SPACE AND GROUND-BASED INVESTIGATIONS OF DAYSIDE RECONNECTION: CLUSTER, DOUBLE STAR AND SUPERDARN OBSERVATIONS

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ABSTRACT

In this paper, we present an overview of several investigations that have exploited Cluster, Double Star and SuperDARN radar data in order to scrutinise the coupling of the solar wind, magnetosphere and ionosphere. The studies introduced have drawn upon simultaneous space- and ground-based data in order to overcome the inherent shortcomings of the *in situ* (space-based) and remotely-sensed (ground-based) measurement techniques. In particular, we shall highlight the results of studies that investigate the dynamics arising from magnetic reconnection at the dayside magnetopause and the resulting ionospheric responses.

Key words: Cluster; Double Star; SuperDARN; Reconnection; Ground-based.

1. INTRODUCTION

Cluster is the first magnetospheric mission designed to harness the power of multi-point measurements in order to resolve the spatial/temporal ambiguities inherent in single spacecraft investigations. This multipoint measurement capability is crucial if the boundaries, structure and dynamics of the complex terrestrial magnetosphere are to be understood. However, Cluster can only measure these characteristics over the spatial scale of the inter-spacecraft separation. During the first five years of the Cluster mission, this has typically been in the range of a few hundred to several thousand kilometers, i.e. small compared to the scale of the magnetosphere. Of course, it is possible to expand the separation of the Cluster spacecraft in order to characterise features that exist on a larger spatial scale, but at what point would the spacecraft cease to act as a single experiment and revert to four individual point-measurements, each with the spatial/temporal ambiguities that the Cluster mission was intended to overcome? One solution might be to deploy more spacecraft, nesting clusters of spacecraft inside larger clusters in order to investigate multiple spatial scales simultaneously. An alternative would be to exploit the pre-existing network of ground-based experiments to provide remotely-sensed measurements of the magnetosphere in support of the Cluster mission. This paper will address the latter of these options.

Ground-based investigations have much to offer the Cluster mission. Typically, ground-based instruments enjoy extensive fields-of-view when mapped from the Earth into the magnetosphere, due either to the large viewing area of each instrument (e.g. ionospheric radars, all sky cameras, riometers) or due to the networking of numerous individual diagnostics (e.g. magnetometers, ionosondes). Furthermore, many ground-based experiments operate continuously and allow the monitoring of ionospheric/magnetospheric conditions over many hours, thus providing context to the multi point *in situ* measurements.

In this paper, we shall focus upon Cluster/ground-based investigations that exploit the Super-Dual Auroral Radar Network (SuperDARN; Greenwald et al. 1995) in order to study the signatures of dayside reconnection. The SuperDARN network currently comprises 17 high-frequency (HF) coherent-scatter radars, 10 located in the northern hemisphere and 7 in the southern hemisphere. The radars are nearly identical and operate in the 8-20 MHz range, routinely measuring the line-of-sight (l-o-s) Doppler velocity and spectral width of, and the backscattered

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power from, decametre scale plasma irregularities which have been shown to drift with the ionospheric $\mathbf{E}\times\mathbf{B}$ velocity (Ruohoniemi et al. 1987; Villain et al. 1985). In normal operation the field of view (f-o-v) of each radar is formed by scanning sequentially through 16 beams of separation 3.24^o, each beam gated into 75 ranges of 45 km each. Typically, the dwell time on each beam is 3 or 7 s resulting in a scan of the complete f-o-v covering 52^o in azimuth and over 3000 km in range every 1 or 2 min. Consequently, the 17 SuperDARN radars routinely monitor the ionospheric convection pattern over a significant fraction of the auroral ionosphere in both hemispheres.

2. INTERHEMISPHERIC OBSERVATIONS OF FLUX TRANSFER EVENTS

In a pair of papers drawing upon data from the first month of Cluster science operations, Wild and co-authors investigated dayside reconnection under southward and duskward interplanetary magnetic field conditions (Wild et al. 2001, 2003). Between 09–11 UT on 14 February 2001, the Cluster spacecraft traverse the high latitude magnetopause in the post-noon sector (∼14 MLT). Figure 1 presents data from the Cluster 1 spacecraft and the ACE upstream solar wind monitoring spacecraft between 09:15–11:15 UT on this day. The top panel shows the clock angle of the interplanetary magnetic field measured at the ACE spacecraft and lagged by 55 min such that comparisons can be made with Cluster observations at the front of the magnetosphere. The next three panels present the component of the magnetic field normal to the magnetopause, the total magnetic field strength, and the angle of the magnetic field in the plane of the magnetopause (the α_{LM} parameter) measured by the FGM instrument onboard the Cluster 1 (Rumba) spacecraft. The fifth and sixth panels present the total ion density profile and ion energy-time spectrogram (all pitch angles) observed by the CIS (HIA) instrument on Cluster 1. Finally, the lower panel presents the electron energy distribution measured in the field-parallel direction by the PEACE HEEA sensor, also on Cluster 1. Overlaid on this figure (dashed lines) are the times of events discussed below. Specifically the centre times of four magnetospheric FTEs, the entry into the boundary layer (BL), three crossings of the magnetopause (MP), and four magnetosheath FTEs are indicated.

Throughout the interval, the solar wind clock angle was typically between 90^0–180^o (i.e. southward and duskward) with only occasional northward or dawnward excursions. Motion of the magnetopause relative to Cluster resulted in the spacecraft encountering the boundary three times during this interval. The first (outward) traversal at ∼10:17 UT was preceded by an encounter with a complex boundary layer. Subsequently, the outward motion of the boundary caused the spacecraft to re-enter the magnetopause at ∼10:22 UT before departing the magnetosphere for the final time (during this interval) at ∼10:33 UT.

Prior to and following the magnetopause crossings, the four Cluster spacecraft observed a series of magnetospheric and then magnetosheath flux transfer events (FTEs). Each was characterised by a normal polarity (positive-negative) bipolar perturbation to the component of the magnetic field normal to the local magnetopause, an enhancement in the overall magnetic field strength, and mixing of the magnetospheric and magnetosheath plasmas. The field tilting effects in the plane of the magnetopause (the α_{LM} parameter) were interpreted as evidence of open northern hemisphere magnetic flux tubes moving poleward and dawnward, following reconnection somewhere duskward and equatorward of the spacecraft, as shown in Figure 2. In Figure 2a, the motion of an open flux tube (solid lines marked '1'-'4') following a low-latitude reconnection event in the dusk sector (near '1') and (b) the temporal evolution of an open flux tube (solid lines marked 'i'-'iv') following a low-latitude reconnection event in the dawn sector (near 'i') are shown. The approximate location of the Cluster spacecraft is also indicated. The grey arrows in the figure show the direction of open field line motion, including westward motion in the northern cusp (and eastward motion in the southern cusp). The arrowed short-dashed lines indicate magnetospheric field lines within the magnetopause boundary region

This interpretation was entirely consistent with the simultaneous ionospheric observations. While the Cluster spacecraft were located within the magnetosphere, their northern hemisphere footprints mapped to the field-of-view of the CUTLASS pair of SuperDARN radars (Lester et al. 2004). Figure 3 presents l-o-s Doppler velocity and backscattered power measurements along three beams of the Finland CUTLASS radar. In the power panels black indicates insufficient signal-to-noise ratio to determine the spectral characteristics of the backscatter. In the Doppler shift panels, velocities are only shown where significant power is observed. Negative velocities represent Doppler shifts away from the radar along the line-of-sight. During this interval the radar's poleward and westward field-of-view straddled the noon sector high latitude ionosphere in the northern hemisphere. These beams look in the westward (dawnward) direction. Superimposed on each panel are the times of note identified in the Cluster observations, as in Figure 1, specifically the centre times of the four magnetospheric FTEs, the entry into the boundary layer (BL), three crossings of the magnetopause (MP), and four magnetosheath FTEs. Throughout the interval, the Finland radar observed a series of poleward-moving radar auroral forms (PMRAFs). These features, indicated by ar-

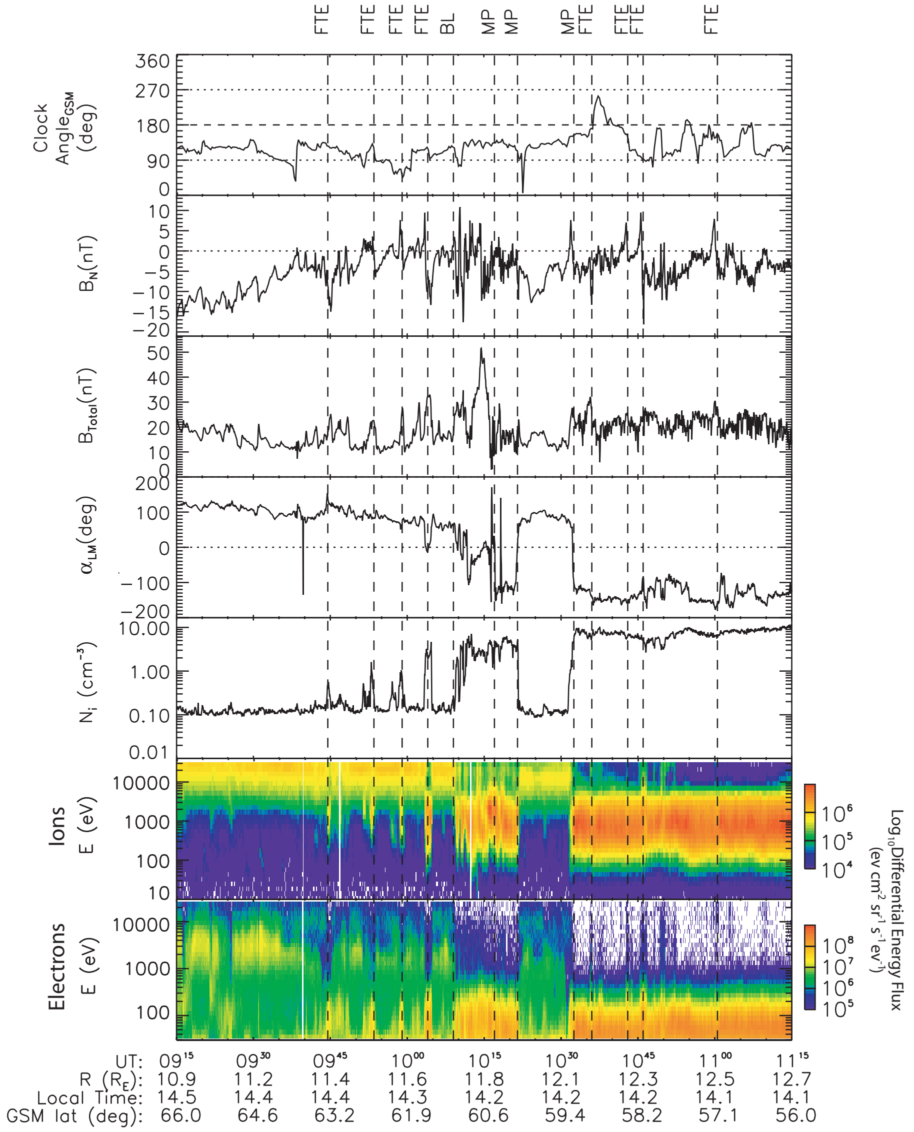

Figure 1. Plot of ACE and Cluster data for the interval 09:15-11:15 UT on 14 February 2001. From Wild et al. (2003).

rows in the upper (beam 1) power panel, are the accepted ionospheric counterparts to FTEs. Related events are observed in each of the other beams shown. These observations correspond to regions of ionospheric plasma being dragged polewards and dawnward across the noon sector at slightly higher latitude ($\geq 76^o$ Mlat) than the Cluster footprint. Ionospheric motion in the lower latitude region (74^o–76^o Mlat) was characterised by low velocity flow essentially westward and northward, in agreement with the positive IMF B_Y, and detailed study of this region revealed pulses of ionospheric flow and of backscatter power. Figure 4a presents the flow measurements in more detail.

Detailed examination of the Cluster and SuperDARN data indicated a clear one-to-one correlation between the signatures of magnetospheric FTEs observed by Cluster and the pulsed enhancements of convection (pulsed ionospheric flows - PIFs) and power observed by the Finland radar in the (74^o–76^o Mlat) latitude range. These observations suggested that the reconnection events had a large spatial scale and that the low-latitude flow region corresponded to the footprint of newly-opened flux tubes. The poleward convection enhancements observed at higher latitudes were the fossil-like signatures of the reconnected flux tubes in the ionosphere.

The ionospheric convection geometry provided by the CUTLASS radars confirmed the dusk location of the magnetopause reconnection site inferred from the Cluster data. The subsequent study of magnetically conjugate Syowa East SuperDARN radar observations in the Southern Hemisphere (Wild et al. 2003) again revealed modulations of the convection

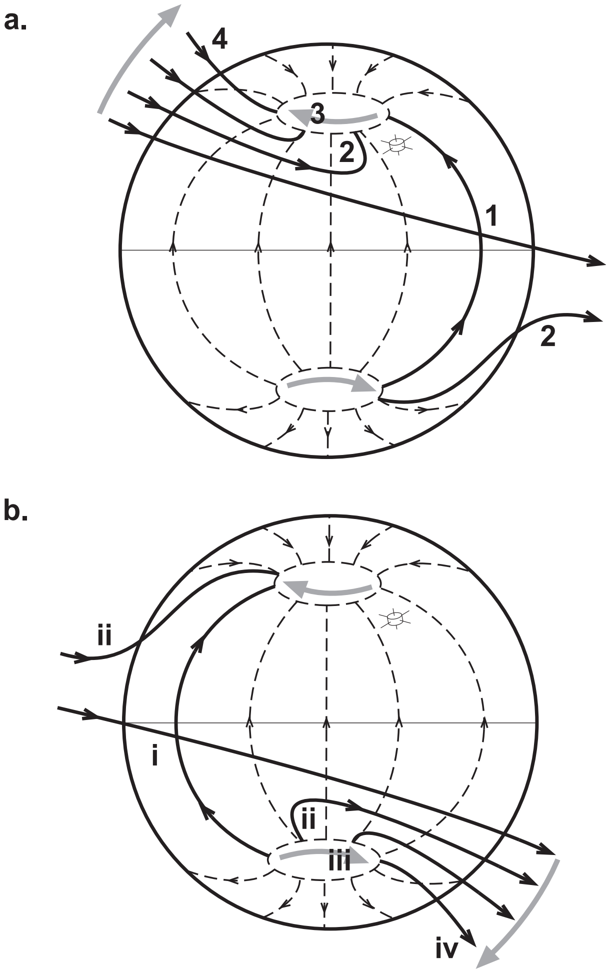

Figure 2. *Sketch of the Earth's dayside magnetopause in a view looking from the Sun, showing the temporal evolution of open flux tubes. From Wild et al. (2003).*

flow at low latitudes and poleward convection enhancements at high latitudes, as presented in Figure 4b and c. These flow modulations were well correlated with the flow pulsations observed by the SuperDARN Finland radar and with the magnetic perturbations observed by Cluster. As expected, the reconnected flux tubes in the Southern Hemisphere propagated poleward and eastward, the asymmetry between the hemispheres being due to the non-zero B_Y component of the IMF. However, the location of this radar around noon MLT implied that the reconnected flux tubes had to be generated on the dawn magnetopause in order to propagate duskward though the field-of-view of the radar. Consequently, the reconnected flux tubes observed in the southern ionosphere were not the same as the reconnected flux tubes seen simultaneously by the Finland radar and Cluster. This is illustrated schematically in Figure 5. In each figure, the view is from a location above the northern magnetic pole with the noon meridian indicated by a long dashed line and dawn (dusk) located to the right (left) of the plot. In each case the open-closed field line boundary (OCFLB) is represented by a solid black line. The field-of-view of the Finland (Syowa East) radar is indicated in the northern (southern) hemisphere by the grey shaded region at approximately 10 UT. Where a perturbation (i.e. a region of newly-opened flux tubes appended to the OCFLB) is shown, the quasi-equilibrium position of the boundary is indicated by a short dashed line. Following integration into the (open) polar cap, the region of newly-opened flux is indicated by a dot-dashed line whilst the ionospheric flow that brings about the inclusion of this region into the polar cap is indicated by a shaded arrow. The expected northern and southern hemisphere responses to the addition of open flux in the post-noon sector are shown in (a) and (b) respectively. Similarly, the expected northern and southern hemisphere responses to the addition of a spatially extended region open flux that straddles noon are shown in (c) and (d). The convection flow modulations observed simultaneously in the two hemispheres in both the pre- and post-noon sectors supported that the reconnection occurred along a single reconnection line extending over at least 4 h MLT. The ground-based data in the Southern Hemisphere were thus necessary to infer the large-scale geometry of the magnetopause reconnection in this case.

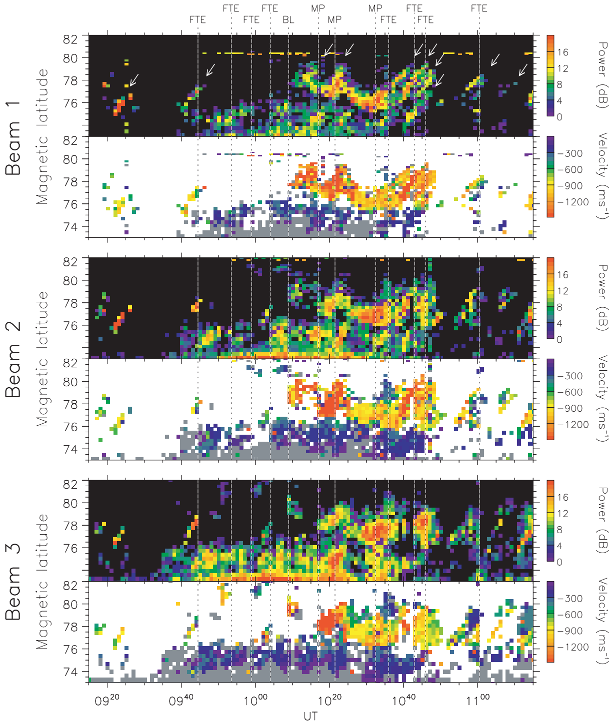

Figure 3. *Three pairs of backscatter power and Doppler shift measurements from beams 1, 2, and 3 of the Finland SuperDARN radar during the same interval as presented in Figure 1. From Wild et al. (2001).*

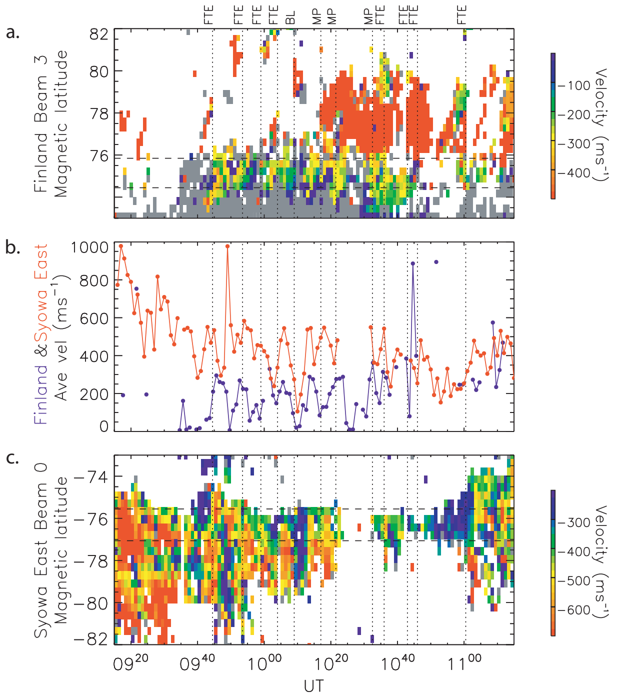

Figure 4. (a) Velocity data from beam 3 of the CUTLASS Finland SuperDARN radar, in a format similar to that in Figure 3, but with a revised colour scale which reveals the pulsing of the line-of-sight flow in the band of lower-latitude scatter. (c) Velocity data from beam 0 of the Syowa East SuperDARN radar, presented in the format of (a), albeit with a different colour scale and a reversed latitude axis. (b) The mean velocity averaged over the latitude range indicated by dashed horizontal lines in (a) and (c) (and given positive values in this case, though in each case the flow is directed away from the radars). The indigo trace corresponds to the Finland average velocities whilst the red trace corresponds to the Syowa East average velocities. Superimposed on each panel are the times of note identified in the Cluster observations, as in Figure 1. From Wild et al. (2003).

3. MULTIPOINT IN-SITU AND GROUND-BASED OBSERVATIONS OF FTES

The launch of the first Double Star spacecraft in late 2003 presented scientists with an opportunity to make *coordinated* multipoint *in situ* measurements at differing spatial scales. As a precursor to such investigations, Wild et al. (2005a) exploited a fortunate and favourable conjunction of the Cluster and Geotail spacecraft on 17 February 2003 during which Geotail skimmed the sub-solar magnetopause as Cluster traversed the high-latitude magnetopause. This conjunction culminated in the observation of a series of flux transfer events (FTEs), characterised by bipolar perturbations in the component of the magnetic field normal to the magnetopause, enhancements in the overall magnetic field strength, and field tilting effects in the plane of the magnetopause whilst the satellites were located on the magnetosheath side of the boundary. These observations are summarised in Figure 6. Whilst a subset of the FTE signatures observed could be identified as being either normal or reverse polarity, the rapid succession of events observed made it difficult to classify some of the signatures unambiguously. By employing the flux tube model of Cooling et al. (2001), the source region and motion of flux tubes opened by magnetic reconnection at low latitudes (i.e. between Cluster and Geotail) was investigated. It was demonstrated that the spacecraft observations were consistent with the motion of northward (southward) and tailward moving flux tubes anchored in the northern (southern) hemisphere passing in close proximity to the Cluster (Geotail) satellites. The multi-spacecraft approach, coupled with a realistic model of flux tube motion in the magnetosheath, enabled the authors to infer the approximate position of the reconnection site, which in this case was located at near-equatorial latitudes. Unfortunately, this favourable conjunction of spacecraft occurred over the Siberian sector, a region where the coverage provided by ground-based experiments is sparse.

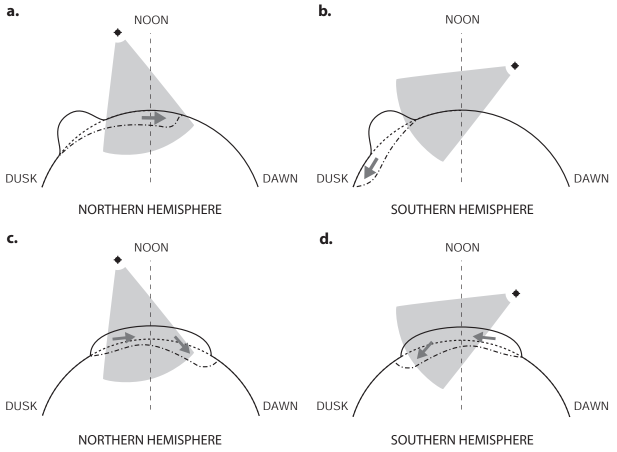

Figure 5. Schematic indicating the expected perturbations to the ionospheric open-closed field line boundary (OCFLB) and the resulting ionospheric flows due to the addition of open flux during a flux transfer event. From Wild et al. (2003).

In one of the first results to come from the Double Star mission, Wild et al. (2005b) exploited measurements from a very similar conjunction to that in Wild et al. (2005a) that occurred on 25 March 2005. At ~07 UT this day, the equatorial Double Star spacecraft (TC1) entered the magnetosphere slightly southward of the subsolar point at ~11.5 MLT (Figure 7). Around one hour later (~8 UT) the four Cluster spacecraft, separated from one another by ~250 km, traversed the mid-latitude magnetopause

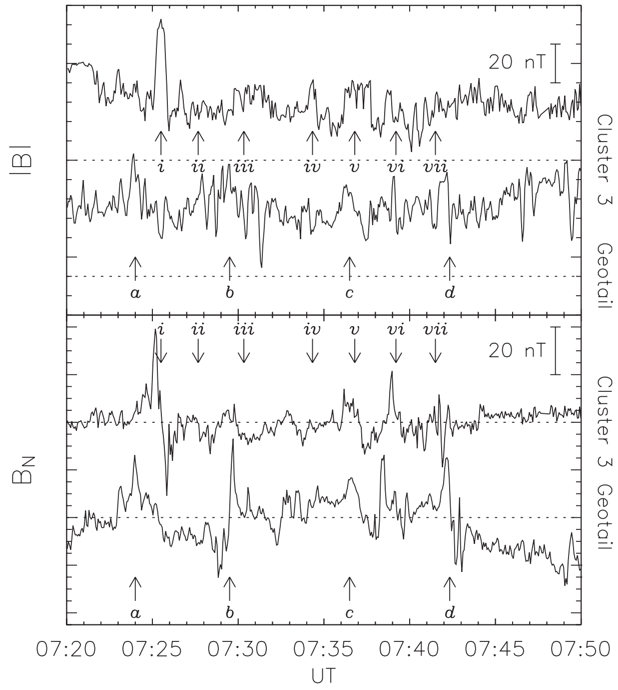

Figure 6. A comparison of $|B|$ and B_N measurements from Cluster 3 and Geotail on 17 February 2003. FTEs indicated by arrows, labelled i–vii *(Cluster) and* a–d *(Geotail). From Wild et al. (2005a).*

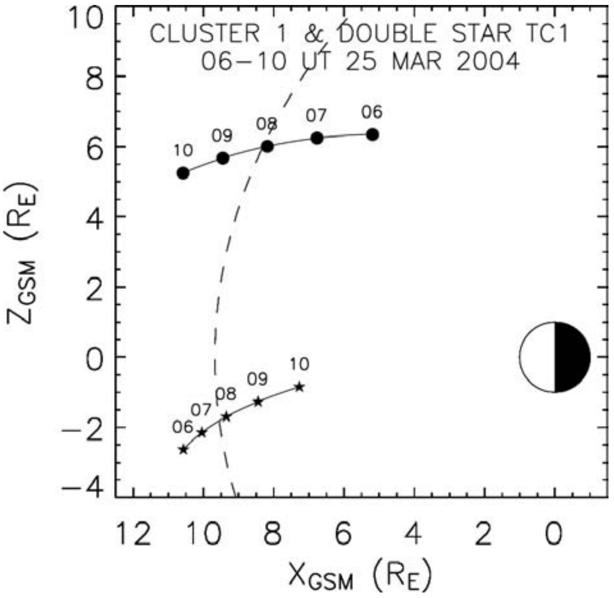

Figure 7. The locations of the Cluster 1 (circles) and equatorial Double Star (stars) spacecraft in the noon-midnight meridian during the interval under scrutiny. The location of a Shue et al. (1997) magnetopause is also indicated. From Wild et al. (2005b).

in the outbound direction at very similar magnetic local time to Double Star's inbound crossing. During the interval 06–09 UT (i.e. during the Double Star and Cluster magnetopause encounters), the IMF was generally dominated by the duskward component with a small and variable north-south component. While still in the magnetosheath, Double Star observed several (at least three) normal polarity FTEs as indicated in Figure 8. Similarly, shortly after entering the magnetosheath, the four Cluster spacecraft also observed a series of normal polarity magnetosheath FTEs. The polarity of these signatures therefore indicated of open flux tubes anchored in the northern hemisphere passing by the spacecraft.

In order to investigate the likely source region of the open flux tubes (FTEs), Wild et al. (2005c) have also employed the Cooling et al. (2001) model of open flux tube motion in the magnetosheath (often referred to as "the Cooling model"). This model employs the simple stress balance computation presented in Cowley & Owen (1989) in order to calculate the velocity of open magnetic flux tubes at the point that the tube penetrates the surface of the magnetosphere (i.e. the de Hoffmann–Teller (DHT) velocity of the flux tube.) In this case, the Cooling model has also been used to calculate the plasma velocity in the magnetopause boundary layer (i.e. the velocity of plasma inside an open flux tube in the rest frame of the magnetosphere). Figure 9 presents the results of the Cooling model that support the data interpretation during this interval. This figure shows six views of the dayside magnetopause in the GSM Y-Z plane as viewed from the Sun. The concentric dotted circles indicate the magnetopause in the GSM Y-Z plane at X positions of X=+5 R_E, 0 R_E, −5 R_E, and −10 R_E while the cusps are represented by the diamond symbol. In this model, the cusps are positioned at the GSM locations [0.5 R_{MP}, 0, $\pm R_{MP}$] where R_{MP} is the radius of the model magnetopause at the subsolar point. In this case, R_{MP} has been set to 10 R_E, roughly the value predicted by the model of Shue et al. (1997) during this interval. Figure 9a shows the boundary layer (BL) flow stream lines resulting from an X-line ∼10 R_E in length that is centred upon the subsolar point and oriented along the direction of the magnetopause current (akin to the component reconnection hypothesis (e.g. Cowley 1976)). Blue (red) streamlines indicated BL flow associated with newly reconnected field lines anchored in the northern (southern) hemisphere. The IMF direction employed corresponds to the appropriately lagged IMF observed by the ACE spacecraft The resulting IMF clock angle, corresponding to 06:50 UT at the magnetopause, is indicated in the upper right-hand corner of the figure. This corresponds to the interval when the Double Star spacecraft was traversing the magnetopause boundary layer just prior to crossing the magnetopause. In this case, the Cooling model indicates that a low latitude reconnection line would result in a boundary layer plasma flow that is directed mainly dawnward at the location of

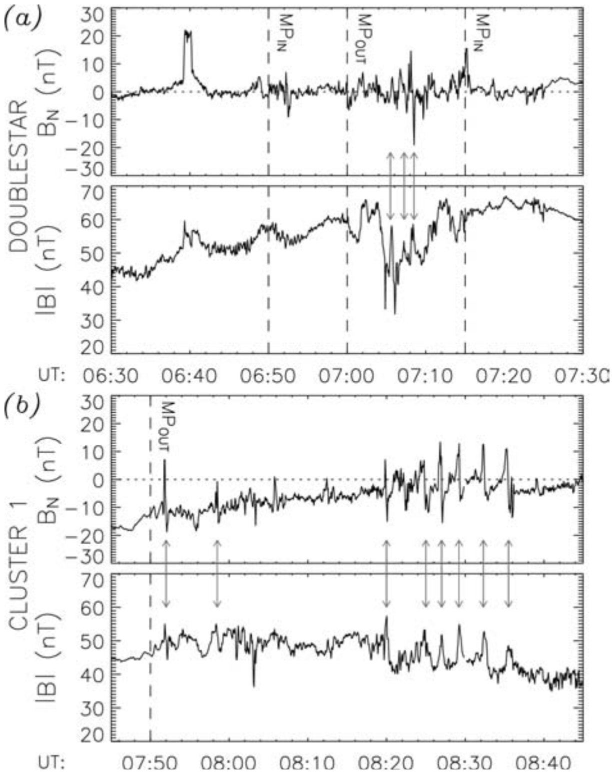

Figure 8. Magnetic field measurements from the (a) Double Star TC1 and (b) Cluster 1 spacecraft. The component of the magnetic field normal to the local magnetopause and the overall magnetic field strength are presented. Magnetopause crossings and FTEs are indicated by dashed lines and arrows respectively. From Wild et al. (2005b).

Double Star (indicated by a black star). The Double Star plasma measurements (not shown) indicate that at this time the spacecraft briefly passed through a layer of ~130 km s^{-1} dawnward directed plasma flow, exactly as predicted by the Cooling model. By ~07:15 UT Double Star had entered the magnetosphere, re-entered the magnetosheath (where it observed the FTEs presented in 8) and was about the re-enter the magnetosphere for the final time. Due to the single-point nature of the Double Star observations, it is not possible the estimate the direction of propagation of the flux tubes as they passed over the spacecraft. However, based upon the results of the Cooling model (9b), the open northern hemisphere flux tubes launched from a low latitude reconnection would pass over the location of Double Star. This is consistent with the normal polarity bipolar signatures observed by the spacecraft. Conversely, if the location of the X-line(s) is defined by the antiparallel reconnection hypothesis (e.g. Crooker 1979), as in Figure 9c, newly-opened flux tubes would move tailwards under the action of the solar wind flow in which one end of each field line remains embedded. As such, it seems unlikely that flux tubes (FTEs) observed by Double Star originate from high-latitude reconnection X-lines. Indeed, it should also be noted that flux tubes are dragged across the X-line in both hemispheres, indicating that steady reconnection at these X-lines is not possible.

A similar comparison between Cluster measurements and model is presented in figures 9d, e and f. Figure 9d shows the boundary layer flow streamlines corresponding to the IMF orientation at 07:55 UT (when Cluster traversed the magnetopause boundary layer) while Figure 9e shoes the loci of open flux tubes over the surface of the magnetopause at 08:25 UT (when Cluster was observing FTEs). The location of the Cluster quartet is indicated by the black filled circle. The direction of poleward and dawnward boundary layer plasma flow observed by Cluster (not shown) was almost identical to the expected BL plasma flow predicted by the Cooling model, although in this case, the speed of the modelled BL plasma flow (~180 km s^{-1}) was larger than the observed flow (~120 km s^{-1}) by ~50%. Of course, the multipoint Cluster measurements allow the speed of the open flux tubes to be calculated as the characteristic bipolar signature convected over the four spacecraft. In this case, multi-spacecraft analysis techniques indicated that the open flux tubes were were travelling at ~65 km s^{-1} in the poleward and dawnward direction. At the location of the Cluster spacecraft, the Cooling model predicted that flux tubes would be travelling in exactly the direction observed, but at much greater speed (~190 km s^{-1}). As was the case previously (and despite a rotation of the IMF at this time to a duskward and slightly southward orientation) open flux tubes originating from the X-line defined by the antiparallel reconnection hypothesis (Figure 9f) would be expected to be dragged tailward, *away* from the location of the Cluster and Double Star spacecraft.

From these observations, it is concluded that while in the vicinity of the magnetopause between 07–08 UT on 25 March 2005, the Cluster and Double Star spacecraft observed open flux tubes that were anchored in the northern hemisphere retreating from a low-latitude X-line which was probably tilted with respect to the magnetic equatorial plane. The Cooling model is able to accurately reproduce the direction of boundary layer plasma flow and flux tube motion observed by the spacecraft during this interval. However, at higher latitudes, the Cooling model consistently over-estimates the plasma and flux tube speeds. This might be explained by the recent findings of Longmore et al. (2005) who, based upon 4 years of Cluster data, reported sub-alfvénic flow in the vicinity of the magnetospheric cusps. This sub-alfvénic flow region is not described by the gasdynamic model of magnetosheath plasma flow on which the Cooling model is based.

Figure 10 presents an overview of the ground-based data during this interval. At 07:30 UT, the Double Star and Cluster spacecraft were all located

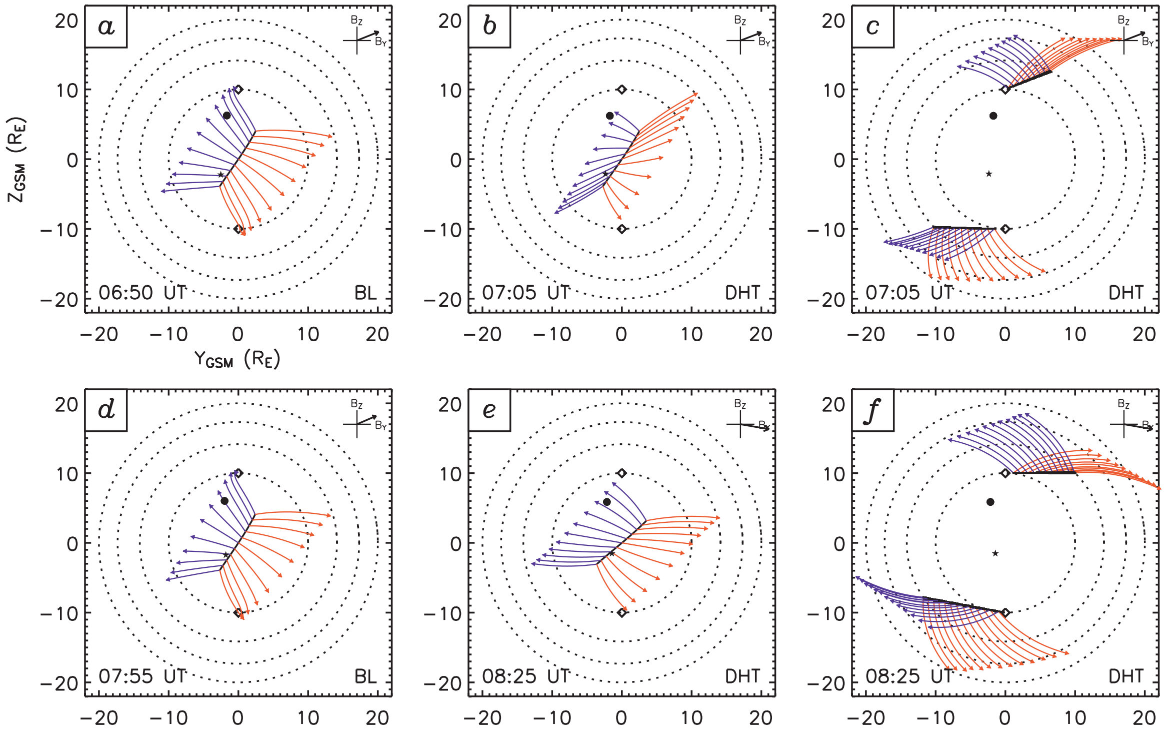

Figure 9. Modelled magnetopause boundary layer streamlines and flux tube loci for the FTEs observed by Double Star and Cluster on 25 March 2005. Adapted from Wild et al. (2005c).

within the magnetosphere, TC1 having recently traversed the low latitude magnetopause from the magnetosheath (where FTEs were observed), while Cluster 1 was approaching the mid-latitude magnetopause (where FTE signatures were also observed). The satellites' northern hemisphere ionospheric footprints were located within the fields-of-view of the easternmost CUTLASS pair of SuperDARN radars. Figure 10 presents the ionospheric convection pattern at this time, inferred from all available northern hemisphere SuperDARN data. The estimated ionospheric flow pattern is as expected for convection driven by a dominant IMF B_Y component (in this case duskward) with ionospheric plasma in the noon sector flowing dawnward and poleward into the polar cap as newly reconnected magnetic field lines, one end of which remains embedded in the solar wind, respond to magnetic tension forces and the influence of the anti-sunward directed solar wind flow. Detailed examination of high-latitude ($\geq 75^o$ Mlat) line-of-sight velocity measurements from individual radars located in the noon and pre-noon sector reveals pulsed ionospheric flows - bursts of high speed ($\sim$1000 m s^{-1}) ionospheric plasma flow directed into the polar cap. These are entirely consistent with the interpretation of newly opened magnetic flux tubes passing in a dawnward and poleward/tailward direction over the Cluster spacecraft in the noon sector, their footprints dragging ionospheric plasma dawnward and poleward as they are incorporated into the open polar cap. These observations are supported by detailed measurements of the highly time-varying structure of the polar ionosphere north of the Svalbard archipelago as observed by the EISCAT Svalbard Radar (ESR), discussed in more detail in Wild et al. (2005c).

Ionospheric measurements made at lower latitudes reveal further evidence of solar wind–magnetosphere–ionosphere coupling. Figure 11 presents data from beam 5 of the CUTLASS Iceland SuperDARN radar. This beam points in a poleward and eastward (duskward) direction and the data, corresponding to the early morning sector ionosphere (08-09 MLT) in the region $\leq 76^o$ Mlat, are interpreted as follows. The Doppler spectral width of the echoes observed by the radar are small suggesting that the observed ionospheric irregularities are associated with closed magnetic field lines (large Doppler spectral widths being an accepted signature of the ionospheric projection of the magnetospheric cusp (e.g. Baker et al. 1995)). The line-of-sight Doppler velocity measurements observed during this interval were generally all negative (i.e. away from the radar), the chosen colour-coding therefore discriminates between small and large eastward velocities. Immediately apparent are periodic fluctuations of the eastward flow, varying between 0–500 $m\ s^{-1}$ with a timescale between 5–10 minutes. Closer investigation of the velocity fluctuations reveals them to be almost sinusoidal $\pm 250\ m\ s^{-1}$ perturbations superimposed upon a steady eastward background flow of $\sim 250\ m\ s^{-1}$. These are inter-

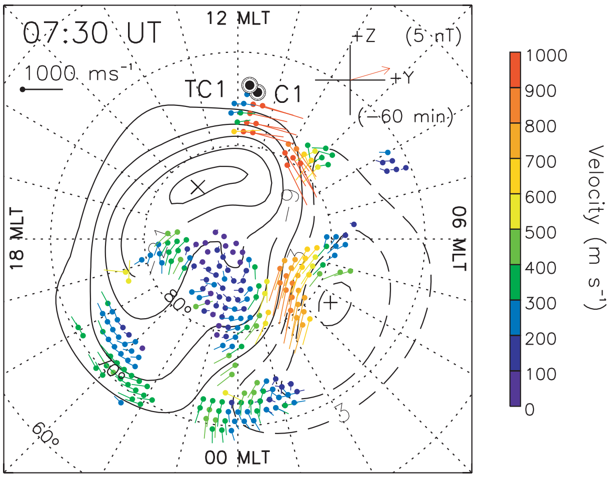

Figure 10. SuperDARN northern hemisphere ionospheric convection pattern at 07:30 UT on 25 March 2004, derived using the technique of Ruohoniemi & Baker (1998). The location of the magnetic footprints of the Cluster 1 and TC1 spacecraft are also indicated. Adapted from Wild et al. (2005b).

preted as the ionospheric signatures of ultra-low frequency (ULF) wave activity in the Pc5 frequency band (e.g. Provan & Yeoman 1997). The morning sector radar data were supported by further evidence of ULF wave activity throughout the morning and daytime ionosphere. Although not shown here, the signatures of ULF waves could be seen in magnetograms recorded by the IMAGE and SAMNET magnetometer arrays that span the Icelandic–Scandinavian sector and the ionospheric parameters measured by the mainland UHF EISCAT incoherent scatter radar. These, and other datasets, are described in detail in Wild et al. (2005c).

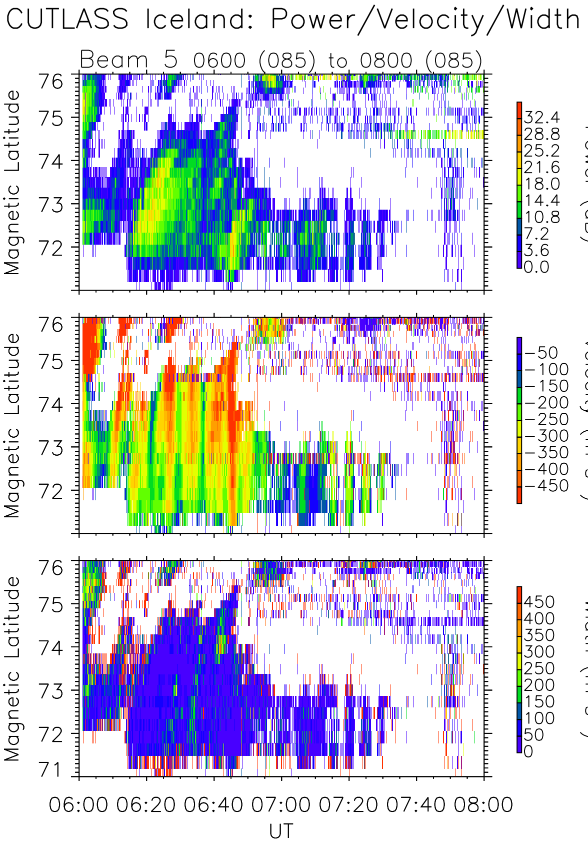

Figure 11. Measurements from the CUTLASS Iceland SuperDARN radar during the interval 06–08 UT on 25 March 2005. Backscattered power (top panel), line-of-sight Doppler velocity (middle panel) and Doppler spectral width (bottom panel) are colour-coded and presented as functions of magnetic latitude and universal time. Adapted from Wild et al. (2005c).

The simultaneous space- and ground-based data recorded on 25 March 2004 highlight several of the mechanisms of solar wind-magnetosphere-ionosphere coupling. Magnetic reconnection was occurring in the vicinity of the sub-solar point during an interval of duskward oriented IMF. The newly opened flux tubes retreated away from the reconnection site and passed over the Double Star and Cluster spacecraft located near to the low- and high-latitude magnetopause respectively. In the high-latitude ionosphere, in the ionospheric projection of the cusp, ionospheric plasma associated with the newly opened flux tubes was observed to rapidly move dawnward and poleward as the open flux tubes were incorporated in polar cap. Equatorward, in a region that is magnetically separate from the reconnection driven dynamics at higher latitudes, ionospheric flows excited by global-scale ULF wave activity dominate the motion of the morning and daytime sector ionosphere. In the past, similar observations have been interpreted as evidence of a forward coupling mechanism by which ULF wave activity modulates the reconnection rate at the dayside magnetopause (Prikryl et al. 1997). However, in this case, there is no evidence of a solar wind driver of the ULF waves, indeed the source of the driving mechanism remains unclear. Therefore, the relationship between ULF wave dynamics and dayside magnetic reconnection will form the basis of future space- and ground-based investigations.

4. SUMMARY

In this paper, we have highlighted the results of several Cluster- and ground-based investigations of dayside solar wind–magnetosphere–ionosphere coupling. These results, which illustrate the powerful synergy of multi-point space- and ground-based experiments, include:

- the synchronous observation of flux transfer events at the magnetopause and the pulsing of ionosphere flow in both hemispheres
- the estimation of a lower limit to the azimuthal extent of a low latitude X-line during an interval of southward IMF
- the relationship between pulsed ionospheric flows and poleward-moving radar auroral forms
- the location and orientation of a low-latitude reconnection X-line during and interval B_Y dominated IMF
- the contrasting ionospheric flow at mid- and high-latitudes during an interval of ongoing dayside reconnection
- the simultaneous, and possibly related, occurrence of global-scale ULF wave activity and dayside magnetic reconnection

Of course, these studies are a snapshot of the Cluster and ground-based investigations carried out to date (for a comprehensive review, the reader is referred to Amm et al. (2005)). The investigations discussed above have exploited upon data from the first 5 years of the Cluster mission, during which time the inter spacecraft separation on the dayide has varied between a few hundred to a few thousand kilometres. When mapped to the ionosphere, even at the largest separations, the spatial separation of the satellites' footprints has tended to a scale comparable to the resolution of most ground based instruments. During the extended mission, the inter-spacecraft separation will be increased to ∼10,000 km. At this much larger separation, the spacecraft will map to ionospheric footprint displaced by hundreds of kilometres - a scale much more suited to coordinated Cluster and ground-based investigations. It is therefore anticipated that during the reminder of this highly-successful mission, the already vibrant programme of Cluster and ground-based research will yield a greater insight into the structure, mechanisms and dynamics of the coupled solar wind-magnetosphere-ionosphere system

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