. For the generalized Southwood *et al.*/Scholer model there are no discrete cusp patches, but the change in reconnection rate will manifest itself as a change in the gradient of the dispersion signature. For the other limit of the model, where the reconnection becomes quasi-steady, the jumps flatten and a continuous (steady-state) ion dispersion signature will be seen. Thus, the cusp patches will be seen most clearly for the discrete limit: as the reconnection rate becomes more steady-state, then the "jumps" in ion energy will be less apparent.

The ion energies in Fig. 8 are lower cut-off values, i.e. the minimum values that are observed at a given place and time. This is because we have only considered those ions injected at the X-line at the subsolar magnetopause. The cusp definition employed by Newell *et al.* (1989) is based upon the average energy, which will be somewhat higher than the values in Fig. 8. In addition, the electron characteristics have not been considered here. Hence it is not possible to define cusp and mantle, using the Newell *et al.* criteria, from these simple considerations of the lower cut-off energy. We note that the ion energy jump may frequently cross the threshold between the cusp and mantle (as defined by Newell *et al.*), hence the mantle/cusp boundary would then be placed at the boundary between two FTE signatures.

6. DISCUSSION

The simple model used in this paper was not designed to model the full complexity of the real cusp (for example, FTE footprints will have widely varying speeds, lifetimes, local time extents and generation points). Our aim was to show how a polar orbiting spacecraft would observe a series of discrete FTEs on a statistically averaged basis. The cusp width will be dependent on event speed, extent and lifetime. However, to a polar-orbiting spacecraft the FTE footprints would look almost exactly the same as a stationary cusp.

The statistical patterns should thus be treated with caution. They do provide an "average" picture of the magnetosheath particle injection under varying conditions. However, the fact that the statistical surveys of the cusp previously published find high occurrence probabilities near noon does not necessarily suggest the cusp to be time-stationary. Using a very simplified model, we have demonstrated that the observed distributions can be produced by a series of discrete, moving features. This has been achieved using event dimensions and zonal motions which have been observed in a limited number of cases by ground-based radars and optical instruments. In order to match the observed cusp occurrence distributions, we have introduced a shift in the M.L.T. of the merging gap which is consistent with that predicted by Cowley *et al.* (1991b).

We also stress that the ideas put forward by Lockwood and Smith (1989) and Smith and Lockwood (1990) do not argue that the cusp is always a series of discrete events, but that discrete events are one limit of the more general LS model, the other limit being a steady-state cusp. However, in general, the reconnection rate behaviour (and hence that of the cusp) will fall between these two extremes. A survey of the predicted jumps in the ion energy dispersion characteristics is required to determine the range of behaviour of the cusp in general.

Lastly, we point out that this paper has not discussed the northward IMF cusp. The reason is simple: the pulsating cusp concept has grown out of the ground-based observations of transient auroral and plasma flow bursts and these can only be observed, at present, when the IMF is southward. For northward IMF the cusp is too far poleward for such observations. We note however that recently published ISEE observations (Gosling *et al.*, 1991) verify the existence of reconnection at the tail lobe magnetopause. In addition, Sandholt (1991) has recently found evidence for sunward-moving auroral transients on the poleward edge of the cusp during northward IMF. Thus the pulsating cusp concept, driven by transient reconnection at the sunward edge of the tail lobe, may be applicable to northward IMF conditions as well.

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