Observations of tail dynamics using ground and space based instruments during a period of multiple substorm events

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Abstract: We present initial observations from an ongoing investigation into the dynamics of the magnetotail during a period of multiple substorms. The investigation coordinates data from ground and space-based instruments including the Cluster and IMAGE spacecraft, SuperDARN and ground magnetometers during the period 00:00UT to 05:00UT on 25th August, 2003. The first substorm expansion phase, which is preceded by two pseudo-breakups at 00:38UT and 00:57UT, takes place between 01:11UT and 01:50UT during which time IMAGE WIC(FUV) data for the Southern auroral oval shows enhanced auroral activity almost solely in the post-midnight sector and the occurrence of auroral streamers within the auroral bulge. SuperDARN map potential analysis shows a flow diversion with a northern hemisphere footprint that is conjugate to a southern hemisphere auroral streamer. During this time, Cluster CIS and FGM instruments detect the passage of under-populated flux tubes, or plasma bubbles, and a field rotation event, discussed as a flux rope. These observations agree with current predictions on the relationship between streamers and under-populated flux tubes in the tail from the Chen and Wolf model.

Key words: Substorms, Cluster, Magnetotail Dynamics, Auroral Streamers, Under-populated flux tubes.

1. Introduction

Magnetotail dynamics and their auroral and ionospheric manifestations have been the subject of much debate since Akasofu [1] published his seminal paper on auroral substorms. Now, with space based instrumentation, such as that onboard the Cluster and IMAGE satellites, and ground based instrument networks, such as SuperDARN and various magnetometer arrays, we can relate auroral and ionospheric signatures to the dynamic morphology of the magnetotail.

During the interval between 00:00UT and 05:00UT on the 25th August, 2003, the Cluster spacecraft were near apogee, downtail, in the post-midnight sector of the southern plasma sheet, the IMAGE spacecraft was monitoring the Southern auroral zone and the magnetometers of the IMAGE, Greenland and CANOPUS chains and radars of SuperDARN were passing through the night sector. During this interval, multiple substorm onsets and auroral enhancements were detected by these instruments. One of these onsets showed North-South auroral forms, or streamers [12], in the IMAGE WIC(FUV) and Greenland magnetometer data and under-populated flux tubes, or plasma bubbles, in the Cluster CIS and FGM data. Another was preceded by a quasi-periodic B_x component in the Cluster FGM data.

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2. Observations

2.1. Interval Overview

2.1.1. IMAGE WIC(FUV)

During the interval, IMAGE WIC(FUV) [7, 8] monitored the Southern auroral zone, with the optimum field of view (i.e. time before auroral oval was at the edge of the field of view) being before 03:00UT. Three substorms were identified based on the following criteria; duration (>10min), poleward expansion (>10 °magnetic latitude), extension (>2hrs magnetic local time). These substorms began at 01:17UT, 02:29UT and 04:17UT. Three further events (enhancements) were observed, although we do not classify these as substorms since one or more of the criteria were not met. These enhancements began at 00:38UT, 00:57UT and 01:50UT.

2.1.2. Cluster

The Cluster spacecraft were located near apogee in the Southern post-midnight sector throughout the interval, during which time the Fluxgate Magnetometer (FGM, [3]) (Fig. 1) measured two large (>10nT) decreases in the field strength, which was dominated by the B_x component throughout the interval. The first of these decreases begins at 01:15UT and lasts until 02:00UT and coincides with the first substorm expansion phase seen in the IMAGE WIC(FUV) data. During this event, the field strength becomes very close to 0nT at 01:27UT. The second major field decrease starts at 03:50, with the B_x component appearing to be quasi-periodic until 04:25UT. During this substorm the field drops by approximately 10nT to a level below that predicted by the Tsyganenko T96 field model.

The Cluster Ion Spectrometer (CIS, [10]) showed drops in ion density (not shown) between 00:45UT-01:15UT and 02:45UT-04:00UT indicating that Cluster moved from the plasma sheet boundary layer (PBSL) [4] into the tail lobes. Preceding and following Cluster passing into the lobes, there is a slight increase in the plasma density above the level seen in the PBSL, indicating that Cluster briefly passed into the central plasma sheet.

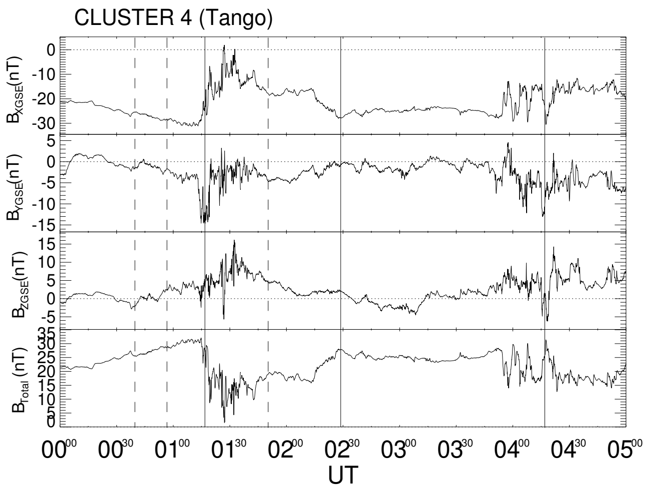

Fig. 1. Cluster FGM data from 25th August, 2003 (00:00UT-05:00UT). The B_x, B_y, B_z components in GSM coordinates and B_{Total} component are shown from Cluster 4 (Tango). Dashed lines indicate enhancements from the WIC(FUV) data and solid lines represent expansion phase onset from the same data.

2.1.3. Ground Magnetometers

The magnetometers of the CANOPUS [13], IMAGE [16] and Greenland (e.g. [9]) chains pass through the night sector during the 5hr interval. The B_x (northward) components of the magnetometers give an indication of substorm related electrojet activity over the various chains at different times. The Sodankyla (SOD) station of the IMAGE chain shows a magnetic bay of 400nT (Fig. 2) occurring in conjunction with the first substorm expansion phase onset as seen in the IMAGE WIC(FUV) data. The Scoresbysund (SCO) station in the Greenland East chain shows three negative bays in the field of 500nT, 100nT and 500nT respectively that begin in conjunction with the respective substorms. The Narsarsuaq (NAQ) station of the Greenland West chain measures negative bays of 200nT, and 150nT in association with the first enhancement and the first substorm respectively. The Gillam (GILL) station of the CANOPUS chain shows a 400nT negative bay in conjunction with the second substorm and a 300nT negative bay starting 75mins before the last substorm.

2.2. Substorm 1: Post-midnight sector substorm

2.2.1. Ground Magnetometers

Previous work [2] has demonstrated that the passage of auroral streamers over ground magnetometer arrays relates to specific magnetic signatures; a minimum in B_z and a sawtooth-like feature in B_y. Assuming that auroral disturbances in the southern hemisphere map to similar locations in the northern hemisphere, we find that the Ammassalik (AMK) and Narsarsuaq (NAQ) stations were closest to the auroral bulge formed during the substorm and in the vicinity of the auroral streamers.

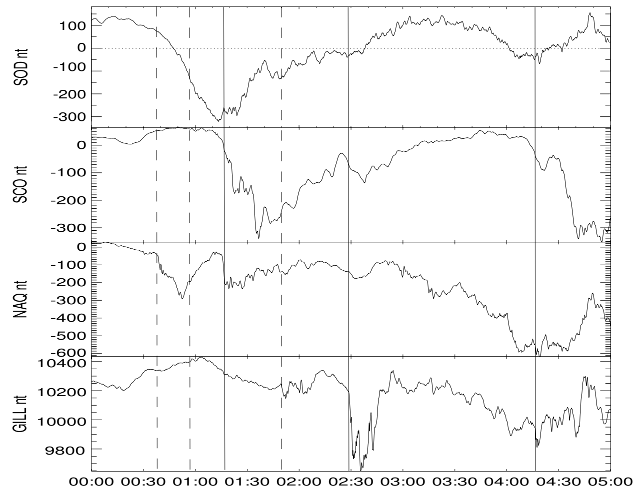

Fig. 2. Ground magnetometer data from 25th August, 2003 (00:00UT-05:00UT). The B_x (northward) component is shown from Sodankyla (IMAGE), Scoresbysund (Greenland East), Narsarsuaq (Greenland West) and Gillam (CANOPUS). Dashed lines indicate enhancements from the WIC(FUV) data and solid lines represent expansion phase onset from the same data.

The B_x (northward) components recorded by the Greenland magnetometer stations Ammassalik and Narsarsuaq (Fig. 3) show the first substorm expansion phase onset begins at 01:15UT, as indicated by the formation of a negative bay. The B_y component at both stations shows an increase followed shortly after by a drop to below 0nT. The interval between the maxima is 4-5mins, with a similar time for the interval between the minima. We note that the field feature at AMK has a form that is more like a sawtooth than the field at NAQ. The B_z (radially inwards) components show minima that coincide with the peaks in the B_y components at each station, however the Narsarsuaq station shows a further drop in the field that is coincident with the minima in the B_y component.

2.2.2. Cluster

At Cluster, the total field (Fig. 4 panel 6) begins to drop from 30nT at 01:15UT, dominated by the drop in the B_x component (Fig. 4 panel 3). The field remains in decline until 01:27UT, at which point the field begins to increase towards the Tsyganenko [15] model field level, indicated by the dashed line. Between 01:24UT and 01:26.30UT the B_z component (Fig. 4 panel 5) increases by 5nT and the B_x component shows deviation away from its decline by 10nT, with both components showing a brief spike back to the expected level at 01:26UT. Between 01:26.30UT and 01:27.30UT all of the field components changed direction and the angle of the field in the XZ plane (Fig. 4 panel 7) rotated through over 180°before rapidly returning to it's previous direction.

The Cluster Ion Spectrometer CODIF instrument on Cluster 4 shows that the density (Fig. 4 panel 2) throughout varies

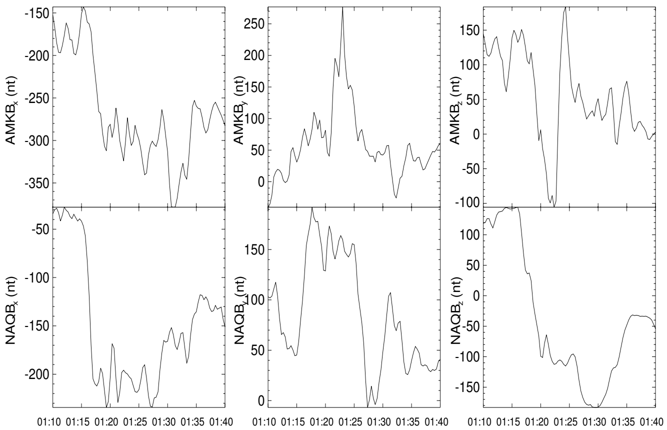

Fig. 3. Ground magnetometer data from 25th August, 2003 (01:10UT-01:40UT). The B_x (northward), B_y (westward) and B_z (radially inward) component ares shown from Ammassalik (top line) and Narsarsuaq (bottom line) of the Greenland East and West chains respectively.

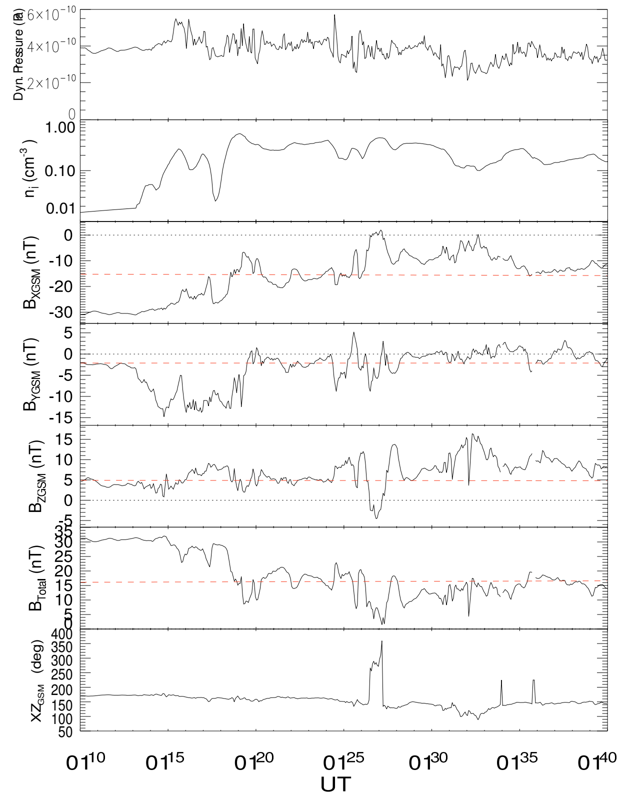

Fig. 4. Cluster CIS and FGM data from 25th August, 2003 (01:10UT-01:40UT) from Cluster 4 (Tango). The dynamic pressure is shown (panel 1), along with total ion density measured by the CIS instrument and the B_x, B_y, B_z components in GSM coordinates and B_{Total} component measured by the FGM instrument. The dashed line indicates the Tsyganenko [15] model field level

about 0.25cm^{-3}. There are drops in the density to approximately 0.1cm^{-3} that coincide with the increases in the B_z components as seen in the FGM data. There are also decreases, lasting approximately 1min, at 01:16UT and 01:17UT down to 0.1cm^{-3} and 0.01cm^{-3}. This indicates that Cluster was in the plasma sheet throughout the substorm although there were times when Cluster was in an area of much lower plasma density.

2.2.3. SuperDARN

A map potential analysis [11] of the line of sight velocities measured by the northern hemisphere SuperDARN radars provides the global ionospheric flows during the substorm (Fig. 5). From 01:18UT to 01:30UT, there is a diversion of the flow in the 01MLT sector that moves dawnwards and approximately coincides with the auroral form as seen in the southern hemisphere. This may indicate a flow signature of the auroral streamer for the northern hemisphere. Radar scatter for the southern hemisphere was very weak, hence the map potential flows are dominated by the model flows and consequently are not used further.

2.2.4. IMAGE WIC(FUV)

At 01:18UT, IMAGE WIC(FUV) images show that an auroral bulge had formed and extended through 5hrs of magnetic local time and had a width of approximately 10°of magnetic latitude at its widest point. Prior to this, the auroral bulge had expanded from an active auroral oval, although its intensity had been constant. At this time, IMAGE WIC(FUV) shows that the bulge intensity increased considerably, indicating substorm expansion phase onset. The bulge then expanded polewards, reaching a maximum poleward excursion at 01:42UT, when the majority of the poleward edge of the bulge had reached -87°(magnetic latitude).

From 01:20UT (Fig. 6), there are structured areas of enhanced intensity within the auroral bulge. These enhancements stretch across approximately 7°of magnetic latitude of the auroral bulge and lie approximately along the lines of magnetic longitude. One structure began in the 23MLT sector, moved to the midnight meridian at 01:22UT and then propagated westwards until it was absorbed into the background auroral oval on the 23MLT meridian. A second structure began near the 01MLT meridian and moved mostly dawnwards throughout the interval, although its termination cannot be determined accurately due to its proximity to the field of view of the spacecraft.

3. Discussion

We have shown data from a period of three substorm events, as identified by the IMAGE WIC(FUV) instrument, two of which are seen by Cluster and all of which are seen in various ground magnetometer chains. We shall now comment on the ionospheric and tail signatures from the first event.

Auroral images of the southern auroral oval from the IMAGE WIC(FUV) show that during the substorm expansion phase there was significant structure within the auroral bulge. These structures have a north-south form and can be interpreted as being auroral streamers. Their presence in the north cannot be directly observed due to the positions of the various auroral imaging spacecraft and all-sky camera data being limited by the northern hemisphere summer. Using the SuperDARN radars of the northern hemisphere and comparing this to the IMAGE WIC(FUV) data, we are able to infer flow signatures that indicate that auroral streamers are present in the northern hemisphere and move dawnwards over the Greenland magnetometer chain during the substorm.

Intervals of lower ion density, stronger magnetic fields and constant plasma pressure in the magnetotail are the signatures of an under-populated flux tubes ([14] and references therein). During the substorm expansion phase, the plasma ion pressure is dominated by the ion density and hence the drops in plasma density represent drops in plasma pressure. At 01:25 there is a significant drop in plasma density and a corresponding increase in B_z at Cluster. The plasma pressure (Fig. 4 panel 1) shows little variation during this time. This indicates that Cluster detected an under-populated flux tube, or plasma bubble. Furthermore, comparing the FGM data from the four Cluster spacecraft seems to indicate that the bubble is travelling in a dawnwards direction.

The ground magnetic signature of auroral streamers has been described [2] as a sawtooth-like B_y component and a minimum in the B_z component coinciding with the maximum in B_y. The signatures seen in the ground magnetometers are similar to this description, although not as well defined. However, coupling this with the southern hemisphere auroral data, which shows definite structures in the southern auroral bulge, it is reasonable to conclude that there were similar north-south auroral forms in the northern hemisphere.

The Tsyganenko T96 model indicates that the footprint of Cluster 4 is in the vicinity of AMK during the interval, and comparison of the ground magnetometer data and Cluster FGM and CIS data shows that there is a 4min delay between the start of the signature at AMK and the detection of the under-populated flux tube at Cluster. The Tsygankenko model-based Cluster footprint moves by up to 15min MLT in a random motion between the successive images from the IMAGE WIC(FUV) instrument, indicating that during the substorm period the footprint location is variable, but also that there are limitations to the model during such periods. As the footprint of Cluster is always east of AMK during this interval, and the Cluster FGM data shows that the plasma bubble is moving eastwards, it is not unreasonable to suggest that the ground and space signatures are from one and the same feature, i.e. that the auroral streamer is closely associated with the plasma bubble. Chen and Wolf [5] predicted that under-populated flux tubes would cause a localised current wedge and Amm et al. [2] showed that under a westward moving streamer, the predicted current system from this localised current wedge matched the observed currents.

The rotational field feature seen in the FGM data at 01:26.30UT can be shown to be clearly associated with the low field event. Comparing the field angle and the field magnitude (Fig. 4) indicates that the field strength is much lower during this rotation and appears to show no gradual change between the low and high field states. This suggests that the rotation is due to some magnetic structure, possibly a plasmoid or flux rope, which moves over the spacecraft. A comparison of magnetic field data at 4s-resolution from the individual Cluster spacecraft indicates that the structure passes partially over the constellation in an Earthwards direction, then changes direction and moves tailwards.

4. Conclusion

Data from IMAGE WIC(FUV), SuperDARN and the Ammassalik magnetometer indicate the dawnward propagation of an auroral streamer during the substorm expansion phase between 01:15UT and 01:45UT on the 25th August, 2003. Using the Tsyganenko T96 model, the footprint of Cluster 4 (Tango) is mapped to the ionosphere in the vicinity, but dawnwards, of Ammassalik. In the Cluster FGM and CIS data, the signature of a dawnward moving under-populated flux tube can be seen shortly after the streamer's passage in the ionospheric data. These observations match the prediction of Amm et al. [2] that the current system within the auroral streamers, and hence the streamers themselves, are the ionospheric manifestation of under-populated flux tubes.

Data from Cluster indicates that shortly after the passage of the under-populated flux tube there is a further structure observed and that this structure has a low magnetic field that rotates through $>180°$as the structure passes over the spacecraft. Analysis of the 4s-resolution FGM data shows that the structure is initially moving Earthwards, then moves tailwards. We suggest that this structure is a plasmoid or flux rope, but that the whole of the structure is not seen by Cluster. We also suggest that this structure is independent of the under-populated flux tube, given that this structure is seen to pass Cluster both Earthwards and tailwards, whereas the under-populated flux tube is seen only to move Earthwards.

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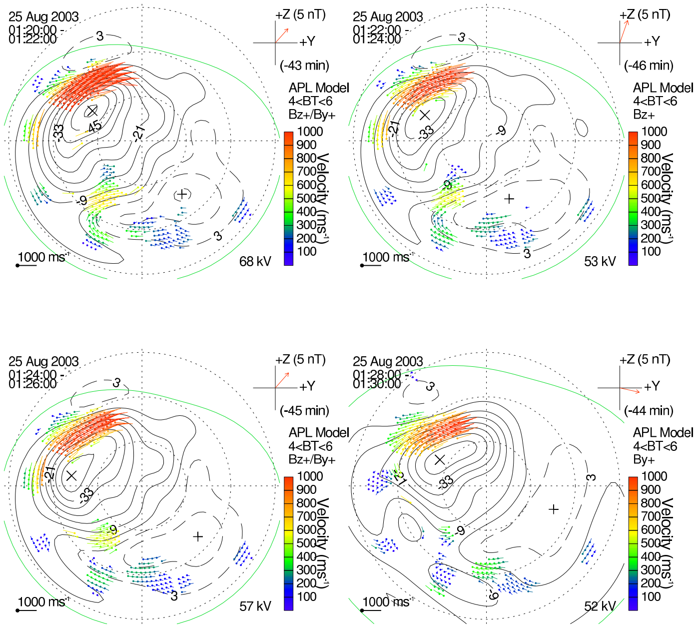

Fig. 5. SuperDARN map potential models from 25th August, 2003 (01:10UT-01:40UT). Flows in the post-midnight sector appear to divert around a feature that moves dawnwards. This coincides with the auroral streamer in the southern hemisphere IMAGE WIC(FUV) data.

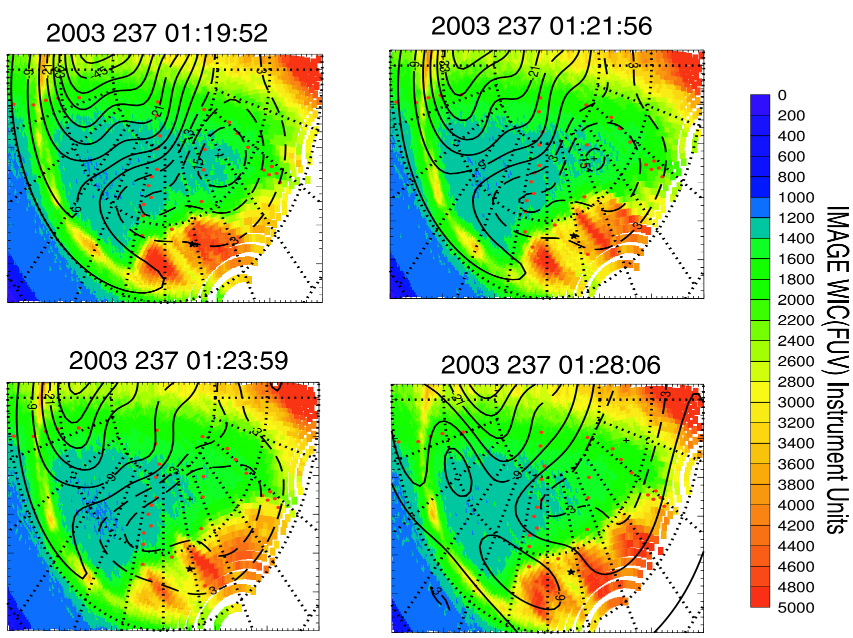

Fig. 6. IMAGE WIC(FUV) data mapped to magnetic coordinates. Timestamps above each image indicate the time of the IMAGE WIC(FUV) image. Contours from the SuperDARN map potential model are also shown.The black star represents the footprint of Cluster 4 using the Tsyganenko model [15]. The filled circles represent the locations ground magnetometers discussed.