The ionospheric response to flux transfer events: the first few minutes

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Abstract. We utilise high-time resolution measurements from the PACE HF radar at Halley, Antarctica to explore the evolution of the ionospheric response during the first few minutes after enhanced reconnection occurs at the magnetopause. We show that the plasma velocity increases associated with flux transfer events (FTEs) occur first ~100–200 km equatorward of the region to which magnetosheath (cusp) precipitation maps to the ionosphere. We suggest that these velocity variations start near the ionospheric footprint of the boundary between open and closed magnetic field lines. We show that these velocity variations have rise times ~100 s and fall times of ~10 s. When these velocity transients reach the latitude of the cusp precipitation, sometimes the equatorward boundary of the precipitation begins to move equatorward, the expected and previously reported ionospheric signature of enhanced reconnection. A hypothesis is proposed to explain the velocity variations. It involves the rapid outflow of magnetospheric electrons into the magnetosheath along the most recently reconnected field lines. Several predictions are made arising from the proposed explanation which could be tested with ground-based and space-based observations.

1 Introduction

The concept of reconnection at the dayside magnetopause, introduced over 30 years ago (Dungey, 1961), has been very successful in describing many of the large-scale features of the high-latitude ionosphere and magnetosphere. The influence of the interplanetary magnetic field (IMF) on the magnitude and direction of high-latitude ionospheric convection patterns, and the explanation of the cusp ion plume are two notable achievements. However, many aspects of reconnection are still poorly understood despite the fact that it is a process of paramount importance in determining the structure, dynamics and variability of the high-latitude ionosphere-magnetosphere system. There remains major controversy whether reconnection occurs in a quasi-steady manner (Newell and Sibeck, 1993) or as a transient phenomenon at a single site on the magnetopause (e.g. Lockwood *et al*., 1994), or indeed whether reconnection occurs simultaneously at multiple sites on the magnetopause (Kan, 1988; Pinnock *et al*., 1995). For any set of prevailing solar wind conditions, there is no accurate quantitative model to determine when, where or for how long reconnection occurs on the magnetopause. Therefore it is impossible to determine accurately the energy transferred into near-geospace from the solar wind, and thus predict with any degree of confidence the consequences of reconnection on the closely-coupled magnetosphere-ionosphere system.

There is an increasing body of evidence that suggests that transient reconnection events, commonly termed flux transfer events (FTEs), can be the major source of energy transfer from the solar wind into the magnetosphere. Initially, FTEs were studied using data from single or dual spacecraft in orbits that were not ideal for understanding the physics involved (e.g. Russell and Elphic, 1979; Rijnbeck *et al*., 1984). The search for the ionospheric signatures of FTEs has increased markedly in the last decade. The first observations were made using the STARE VHF radar system (Goertz *et al*., 1985), and thereafter signatures using incoherent scatter radar (Lockwood *et al*., 1990, 1993); optical (Sandholt *et al*., 1990); magnetometer (Lanzerotti *et al*., 1990) and HF radar data (Pinnock *et al*., 1991, 1993) followed. With the further development of the HF radar systems (Greenwald *et al*., 1995), measurements of unparalleled spatial and temporal resolution are now possible (Pinnock *et al*., 1995), offering new insight into the ionospheric signatures of FTEs.

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In this work, we shall exploit further the data set described by Pinnock *et al*., (1995). We suggest that our data bring into question the existing concepts for describing the first few minutes of the ionospheric response to flux transfer events.

2 The conventional picture of ionospheric response to a flux transfer event

When enhanced reconnection occurs at the magnetopause, conventional wisdom suggests that two responses in the ionosphere are expected. First, an equatorward protrusion grows onto the ionospheric footprint of the 630 nm auroral emission associated with the cusp precipitation on a time scale of about 3 min., i.e. Alfvén wave travel time from the reconnection site at the magnetopause to the ionosphere (see Fig.1a, c). This concept was introduced by Cowley (1984), and developed further by others (e.g. Southwood 1985, 1987; Freeman and Southwood 1988; Cowley *et al*., 1991; Cowley and Lockwood, 1992). If reconnection continues, then the protrusion grows with time. If reconnection diminishes, then the 630 nm emission protrusion relaxes to its original quasi-circular shape.

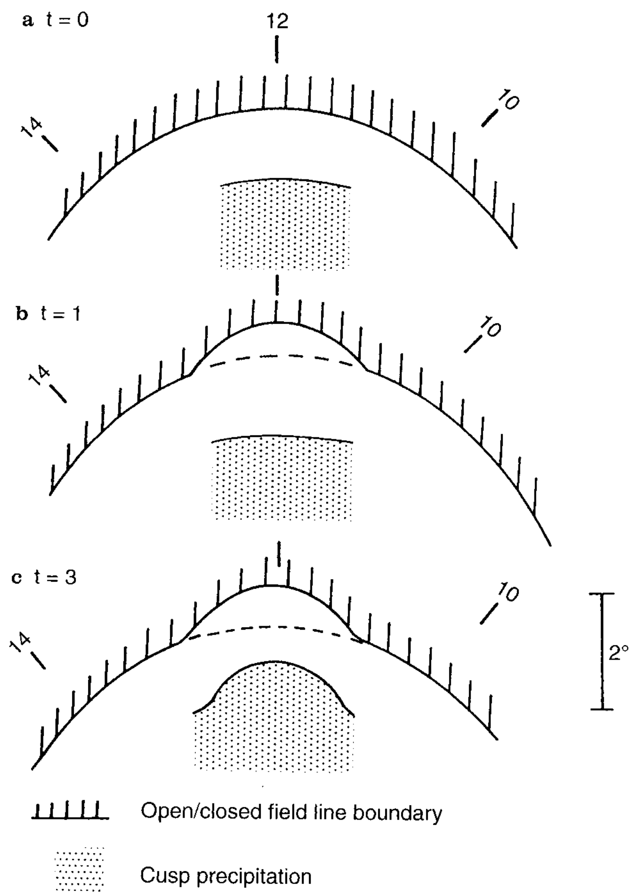

Fig. 1 a–c. Schematic diagram showing the relationship between the ionospheric footprint of the open/closed field line boundary, marked by poleward edge of the 557.7 nm emission (*hatched area*), and the location of the 630 nm emission caused by cusp like energetic particle precipitation (*stippled area*). **a** is for 'steady state' conditions, $t = 0$, **b** as **a** but for a few 10s of seconds after reconnection at the equatorial plane has been enhanced, and **c** for $t = 3$ minutes after enhanced reconnection has occurred in the equatorial plane, and the associated Alfvén wave has arrived at the ionosphere. Assumptions made in constructing this figure are explained in the text.

There is a latitude displacement between the ionospheric location of the open/closed field line boundary and the location of the 630 nm emission caused by cusp precipitation (e.g. Lockwood and Smith, 1992; Minow, 1995, private communication). The open/closed field line boundary is marked by the poleward limit of a weak 557.7 nm emission that results from plasmasheet particle precipitation (Fig. 1a). This latitude displacement arises because the most energetic cusp ions take about 3 min to transit from the dayside reconnection site to the ionosphere, during which time the flux tubes convect poleward. The factors affecting the latitude extent of this "auroral dark" region are the distance from the reconnection site on the magnetopause (normally assumed to be the sub-solar point) to the ionosphere, the field-aligned energy of the ions, and the component of the reconnection electric field that translates into poleward plasma velocity in the ionosphere. Here we have ignored the azimuthal component of motion caused by the y-component of the IMF. We note that the above description is accurate only if two assumptions hold. First, there is some background level of reconnection occurring, otherwise the open/closed field line boundary and the equatorward limit of the 630 nm emission will be collocated. Second, the poleward flow remains constant. In practice, the poleward flow may increase owing to the enhanced reconnection electric field. Therefore the equatorward protrusion will not be as pronounced because the cusp ions will convect further poleward during their transit from the magnetopause, compared with their counterparts immediately before enhanced reconnection started.

Second, the Alfvén wave also carries with it the first information about reconnection at the magnetopause, and the orientation of the sheath magnetic field, a proxy for the IMF. Therefore the first dynamical response in the ionosphere, namely an increase in plasma velocity, would also be expected to be observed at the equatorward edge of the 630 nm emission region (Southwood, 1987) about 3 min after enhanced reconnection occurred at the magnetopause. This suggestion is supported by the observations of Lockwood *et al.* (1993) and Pinnock *et al.* (1993) who show plasma velocity increases associated with FTE signatures occurring within the region of cusp precipitation. Their examples are for occasions when the IMF was likely to have had a significant y-component. Thus the effects of field-line tension will force the ionospheric plasma to have a considerable azimuthal component to its motion which makes the events easier to detect.

Important issues remain. For example, it has not yet been determined what controls the magnitude of the equatorward motion of the 630 nm emission or the increase in ionospheric plasma velocity arising from enhanced reconnection at the magnetopause. In practice, both the boundary and the plasma velocity appear to respond to enhanced reconnection (e.g. Lockwood *et al.*, 1993). Also none of the authors cited considers the ionospheric consequences to the region of 557.7 nm emission, i.e. the open/closed field line boundary, in the first few minutes after enhanced reconnection at the magnetopause.

3 A revised view of the ionospheric response to flux transfer events

A re-examination of the Halley PACE radar (Baker *et al.*, 1989) data for 5 February 1994, originally presented by Pinnock *et al.*, (1995), has caused us to question the current description of the ionospheric effects of flux transfer events in the first few minutes after reconnection occurs at the magnetopause. We suggest that the initial ionospheric disturbance associated with an FTE is a velocity perturbation occurring in the vicinity of the open/closed field line boundary, rather than near the equatorward edge of the cusp ion precipitation. Our new observations impose severe constraints upon the time variation of the imposed electric field.

3.1 High time resolution data

The HF radar data used in this study are from a sounding pattern that optimises the spatial and temporal resolution capabilities of the radar. The sounding mode alternately samples on a chosen beam whilst sequentially scanning through the other beams. The integration time for each beam is 5 s, giving 10 s resolution on the chosen beam, which for this study is the beam along the magnetic meridian. Each 160 s, a full scan is completed. The range resolution is 15 km.

The line-of-sight velocity (Vlos) data (Fig. 2) show that there is a region at the furthest ranges with considerable velocity variability between adjacent ranges and between consecutive 10 s samples from the same range. This is especially clear between 1500–1600 UT. The power spectra from individual ranges for this region have broad (>200 m s^{-1}) Doppler spectral widths, the principal characteristic of the ionospheric footprint of cusp precipitation (Baker *et al.*, 1995; Rodger *et al.*, 1995). More equatorward, a second region is observed where the Vlos measurements are more consistent from one range to the next and from one sample to the next. The corresponding power spectra have narrow Doppler spectral widths (<150 m^{-1}), and therefore this region is not the ionospheric footprint of cusp precipitation (Baker *et al.*, 1995). On this occasion, we observe scatter several degrees equatorward of the ionospheric signature of cusp precipitation. This is rare. We have not yet determined under what circumstances it occurs, and thus detailed examination of other examples is not yet possible.

There are many short-lived Vlos enhancements, first seen 100–200 km equatorward of the region to where the

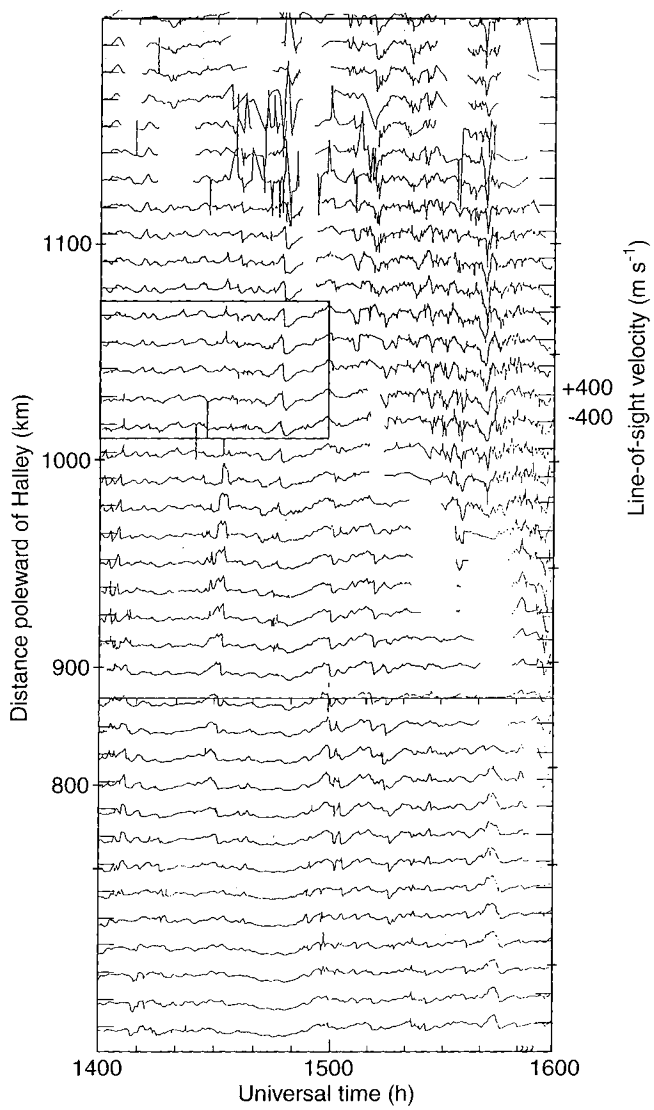

Fig. 2. The line-of-sight velocity determined at 15 km range intervals from 700–1200 km poleward of Halley for the period 1400–1600 UT on 5 February 1994. The region of highly variable line-of-sight velocity which moves progressively equatorward is where cusp precipitation is occurring. This is especially clear above ~1000 km range after 1500 UT. The data in the *boxed area* are reproduced in Fig. 3 on an expanded scale

cusp precipitation maps. The rise in speed appears long in comparison with the fall in speed. These events move poleward with time, a feature more easily seen in Fig.1 of Pinnock *et al.* (1995). The largest amplitude Vlos variations occur within 3–5 range gates (45–75 km) of the most equatorward limit where the variation can be identified i.e. well equatorward of the region showing the highly variable Vlos measurements. Similar observations have been made with EISCAT in the early afternoon sector by Moen *et al.*, (1996), but these authors did not focus upon the equatorward extent of the velocity transients. Optical observations made from Svalbard do not show any evidence of such large or rapid equatorward motion of the 630 nm cusp precipitation region, e.g. Sandholt *et al.* (1994).

A further critical factor is that the equatorward edge of the broad spectral width region (i.e. cusp precipitation) often moves equatorward by up to 50 km immediately after velocity transients reach this location. Examples occur at 1505, 1510 and 1545 UT, which can be readily seen in Fig. 1 of Pinnock *et al.* (1995). This is what is predicted by previous work (e.g. Southwood, 1987).

Pinnock *et al.* (1995) conclude that the Vlos signatures of these events are identical to the ionospheric signature of FTEs described by Pinnock *et al.* (1991; 1993), when allowance is made for the 3 min resolution of the full scan data. Occasionally events are observed well equatorward of the cusp precipitation region, but do not propagate poleward into it. An example occurs at ~1432 UT between 900–1000 km poleward of Halley. For these occasions, we believe that the disturbance drifts azimuthally out of the beam used for these high resolution measurements.

In Fig. 3, we present a subset of Fig. 2 to demonstrate the precise character of the rising and falling Vlos signatures. Each event has the characteristics of a "shark's fin", namely an exponential rise followed by an exponential fall in the value of Vlos. We have compared exponential functions of the form $V = V_o(1 - e^{-t/T})$ to each of the events labelled 1–3 on Fig. 3. These events were selected to represent a range of velocity variations and durations.

Figure 4a shows the average Vlos for the five ranges shown in Fig. 3 for the event that starts about 1416 UT. The data have been averaged by determining the start time of the event in each range, and designating this time as $t = 0$. Data from each subsequent time step is then averaged. The typical uncertainty of the averaged Vlos is ~20 ms^{-1}. Using this technique, the poleward motion of

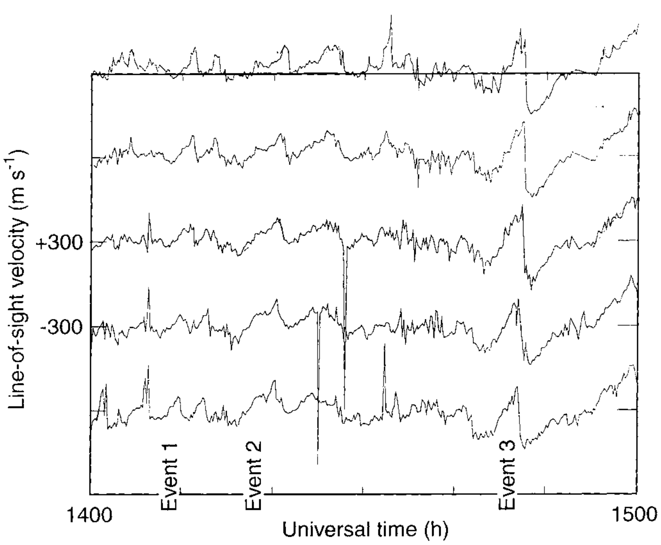

Fig. 3. Five contiguous ranges of the line-of-sight velocity for the interval 1400–1500 UT on 5 February 1994. The three events marked are studied in further detail, together with the rapid fall in velocity immediately following event 3. There are two very large negative velocity spikes at 1425 and 1428 UT. We believe that these are caused by interference, and are not geophysically significant.

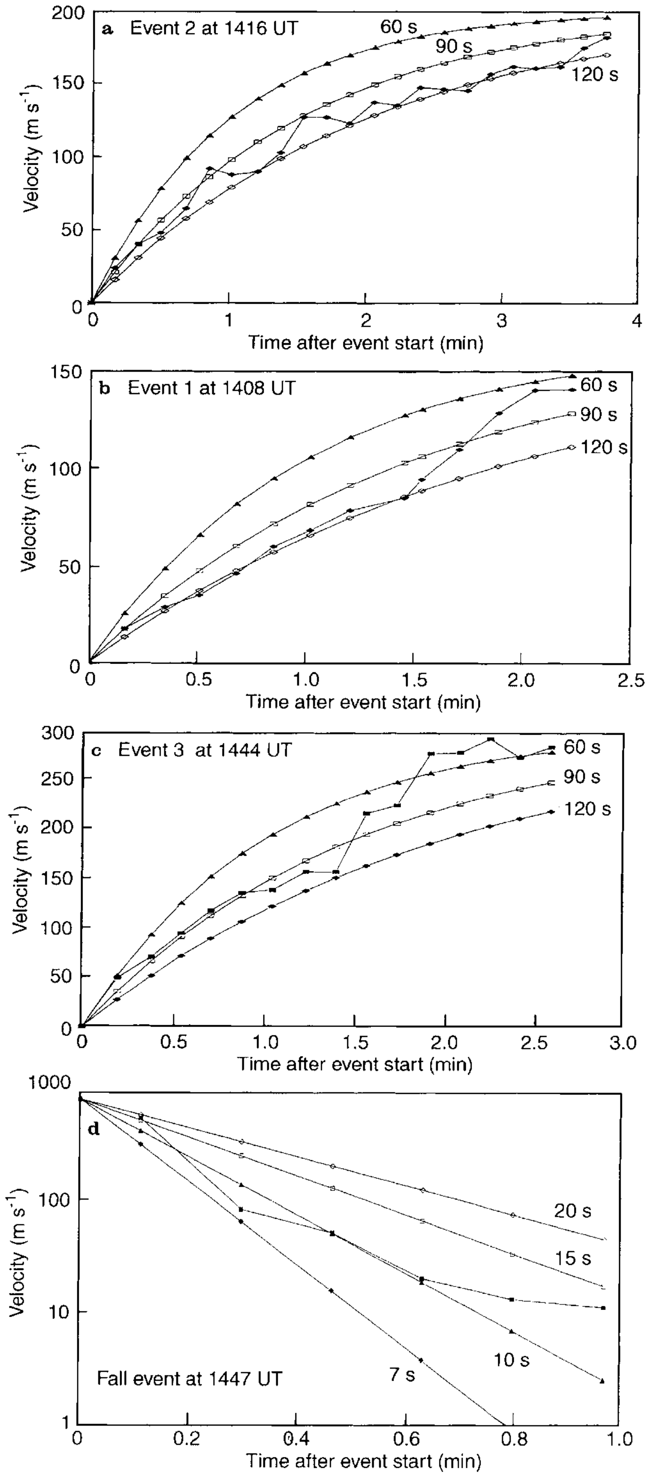

Fig. 4a–d. Line-of-sight velocity measurements, averaged over the 5 range gates shown in Fig.3, as a function of time since the start of the event. The way in which the line-of-sight velocity measurements have been averaged is described in the text. Exponential curves of the form $V = V_o(1 - e^{-t/T})$ are shown using three time constants, $T = 60, 90$ and 120 s. **a** event 2 starting at 1416 UT, **b** event 1 starting at 1408 UT and **c** event 3 starting at 1444 UT. **d** Falling line-of-sight velocity measurement for interval immediately following event 3. *Curves* derived using the time constant curve $V = V_o(e^{-t/T})$ with $T = 7, 10, 15$ and 20 s are shown.

the event 2 across these five ranges is ~1.5 km s^{-1}, whereas the plasma motion varies between ~200 and 500 ms^{-1} over the same interval (Fig. 3). The difference between the phase and plasma motion can be reconciled if the disturbance front of the event is tilted with respect to the perpendicular to the observing direction.

Exponential curves with time constants (T) of 60, 90 and 120 s are also shown as Fig. 4a. These suggest that a time constant of ~100 s is appropriate. The data for events 1 and 3 have been treated in the same way (Fig. 4b,c). Again a time constant of ~100 s is consistent with the observations, though we note that both of these events may comprise the superposition of two events lasting 1–1.5 min. The phase speed for event 1 (1408 UT) is about 0.8 km s^{-1} whereas for event 3 (1444 UT) the event occurs simultaneously in all ranges suggesting a phase speed > 7.5 km s^{-1}.

We have adopted a similar approach when considering the falling event that closes event 3 (see Fig. 3). On this occasion (Fig. 4d), we use the form $V = V_o(e^{-t/T})$. We have used a range of time constants ranging from 5 to 20 s, and plotted both these curves and the observation on a logarithmic scale. The time constant that corresponds best to the data is about 10 s, but our measurements are at 10 s intervals with a 5 s integration period. Therefore, there is considerable uncertainty in this time constant.

4 Implications and interpretation of the new observations

The ionospheric effect of the Vlos changes is seen up to 200 km equatorward of the location of the cusp precipitation. We suggest that this separation comprises two parts. First, the distance between the open/closed field line boundary and the cusp precipitation region. Over this study interval, the poleward speed of the plasma varies between about 400 and 800 m s^{-1}. If the time for the energetic ions to travel from the magnetopause reconnection site to the ionosphere is 3 minutes, then they will arrive between 70 and 150 km poleward of the open/closed field line boundary. The second component arises because the ionosphere is incompressible. Figure 2 indicates that the largest velocity variations are within 3–5 range gates (~45–75 km) of the equatorward limit of the velocity perturbations. We suggest that where the largest velocity variations occur marks the ionospheric footprint of the open/closed field line boundary, and owing to flux continuity the velocity variations can be observed somewhat equatorward of this boundary. The combined distances from these two elements is 115–225 km, very close to the observations. Therefore, we suggest that the Vlos variations are caused by a process associated with the open/closed field line boundary. Cowley and Lockwood (1992) discuss the effects of enhanced reconnection on the open/closed field line boundary but do not identify clearly either the field-aligned current carriers or the separation between the open/closed field line boundary and the ionospheric footprint of cusp ion precipitation.

To accelerate plasma near the ionospheric footprint of the open/closed field line boundary, an additional electric field is required. We suggest that this may be achieved by the establishment of a field-aligned current caused by the outflow from the magnetosphere of energetic magnetospheric particles. It is well accepted that during reconnection magnetosheath particles enter the magnetosphere, one of their ionospheric signatures being the 630 nm cusp emission. At the same time, magnetospheric electrons can 'escape' into the sheath (e.g. Gosling *et al.*, 1990). The characteristic energy of the magnetospheric electrons near $L = 9$ in the equatorial plane, a typical value of the last closed flux tube on the dayside, is ~ few keV. Indeed it is the part of this population with low pitch angles that is responsible for the weak 557.7 nm emission (Fig. 1). As the bounce time of such particles is short (~ a few seconds), one immediate consequence of enhanced reconnection is that the flux of keV electrons causing the 557.7 nm emission will be lost through the magnetopause to the magnetosheath. Thus, the dark region of no emission will grow an equatorward protrusion. This is the first prediction of our new description, and is shown schematically in Fig. 1b. High-time resolution, sensitive all-sky imager data will be required to observe such events. At oblique incidence, the finite height emission profile will make it impossible to detect the "dark region". Therefore to be observed, the dark equatorward protrusion must be close to the observing station which obviously must be in darkness. Hence South Pole station and Svalbard are key locations to search for these events, being well-instrumented sites frequently under the ionospheric footprint of the cusp and in darkness at magnetic noon in winter.

The energetic magnetospheric electron population will be lost to the magnetosheath very quickly (~ a few bounce periods) after the flux tube is involved in reconnection. It is necessary to maintain change neutrality. Onsager *et al.* (1995) have noted the importance of the ionospheric source of electrons in maintaining charge neutrality. We also noted that recently small fluxes of very energetic ions (~200 keV) have been detected by the POLAR satellite on open cusp-like field lines (Spence, private communication). These particles too may have a role to play in maintaining charge neutrality. At mid-altitudes (20, 000 km), Burch (1985) suggests that charge neutrality is maintained by a precise balance between the number of energetic ions and electrons of sheath-like energies. However he does not consider the situation in the critical region discussed here, namely the open/closed field line boundary. In summary, we consider that the way in which charge neutrality is maintained on recently-opened flux tubes is an outstanding question.

Associated with the enhanced plasma motion near the ionospheric footprint of the open/closed field line boundary will be a field-aligned current system. The energetic electrons being lost into the sheath could form part of the current system but exactly how the current is carried in the magnetosphere remains an unresolved issue too. Data from the POLAR satellite and any reflight of CLUSTER should be able to address this matter.

One further consequence, which is probably of minor importance, is that during the 3 min period between reconnection occurring and the sheath particles arriving in the ionosphere, energetic ring current protons (electrons) drifting westward (eastward) in the outermost flux tubes of the magnetosphere under gradient and curvature drift will encounter the equatorward protrusion of the open/closed field line boundary. Thus, they will be lost from the magnetosphere, setting up a small upward field-aligned current from the western end (proton loss), and a downward field aligned current (electron loss) at the eastern end of the protrusion. The electric field associated with these currents will tend to decelerate the poleward plasma in the region between the two currents.

The time constants of the rise and fall in the line-of-sight velocity are very approximately 100 and 10 s respectively. We cannot explain either time scale but point out that the rise time is very long compared with the electron bounce time. Hence the rise time may be controlled by processes associated with reconnection.

As a final comment, we note that recent studies of travelling convection vortices (TCVs) (e.g. Yahnin and Moretto, 1996) show that events appear to maximise in their magnetic field variations 1–2° equatorward of the cusp precipitation, and indicate that many TCVs are field-aligned current systems that are evolving very rapidly in space and time. Therefore, some TCVs may be another ionospheric manifestation of the proposed new current system.

5 Conclusions

We have provided new observations of the ionospheric signatures of flux transfer events using high-time resolution measurements from the Halley PACE radar. We find that they are not consistent with current description of FTEs (e.g. Southwood, 1987) in two important ways. Events occur first 100–200 km equatorward of the ionospheric footprint of cusp precipitation, and their maximum velocity variations occur very close to where these events are first observed. We suggest that the velocity variations are initiated in the vicinity of the ionospheric footprint of the open/closed field line boundary. This is contrary to current model descriptions which place both effects at the ionospheric footprint of cusp sheath-like precipitation. We suggest that the observed velocity variations are caused by an electric field that is in addition to that carried by the Alfvén wave associated with enhanced reconnection that maps to the equatorward edge of the cusp precipitation. The rise time of the new electric field is ~100 s, and its fall time is ~10 s.

A hypothesis for these new observations is proposed. It involves the rapid outflow of magnetospheric electrons from the flux tubes that have just undergone reconnection, which establishes a field-aligned current very rapidly in the vicinity of the open/closed field line boundary. This new hypothesis indicates that there should be an immediate equatorward protrusion of the region of auroral darkness that occurs between the open/closed field line boundary and the cusp precipitation which should be detectable with good ground-based optical observations. Further, the proposed new field-aligned current should be detectable by ISTP spacecraft.

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