Review of ionospheric effects of solar wind magnetosphere coupling in the context of the expanding contracting polar cap boundary model.

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Abstract

This paper reviews the coupling between the solar wind, magnetosphere and ionosphere. The coupling between the solar wind and Earth's magnetosphere is controlled by the orientation of the Interplanetary Magnetic Field (IMF). When the IMF has a southward component, the coupling is strongest and the ionospheric convection pattern that is generated is a simple twin cell pattern with anti-sunward flow across the polar cap and return, sunward flow at lower latitudes. When the IMF is northward, the ionospheric convection pattern is more complex, involving flow driven by reconnection between the IMF and the tail lobe field, which is sunward in the polar cap near noon. Typically four cells are found when the IMF is northward, and the convection pattern is also more contracted under these conditions. The presence of a strong Y (dawn-dusk) component to the IMF leads to asymmetries in the flow pattern. Reconnection, however, is typically transient in nature both at the dayside magnetopause and in the geomagnetic tail. The transient events at the dayside are referred to as flux transfer events (FTEs), while the substorm process illustrates the transient nature of reconnection in the tail. The transient nature of reconnection lead to the proposal of an alternative model for flow stimulation which is termed the expanding/contracting polar cap boundary model. In this model, the addition to, or removal from, the polar cap of magnetic flux stimulates flow as the polar cap boundary seeks to return to an equilibrium position. The resulting average patterns of flow are therefore a summation of the addition of open flux to the polar cap at the dayside and the removal of flux from the polar cap in the nightside. This paper reviews progress over the last decade in our understanding of ionospheric convection that is driven by transient reconnection such as FTEs as well as by reconnection in the tail during substorms in the context of a simple model of the variation of open magnetic flux. In this model, the polar cap expands when the reconnection rate is higher at the dayside magnetopause than in the tail and contracts when the opposite is the case. By measuring the size of the polar cap, the dynamics of the open flux in the tail can be followed on a large scale.

1. Introduction

In this paper we discuss the impact of solar wind magnetosphere coupling on the ionosphere during so called normal solar wind conditions. The ionosphere represents the lower boundary of the magnetosphere, but perhaps more importantly it represents one of the main sinks of energy which is transmitted from the solar wind to the magnetosphere. Since the ionosphere is only weakly ionised and is coupled strongly to the neutral atmosphere, it also plays a role in coupling that energy through to the atmosphere. There is not sufficient space to discuss the detail of the ionosphere and this can be found in text books such as Rishbeth and Garriott (1969), Schunk and Nagy (2000). The main physical process which mediates the coupling between the solar wind and magnetosphere is reconnection between the interplanetary magnetic field (IMF) and the geomagnetic field as originally proposed by Dungey (1961). Thus, in this paper we concentrate on the flow excitation in the ionosphere by reconnection at the dayside and in the tail.

2. Ionospheric convection

The coupling between the solar wind and magnetosphere is dominated mainly by magnetic reconnection at the dayside magnetopause between the IMF and the geomagnetic field, and was first described for southward IMF by Dungey (1961) and for northward IMF by Dungey (1963). The scenario for southward IMF is illustrated in Figure 1 in which a cross section in the noon-midnight plane of the magnetosphere is presented. Reconnection occurs at the sub-solar point of the magnetopause, resulting in newly opened magnetic field lines which are connected to the IMF at one end and the geomagnetic field at the other. Newly reconnected magnetic flux tubes are transported to the nightside due to the motion of the solar wind and then reconnection of the tail field lines causes closed magnetic field lines to return earthward. This process is often referred to as the Dungey cycle.

Under northward IMF conditions the situation is more complex and involves reconnection at locations which are at much higher latitudes well away from the sub-solar point. Typically it is thought that this occurs at points in the tail lobes where the geomagnetic field would be anti-parallel to the draped northward IMF. The convection process that is driven under such conditions is clearly more complex. For example, reconnection can occur between an individual IMF field line and one lobe only, or when the IMF clock angle is low reconnection can occur simultaneously with both lobes (e.g. Imber et al., 2006).

The magnetospheric convection driven by the Dungey cycle also results in ionospheric convection. When the Z component of the IMF is negative, and there is no Y component, ionospheric convection is a simple two cell convection pattern with antisunward flow across the polar cap and sunward flow in at lower latitudes. The addition of a Y component adds an asymmetry to the flows (e.g. Cowley et al., 1991; see Cowley, 1998 for a review) such that one cell becomes more dominant than the other. Under purely northward IMF conditions, two lobe cells are present with sunward convection in the centre of the polar cap. The addition of a Y component to the Z component causes further asymmetry in the flow, and if the Y component is larger than the Z component then a distorted two cell pattern with strong azimuthal flow in the dayside region is often observed.

Average patterns of ionospheric convection were produced primarily by averaging data sets from ground based radars or from low earth orbiting satellites (e.g. Heppner and Maynard, 1987). However, the interpretation of Flux Transfer Events (Haerendal et al., 1978; Russell and Elphic, 1978, 1979) as transient and patchy reconnection and subsequent observations by other authors of this transient process has lead to an alternative consideration of how ionospheric convection is excited. This is referred to as the expanding/contracting polar cap model and follows an initial discussion by Russell (1982), theoretical work by Siscoe and Huang (1985) and Freeman and Southwood (1988), before being finally formalised by Cowley and Lockwood (1992). In this model as flux is added to the polar cap, a twin cell convection pattern is stimulated in the dayside ionosphere, as illustrated by Figure 2a, where the flow is stimulated by the motion of the boundary as the polar cap seeks to return to equilibrium after the addition of the newly created flux. In Figure 2a, the polar cap boundary, i.e. the boundary between open and closed magnetic field lines, is indicated by the solid circle, with the portion of the boundary at which reconnection occurs indicated by the dashed line. The motion of the boundary is indicated by the open arrows. If flux is removed from the polar cap by reconnection in the geomagnetic tail, then a similar twin cell convection pattern is stimulated in the nightside ionosphere (Figure 2b). A standard two cell convection pattern consists of the summation of the two processes. Cowley and Lockwood (1992) proposed that the flow would be stimulated in order to move the newly reconnected flux at the dayside magnetopause into the polar cap, thereby moving the polar cap boundary equatorward. Likewise, a region of newly closed flux on the nightside would result in the same pattern but the polar cap would contract. The timescale for this process in the absence of other processes would be of order 15 – 20 minutes (Cowley and Lockwood, 1992). Thus the difference between reconnection rates at the dayside and in the nightside would determine whether the polar cap was expanding or contracting.

The study of ionospheric flows in the last decade has been improved with the expansion of the Super Dual Auroral Radar Network (SuperDARN) which consists of networks of radars in both northern and southern hemispheres (Greenwald et al., 1995). Doppler velocity measurements made by these radars can be combined to provide maps of the large scale convection pattern at intervals of 2 minutes in general, and, at times, 1 minute (Ruohoniemi and Baker, 1998). In the remainder of this paper we discuss some results that have been attained with the SD radars over the last 10 years which address flow excitation by the model proposed by Siscoe and Huang (1985) and Cowley and Lockwood (1992).

3. FTE flow signatures

There have been many reports of flux transfer events, with the first model described by Russell and Elphic (1978, 1979) based on typical signatures of the magnetic field in a boundary normal co-ordinate system, where the N component is normal to the local magnetopause boundary while the L and M components are in the plane of the magnetopause. Figure 3 presents sketches of the typical signatures of an FTE which are the bipolar signature in the B_N component and an increase in the total field, B_{tot}. The variation in the other two components depends on the relative motion of the FTE and the spacecraft, although in Figure 3, the M component is shown as increasing. The first unambiguous observation of the ionospheric flow stimulated by FTEs was that by Elphic et al. (1990). Thereafter, a number of observations were made by HF radars of signatures which were assumed to be the response to transient reconnection (e.g. Pinnock et al., 1993; Provan et al., 1998; Milan et al., 2000; McWilliams et al., 2000). The first simultaneous observations of a FTE at the magnetopause and flow enhancement in the ionosphere measured by a SuperDARN radar were made by Neudegg et al. (1999). In this study a clear magnetospheric FTE was observed by Equator-S and this was accompanied by a near simultaneous enhancement of the ionospheric flow by the CUTLASS Hankasalmi radar. Furthermore, it was subsequently shown that this FTE excited strong UV aurora equatorward of the footprint of the newly reconnected field lines (Neudegg et al., 2001). This event also demonstrated that the signatures in HF radar data termed pulsed ionospheric flows (Provan et al., 1998; McWilliams et al., 2000), which had been discussed as likely signatures of FTEs, were indeed ionospheric signatures of transient reconnection.

A subsequent statistical study (Neudegg et al., 2000) demonstrated that if the repetition rate of FTEs was greater than 5 minutes, then the tendency was to identify a clear one-to-one response between FTE and ionospheric flow response. If on the other hand the repetition rate was faster, then the flows tended less to the pulsed behaviour and more to flow behaviour associated with continuous excitation.

More recent observations of FTEs and ground signatures have been made utilising the Cluster spacecraft (Wild et al., 2001; 2003). In the first of these a series of FTEs were observed as the Cluster spacecraft moved through the outer post noon magnetosphere to the magnetosheath in a 2 hour interval. The FTEs were seen as enhancements in the total magnetic field, a bipolar variation in the component of the field normal to the magnetopause and also as small bursts of mixed magnetosphere and magnetosheath plasma. Figure 4 presents the radar observations made during the interval in which Cluster observed the FTEs. In this figure the radar backscatter power and Doppler velocity are presented for each of beams 1, 2 and 3. The dashed vertical lines represent the times at which FTEs were observed by Cluster, in addition to an observation of a boundary layer (BL) and three magnetopause crossings (MP). Although the estimated spacecraft footprint was some 2h in local time to the east of the data presented in Figure 4, there were clear pulsations in both Doppler velocity and backscatter power which moved polewards. These are classic pulsed ionospheric flows (PIFs) and poleward moving radar auroral forms (PMRAFs), the latter being identified by arrows in the panels presenting backscatter power. The time variation in the velocity is less clear and so Figure 5 presents the Doppler velocity in beam 3 (top panel) together with, as a time series, the average Doppler velocity between 75 and 76 ^{o} magnetic latitude in the middle panel (blue line). It is clear that with each of the first 4 FTEs there is an enhancement in the Doppler velocity. It should be noted that where there are such enhancements at these lower latitudes, they precede a PMRAF at higher latitudes. Wild et al. (2001) concluded that the PIF/PMRAF originated at the lower latitudes (close to the footprint of Cluster) and then propagated poleward to higher latitudes where they resemble the more classic signatures. This further suggests that the PMRAFs are fossils of ionospheric structuring which takes place at lower latitudes at the footprint of the reconnection site, or merging gap, as also suggested by Davies et al. (2002).

The flows at this lower latitude region were consistent with westward flow. Since the satellite observations were in the post noon sector and the IMF was directed dawnward and southward, Wild et al. (2001) proposed that this region of westward flow corresponded to the newly opened flux tubes. The extent of this westward flow region is difficult to judge from the northern hemisphere alone. Figure 5 (lower panel) illustrates that there were also pulsed flows in the southern hemisphere in a range nearly magnetically conjugate to the northern hemisphere flows presented in this figure. Furthermore, by averaging the Doppler velocity over the same latitude region as the northern hemisphere observations (Figure 5, middle panel, red curve) we see that in association with the first 4 FTEs the flows in the southern hemisphere are also enhanced in near synchronisation with the northern hemisphere observations. Furthermore, a map potential analysis (Ruohoniemi and Baker, 1998) also demonstrates that the flows in the southern hemisphere occur in the dawn LT sector and are clearly eastward directed (see Wild et al., 2003).

This latter observation is important to help assess the location and potential extent of the reconnection site for these events. The two general scenarios are presented in Figure 6 (based on Wild et al., 2003). The two top panels represent the scenario where the reconnection region is localised in the post noon sector and to the east of the radar field of view. The lower two panels represent a case where the reconnection site extends across the noon local time sector. The flow response is summarised by the arrow and while the northern hemisphere radar data alone would not be able to determine which of the two scenarios is the most likely, the addition of the southern hemisphere data demonstrates that the latter case of an extended region across noon is the most likely case.

4. Flow excitation during magnetospheric substorms

The expanding/contracting polar cap model of flow excitation indicates that reconnection in the geomagnetic tail should stimulate flow in much the same way that reconnection at the dayside magnetopause does. There seem to be two distinct categories of reconnection in the tail, azimuthally localised features, termed bursty bulk flows (BBFs) which have a variety of signatures in the ionosphere (e.g. Grocott et al., 2004, Boralv et al., 2005) and the larger scale reconnection which occurs at some stage during the expansion phase of a magnetospheric substorm. A general discussion of substorms is dealt with elsewhere in more detail (Nakamura, 2005), but here we consider the flow excitation associated with substorms. In one such study, Grocott et al. (2002) used the SuperDARN data to demonstrate the excitation of a twin vortex flow on the nightside associated with a modest substorm which occurred during a period of weak northward IMF but with a strong B_y component. The flows were found to occur in the region of the substorm auroral bulge as observed by Polar VIS. Furthermore, the transpolar voltage increased from 40 kV in the pre expansion phase onset interval to 80 kV after onset, before decaying to about 35 kV some 10 minutes into the recovery phase.

This result was confirmed by a statistical study of flows measured by SuperDARN using the IMAGE FUV auroral imager (Mende et al., 2000) to identify the location of the auroral break-up for 67 substorms (Provan et al., 2004). In this study, the ionospheric flows were ordered by the magnetic latitude and magnetic local time of the auroral break-up to remove any spatial averaging caused by differences in the break-up region. The flows were averaged at 2 minute intervals from 30 minutes before onset to 30 minutes after onset. There is a clear development of a two cell convection pattern during the growth phase. Following expansion phase onset the flows in the nightside region near the auroral break-up region become very weak, and the flow appears to be diverted around this region. The estimated cross polar cap potential appears to peak some 10 minutes after the onset although the variability in this parameter is quite large. The enhancement in the cross polar cap potential from just before onset is of order 30 kV, in agreement with Grocott et al. (2002). This work demonstrated for the first time on a statistical basis that the dayside and nightside reconnection both drive flows independently of each other.

5. Large scale response of the polar ionosphere

The last decade has seen an improvement in the ability to image the global auroral and polar regions from space with good (seconds to minutes) time resolution. The VIS (Frank et al., 1995), and UVI (Torr et al., 1995) imagers on board Polar and the FUV imager on IMAGE (Mende et al., 2000) have all contributed to the observations of the dynamics of the auroral oval and polar cap for intervals of 10 – 12 hours at a time.

By comparing observations of the UV aurora with other observations such as the spectral width parameter measured by the SuperDARN radars and low earth orbiting particle measurements, Milan et al. (2003) have demonstrated that the size of the polar cap, i.e. the region of open flux, can be estimated from global auroral images. Since the variation in the amount of magnetic flux can be used to calculate the transpolar voltage, this is an alternative global method of investigating the expanding contracting polar cap model. Figure 7 illustrates how the polar cap area varies during a period when there were a number of changes in the polar cap area as well as 2 magnetospheric substorms. The polar cap area is plotted in the top panel while the lower panel presents the IMF B_z component for this interval. The grey shading of the polar cap area line represents the uncertainty assuming that the estimate of the polar cap boundary is incorrect by ±1 degree of latitude at all magnetic local times.

There are several points to make about this figure. Firstly, it is clear that during the intervals of southward IMF, the polar cap area does increase. This is most easily seen following 0900 UT and after 1400 UT. In the first case the voltage associated with the expansion of the polar cap area is +52 kV and in the second it is +111 kV, with the higher value being associated with the more negative B_z. The two substorms (SB1 and SB2) result in decreases in area of the polar cap. This is particularly clear in the first case when the polar cap area decreases by a factor of 3 following the expansion phase onset, resulting in a voltage of -119 kV. The second substorm occurs during a period of negative B_z and so the decrease is not as marked as reconnection at the dayside still continues. Furthermore, psuedobreakups or small auroral break ups also result in the decline of the polar cap area in the first case (AB1) and a slowing of the increase in the second case (AB2).

In addition, during the second interval of southward IMF, Milan et al. (2003) were able to calculate the reconnection voltage in the frame of the polar cap boundary by using the flows measured by the SuperDARN radars across the boundary. This technique is described in detail by Baker et al. (1997) and has subsequently been used in a number of studies (e.g. Chisham et al., 2004). Using this technique Milan et al (2003) calculated the integrated reconnection electric field between 05 and 19 MLT to be 104 kV during the second substorm growth phase, in good agreement with the value measured from the change in the polar cap area. There was also evidence during this interval for pulsed reconnection at the dayside magnetopause. The good agreement between the two different estimates of the reconnection voltage during this interval is strong evidence in support of the convection excitation discussed by Siscoe and Huang (1985) and Cowley and Lockwood (1992). Finally, when the IMF was northward and reconnection in the tail had stopped, the polar cap area remained constant. This indicates that, during this interval at least, there was no closure of open flux by lobe reconnection in both hemispheres simultaneously. Observation of several intervals allowed Milan et al. (2006) to estimate the rate and duration of flux closure during magnetospheric substorms. These authors found that during a typical substorm ~0.25 GWb of open magnetic flux in the tail was closed.

6. Outstanding questions

Despite the success of the expanding-contracting polar cap model in predicting many of the signatures of ionospheric flow associated with reconnection at the dayside and in the tail, there remain a number of outstanding questions. In terms of the coupling between the solar wind, magnetosphere and ionosphere, we still have a poor understanding of what happens during northward IMF conditions. Suggestions have been made about the nature of flow excitation but there remain unresolved questions concerning the location of reconnection, whether it occurs in one hemisphere only or both hemispheres simultaneously (e.g. Imber et al., 2006), and the consequences for the ionosphere. There also remain a number of questions about the flow generated during substorms. For example, what are the flows and how much flux is typically reconnected during a psuedobreakup, how quickly after expansion phase onset does flow become excited, how long into the recovery phase does flow continue to be excited? Furthermore, there remain questions about the flow excitation in both hemispheres. Also the high latitude SuperDARN radars have been less successful at measuring the ionospheric flow during very disturbed conditions (e.g. magnetic storms), due mainly to ionospheric effects on the propagation of the HF signal. Lower latitude radars are now being planned and deployed to investigate the ionospheric flow during storms.

This paper has concentrated on flow excitation and the dynamics of the polar cap and to a lesser extent the auroral oval. Of course there are other questions that are important in understanding the response of the ionosphere to the solar wind-magnetosphere coupling that have not been addressed due to space constraints. These include the different spatial and temporal scales of auroral activity, the coupling between the ionosphere and thermosphere and how energy can be transported into the lower atmosphere.

7. Summary

The paper presents an overview of the coupling between the solar wind and magnetosphere and the consequences in the ionosphere. It concentrates on reconnection as the main mechanism for coupling and the flow that is then excited in the ionosphere as a marker of magnetospheric convection. The flow excitation model of Cowley and Lockwood is shown to be supported by a wide range of observations, including dayside reconnection, ionospheric flow stimulation during magnetospheric substorms, and the variation in the polar cap area.

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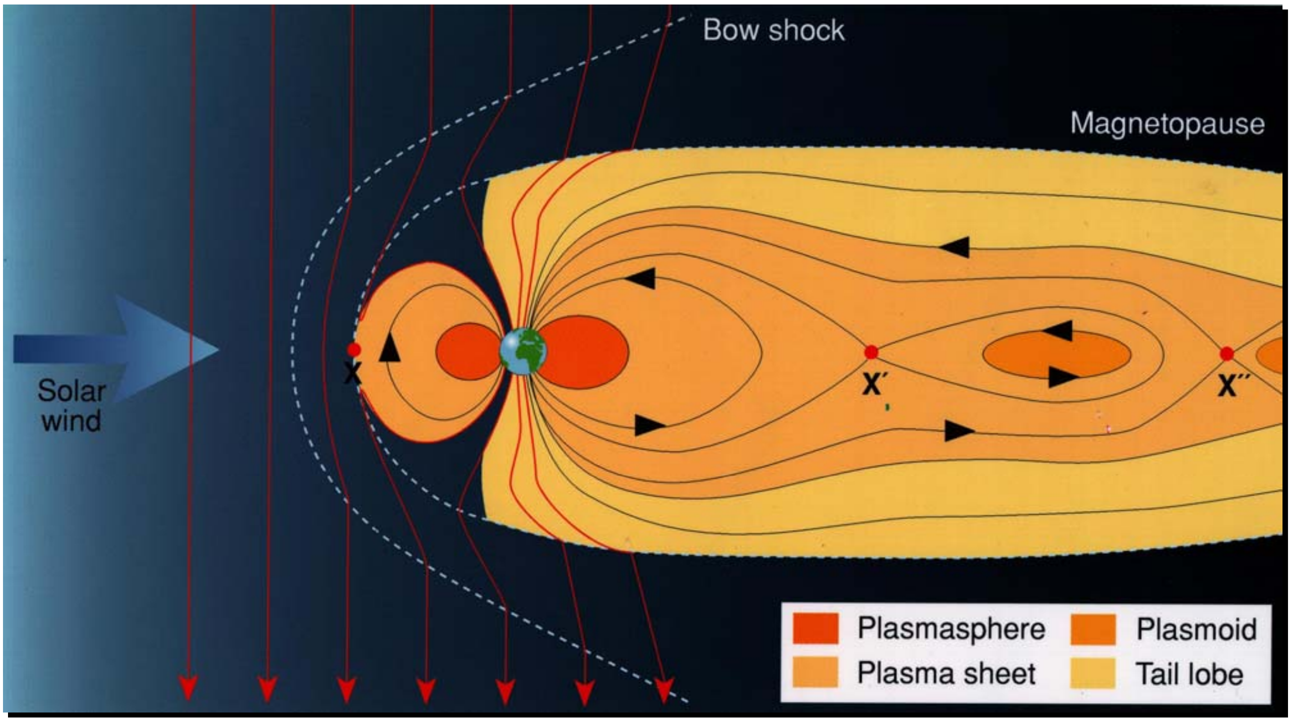

Figure 1. Schematic representation of reconnection at the dayside magnetosphere and in the tail which drives magnetospheric dynamics (after Dungey, 1961).

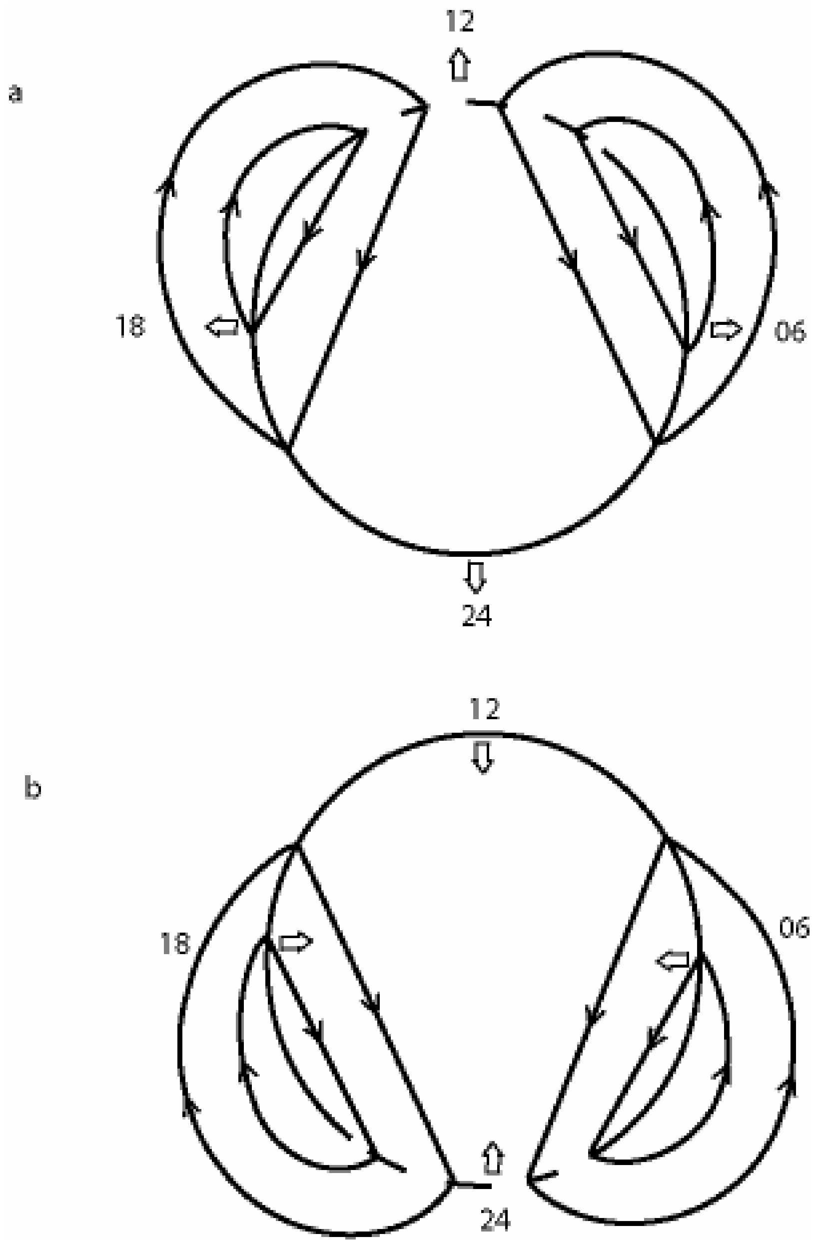

Figure 2. Sketch of the basic form of the time dependent flow excited by reconnection at the dayside magnetopause and in the geomagnetic tail (based on Cowley and Lockwood, 1992)

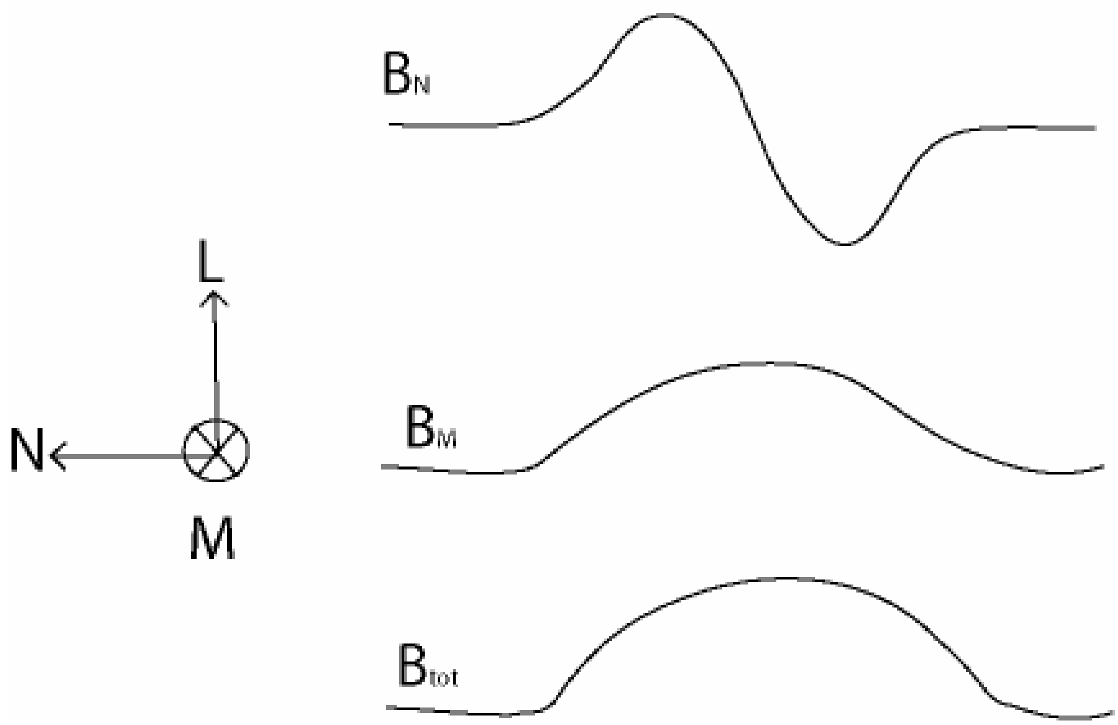

Figure 3. Sketch of the typical signatures of a FTE seen by a space borne magnetometer in boundary normal co-ordinates where the N component is normal to the local magnetopause boundary while the L and M components are in the plane of the local magnetopause boundary.

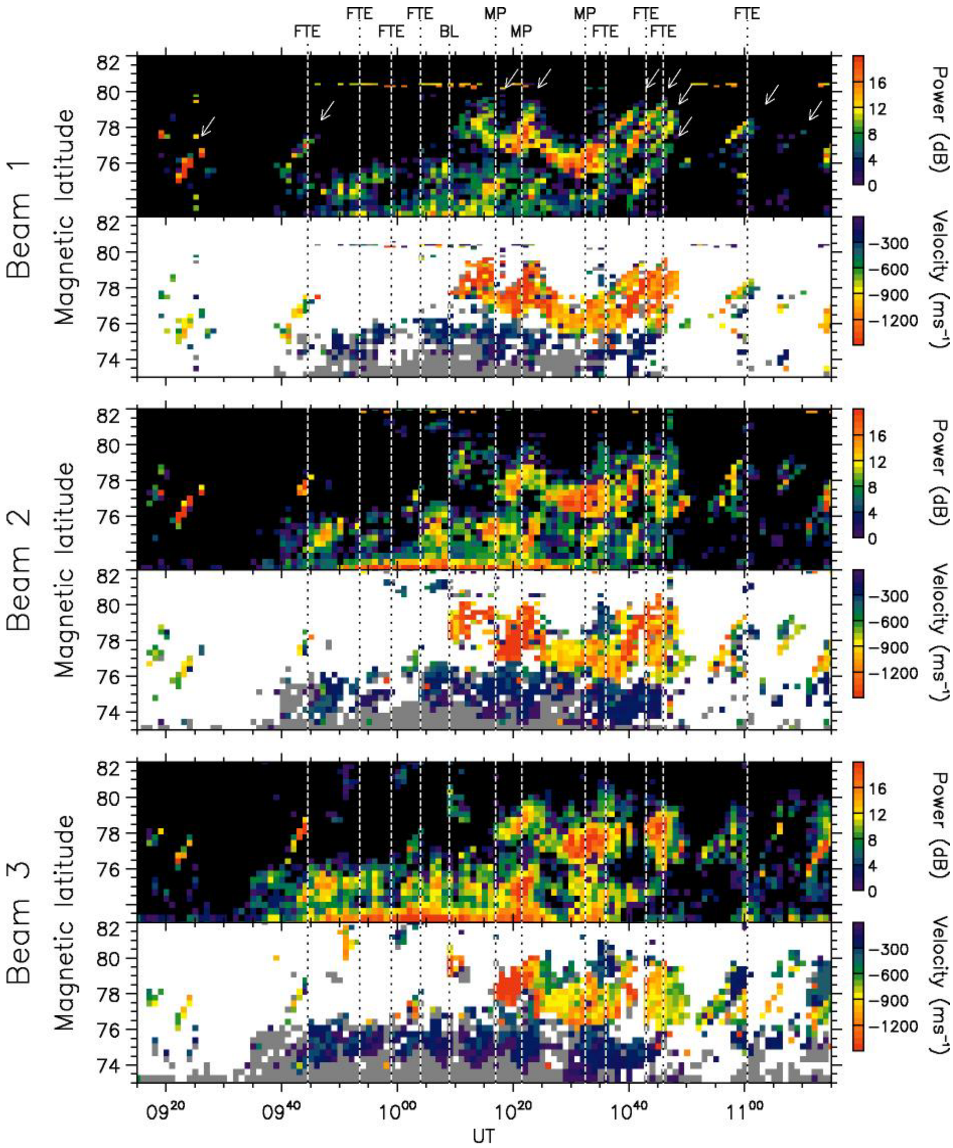

Figure 4. Radar backscatter power and Doppler velocity as a function of magnetic latitude and UT from 3 beams of the CUTLASS Finland radar (after Wild et al., 2001). FTEs and excursions into a boundary layer (BL) and across the magnetopause (MP) are identified by vertical dashed lines.

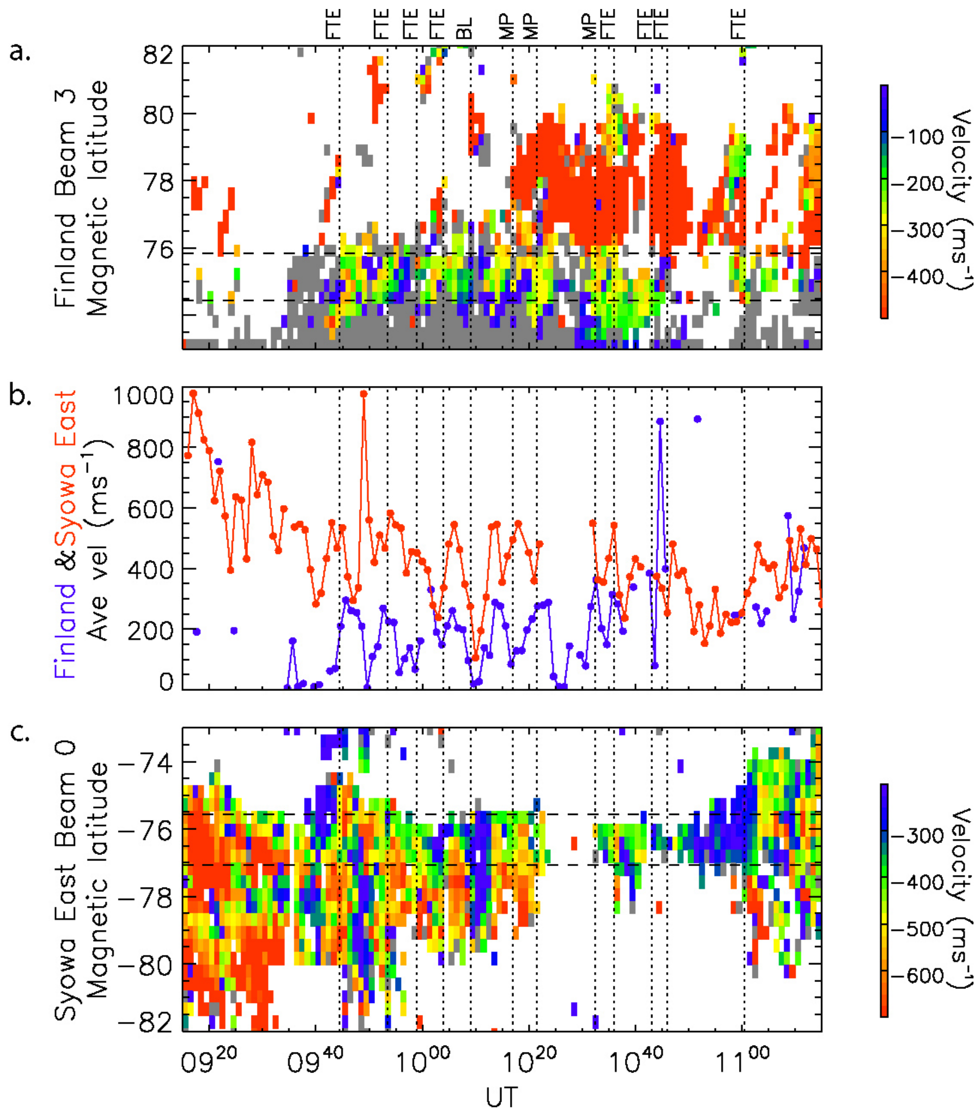

Figure 5. Doppler velocity from Beam 2 of CUTLASS Finland (panel a) and Syowa (panel c). Panel b shows the averaged velocity between the horizontal dashed lines in panels a and c (after Wild et al., 2003).

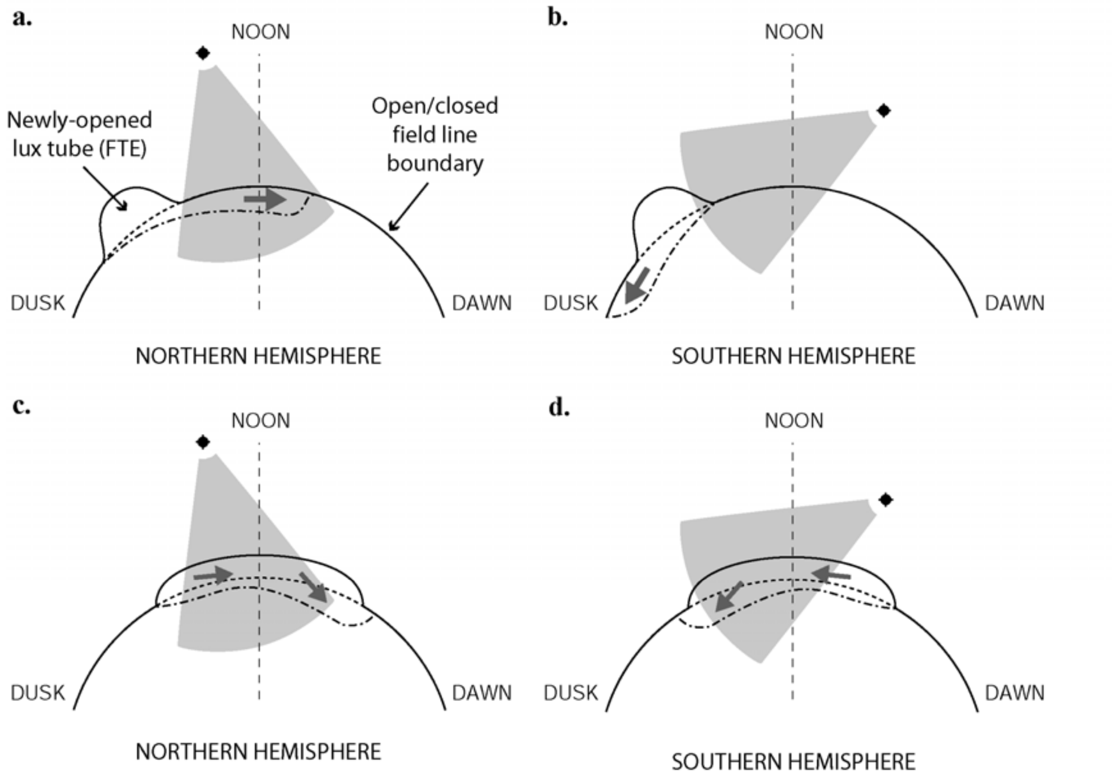

Figure 6. Schematic representations of the possible locations of the newly reconnected magnetic flux at the polar cap boundary and the flows that would be generated for the events shown in Figures 3 and 4. In panels a and b the newly reconnected flux is limited to the post noon sector, while in panels c and d the newly reconnected flux extends across noon.

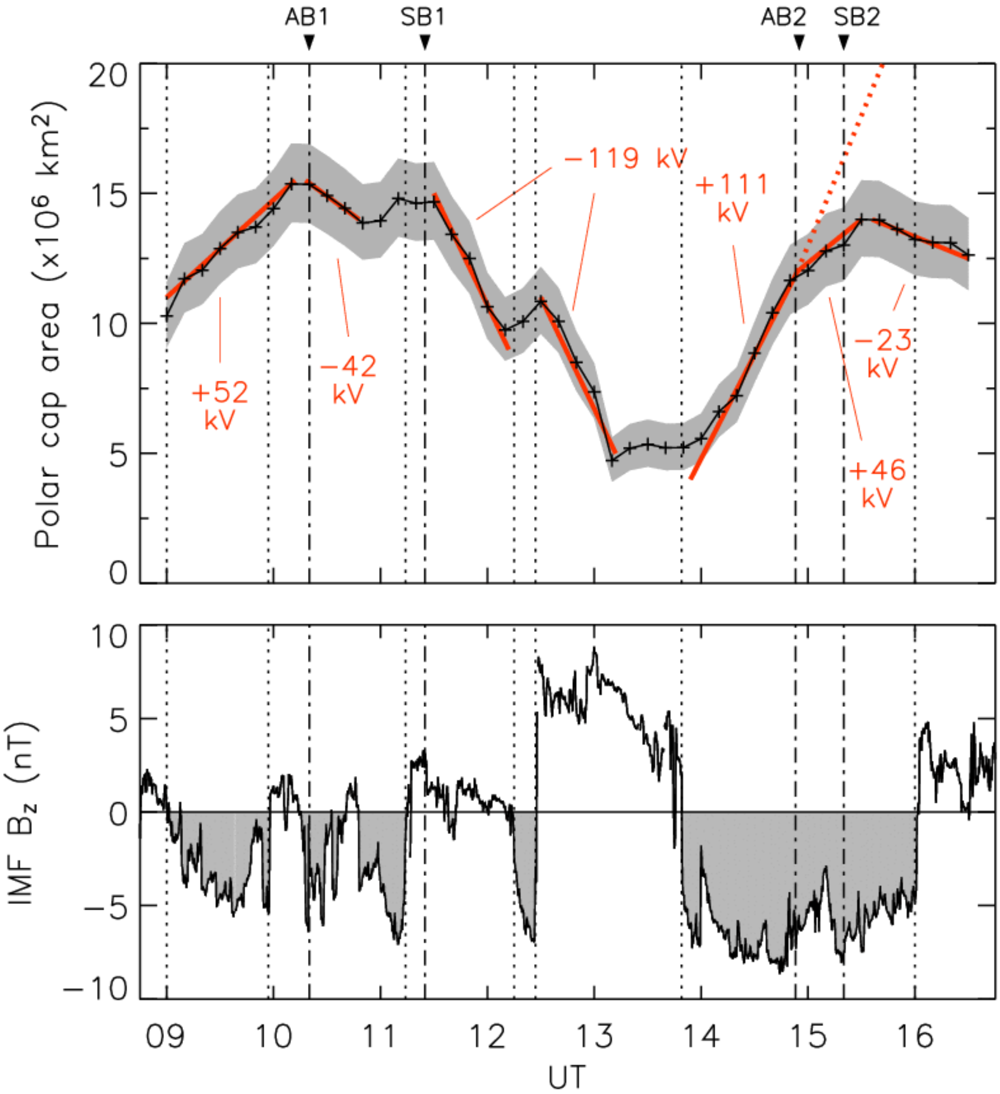

Figure 7. The variation of the polar cap area for the time interval 09 – 16 UT and the IMF B_z component during the same time interval (after Milan et al., 2003).