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Auroral streamers and magnetic flux closure

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[1] On 7 December 2000 at 2200 UT an auroral streamer was observed to develop above Scandinavia with the IMAGE-FUV global imagers. The ionospheric equivalent current deduced from the MIRACLE-IMAGE Scandinavian ground-based network of magnetometers is typical of a substorm-time streamer. Observations of the proton aurora using the SI12 imager onboard the IMAGE satellite are combined with measurements of the ionospheric convection obtained by the SuperDARN radar network to compute the dayside merging and nightside flux closure rates. On the basis of this and other similar events, it is found that auroral streamers appear during the period of most intense flux closure in the magnetotail, most often shortly after substorm onset. The ionospheric convection velocity, as measured by SuperDARN, appears to be reduced in the vicinity of the streamer, suggesting de-coupling of magnetospheric and ionospheric plasma flows in the region of enhanced ionospheric conductance. **Citation:** Hubert, B., K. Kauristie, O. Amm, S. E. Milan, A. Grocott, S. W. H. Cowley, and T. I. Pulkkinen (2007), Auroral streamers and magnetic flux closure, *Geophys. Res. Lett.*, *34*, L15105, doi:10.1029/2007GL030580.

1. Introduction

[2] Streamers are auroral features which extend roughly in the north-south direction, that have been unambiguously related to bursty bulk flows (BBF) in the magnetotail [*Amm and Kauristie*, 2002, and references therein]. They are characterized by enhanced field-aligned currents at their dusk and dawn edges, the current being oriented downward (upward) along the eastern (western) boundary. Several studies have suggested that reconnection plays a role in the dynamics of BBFs [*Angelopoulos et al.*, 1992; *Shiokawa et al.*, 1997; *Fairfield et al.*, 1999, *Chen and Wolf*, 1993].

[3] We have developed of a method that combines global remote sensing of the proton aurora with SI12 and measurements of the ionospheric convection with SuperDARN to estimate the location of the open/closed field line boundary, the open flux and the opening and closure rates of magnetic flux [*Hubert et al.*, 2006a]. The accuracy of the method was discussed by *Hubert et al.* [2006a]. The electric field in the frame of reference of the moving open-closed boundary is computed and integrated along the boundary to retrieve the opening and closure reconnection rates. This method has already been applied to several substorm cycles and to cases of interplanetary shocks [*Hubert et al.*, 2006a, 2006b]. In the present work, we use the method to investigate the relative contribution of auroral streamers in global magnetic flux transfer during a substorm event. The role of BBFs as flux carriers has been estimated, e.g., by *Angelopoulos et al.* [1992] from the basis of magnetospheric in situ observations which provide accurately plasma flow characteristics but lack the global context.

2. Observation of a Streamer

2.1. Data Availability

[4] Images of the proton aurora were recorded by the SI12 instrument of the IMAGE satellite [*Mende et al.*, 2000]. The velocity of the ionospheric convection is obtained from the Super Dual Auroral Radar Network (SuperDARN) measurements, and the ionospheric electric field is deduced by applying the method developed by *Ruohoniemi and Baker* [1998]. The Wide band Imaging Camera (WIC) and the Spectrographic Imager at 135.6 nm (SI13) instruments of the IMAGE-FUV experiment, which are mostly sensitive to the emissions of the electron aurora, are also used to examine the morphology of the auroral features.

[5] On 7 December 2000, the IMAGE-FUV instruments observed a substorm expansion following an onset at 2147 UT. The event started after an interval of southward IMF which had led to the accumulation of open magnetic flux, as evidenced below by the expansion of the auroral oval. The substorm activity was seen as a ~550 nT disturbance in the AE indices. At 2158 UT WIC recorded first signatures of the formation of north-south aligned auroral structures within the auroral bulge. The clearest images of two coincidental auroral streamers were acquired by the WIC and SI13 imagers around 2202 UT (Figure 1a) while by 2206 UT the structures had faded away. One of the streamers was located above northern Scandinavia, which makes it possible to combine space-based data with the ground based observations in that region (midnight). For the other streamer which was located in the ~2200 MLT sector, ground-based data are not available. The open-closed field line boundary determined from the SI12 image at 2201 UT, when the streamers were formed, is presented in Figure 1a. SuperDARN data were available at that time. The data coverage was moderately good. Echoes were recorded above Scandinavia, where the midnight streamer is observed, and above Iceland, not far from the location of the second streamer, thus allowing constraint of the fit used to obtain the ionospheric electric field in the region of interest.

2.2. Ionospheric Equivalent Current, and FUV Observations

[6] The ionospheric equivalent current pattern was retrieved using the MIRACLE-IMAGE magnetometer chain

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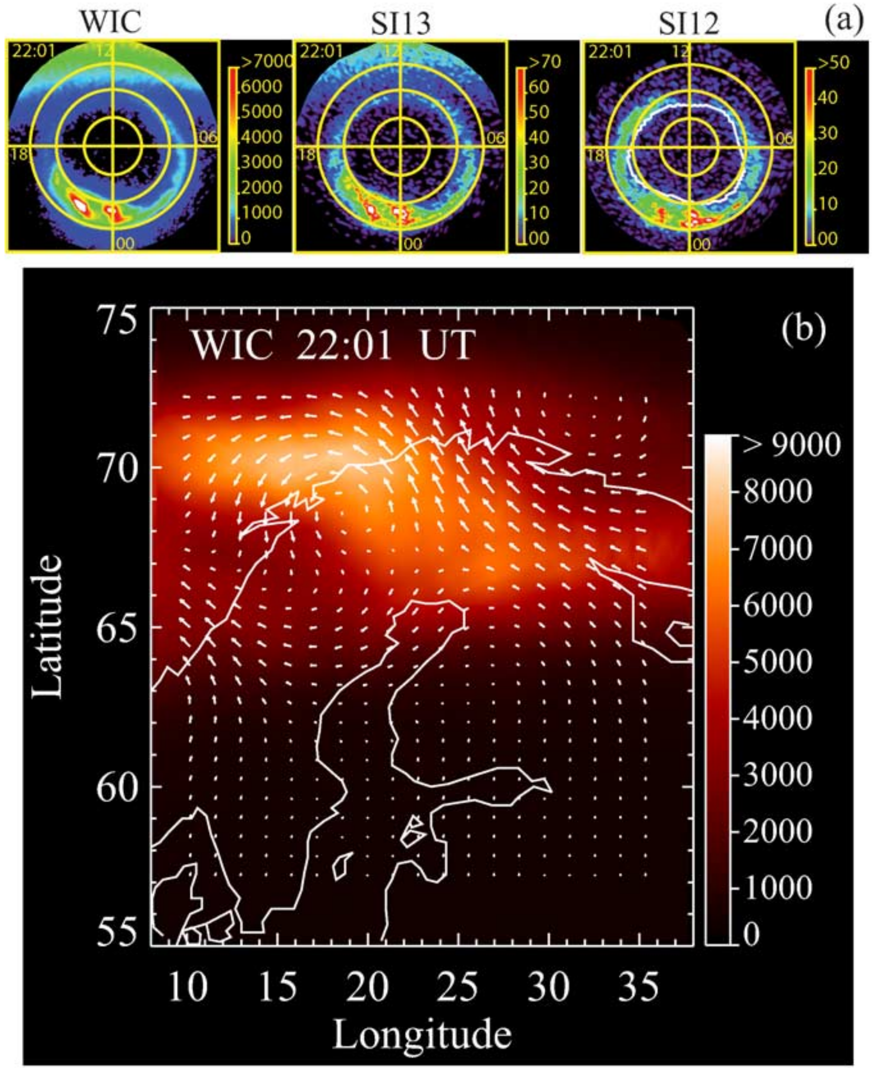

Figure 1. (a) Polar view of the IMAGE-FUV WIC, SI13 and SI12 images (magnetic coordinates), with the open/closed field line boundary overlaid on the SI12 image at 2201 UT. (b) Map of the ionospheric equivalent currents above Scandinavia (geographic coordinates) in arbitrary units, with the auroral signal from the WIC image in AD units.

operated in Scandinavia (Figure 1b) [*Amm and Viljanen*, 1999]. The streamer develops shortly after 2200 UT following the expansion onset at 2147 UT. A map of equivalent current (EC) obtained at 2201 UT is presented in Figure 1b, with the corresponding part of WIC image overlaid. The EC pattern of Figure 1b presents strong poleward currents flowing roughly along the streamer direction and a counterclockwise vortex on the western side of the current channel, consistently with previous studies [*Amm et al.*, 1999; *Kauristie et al.*, 2003]. Assuming a homogeneous conductance, this vortex can be associated with upward field aligned currents (FACs). When the streamer developed, the westward equivalent current moved poleward in concert with the poleward motion of the polar cap boundary deduced from the SI12 observations. Figure 2 shows the EC intensity versus latitude and time in the midnight sector as deduced from upward continuated magnetometer data [*Mersmann et al.*, 1979] with the polar cap boundary identified from SI12 overplotted in black. This figure suggests a close relationship

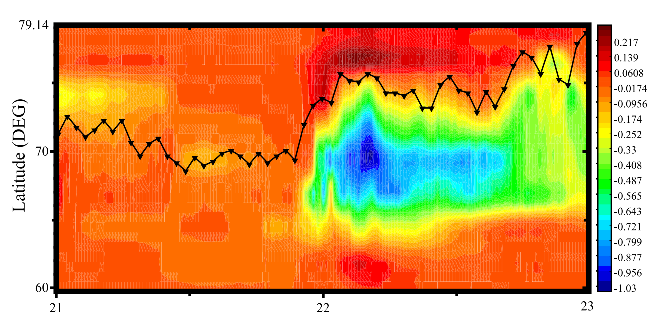

Figure 2. East-west equivalent currents (negative values correspond to westward currents, unit A/m) deduced from the MIRACLE-IMAGE magnetometer network, with the SI12 open/closed boundary overlaid in black (MLT ≈ UT + 2.5).

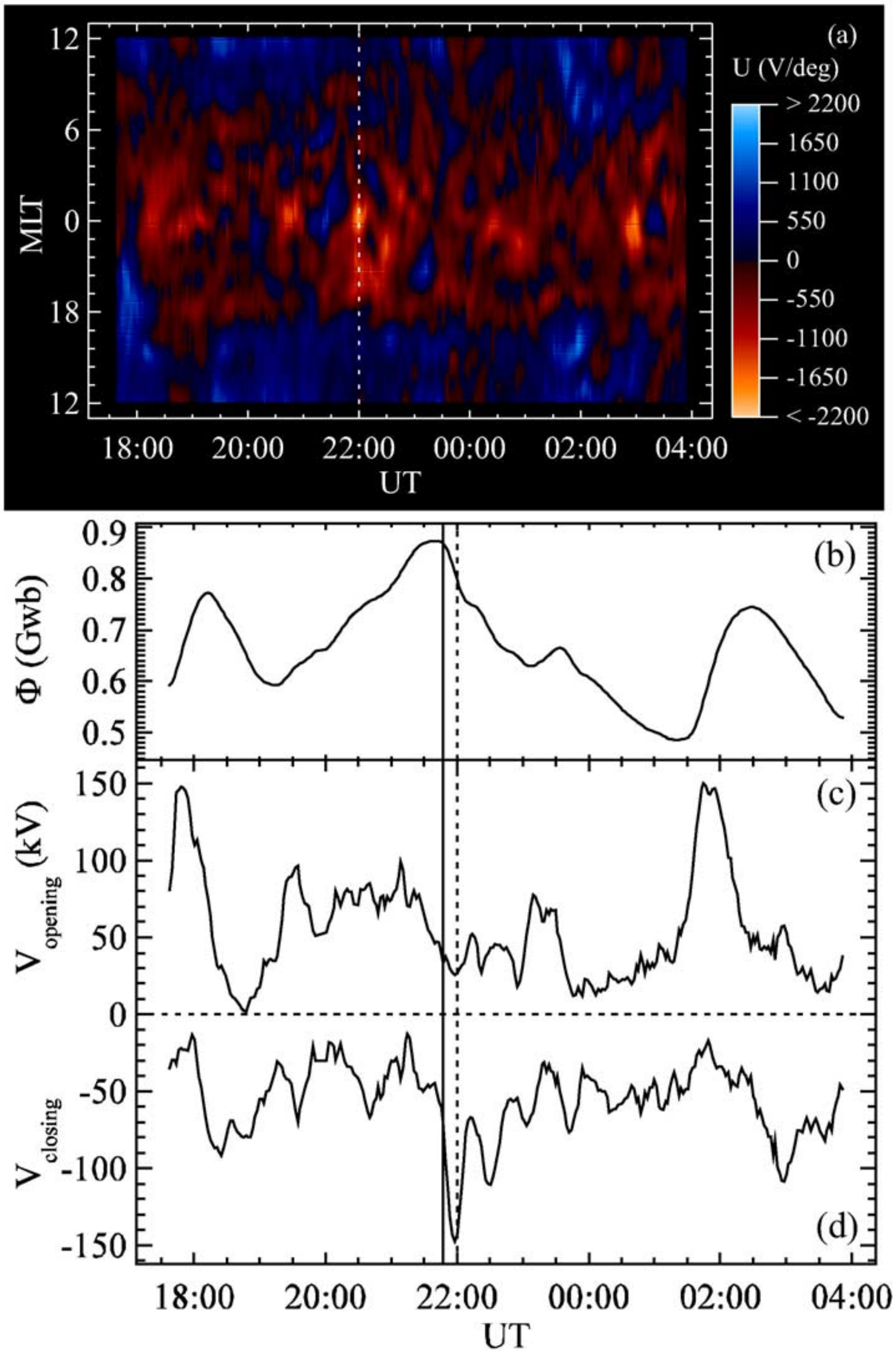

Figure 3. (a) Differential reconnection voltage, (b) open flux, (c) opening voltage and (d) closure voltage obtained from SI12 and SuperDARN observations on 7 December 2000. The solid vertical line indicates the substorm onset, and the dotted vertical lines indicate the development of the auroral streamer.

between the poleward boundary of the electrojet, the poleward optical boundary of the Doppler-shifted Lyman-α emission and the polar cap boundary.

2.3. Reconnection at the Northern Edge of the Streamer

[7] The location and motion of the open-closed field line boundary have been retrieved from the SI12 auroral images. The ionospheric electric field deduced from the SuperDARN data is then coupled with these results to estimate the electric field in the reference frame of the moving boundary, and hence the reconnection rates. Figure 3a shows a UT-MLT plot of the differential reconnection voltage along the open-closed boundary $\frac{\delta V}{\delta MLT}$ (with MLT given in degrees), i.e. the voltage per unit MLT degree, which is proportional to $\vec{E} \cdot \vec{dl}$. Red (blue) shades corre-

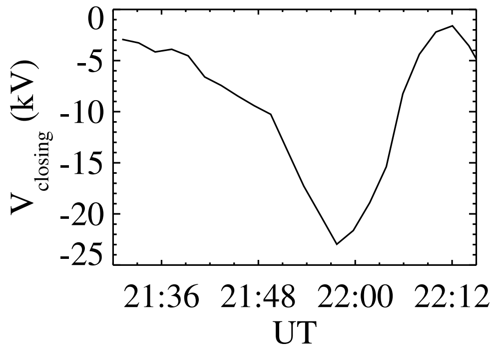

Figure 4. Closure voltage derived from the line integral of the electric field along the open-closed field line boundary in the MLT sector where the auroral streamer is observed.

spond to negative (positive) voltages, i.e. a closure of open (opening of closed) magnetic flux, respectively. The flux closure rate was clearly intensified in the midnight sector around the time of streamer appearance. Closure rates were high between 1800 and 0100 MLT and, in particular along field lines threading the poleward edges of both streamers. A more global view is shown in Figures 3b–3d where we present both the open magnetic flux (Figure 3b) and opening and closure voltages (Figures 3c and 3d) deduced from the IMAGE-FUV and SuperDARN observations. Due to reconnection at the dayside magnetopause, the magnetosphere accumulates up to ~0.9 GWb of open flux until the onset of the substorm expansion phase. The flux closure voltage then reaches ~150 kV around 2200 UT, indicating very intense nightside reconnection at that time.

[8] We have also integrated $\vec{E} \cdot d\vec{l}$ along the open/closed boundary in the MLT sector corresponding to the poleward edge of the observed streamer (2255 to 2330 MLT) to determine the associated closure voltage (Figure 4). A strong increase of the reconnection voltage is observed around 2200 UT, reaching a maximum of ~25 kV. The oscillations observed in the closure voltage in Figure 3 between 2200 and 2330 UT with a period of roughly 30 min are also found when we restrict our attention to that narrow MLT sector, and are due to changes in the poleward velocity of the boundary. In general, the motion of the boundary produces the main contribution to the closure voltage during the expansion phase, as can be expected from the rapid poleward expansion of the substorm auroral bulge. In the present case, this dominance reduces the impact of potential uncertainties related with the limited SuperDARN data coverage in some areas. We suggest that these oscillations are not specific to the streamer itself, because its lifetime is much shorter than the 30 min period. The MLT sector of the streamer contributes less than 20% to the total, and the oscillations of the closure voltage appear as a global process probably related with the development of the substorm expansion phase. Similar results can be obtained concerning the second streamer located in the premidnight sector. Note that the period of ~30 min lies in the range of Pc6 pulsations.

3. Discussion

[9] We discuss observations of a typical streamer which developed during the early stage of a substorm expansion phase, when the flux closure voltage dramatically increased after the onset to reach a maximum magnitude of ~150 kV. The time coincidence between the formation of the streamer and strong overall flux closure rate shortly after the onset suggests a possible causal relation between these two phenomena. However, intense flux closure may not be the only condition necessary to form BBFs and auroral streamers. An enhanced flux closure is the natural signature of the substorm expansion phase, and the simultaneous appearance of the streamer may be considered incidental, unless a mechanism linking BBFs and flux closure would exist.

[10] The flux tubes threading a BBF consists of a so called "plasma bubble" flowing fast Earthward in the tail [*Sergeev et al.*, 2004; *Chen and Wolf*, 1993, 1999]. In the case of BBFs and under the frozen-in approximation, the flux tubes that go through closure must be initially depleted compared to the surrounding medium, as BBFs present a low plasma density. This might be due either to localised time-dependence of the lobe plasma density flowing into the reconnection region, or to a localised displacement (e.g. earthward) of the reconnection region itself. Now the initial earthward-directed velocity of the newly-closed flux tubes and accelerated plasma following tail reconnection is $\sim V_A$, the Alfven speed in the tail lobes [see, e.g., *Owen and Cowley*, 1987]. Since V_A is larger for lower plasma density with a given tail lobe field strength, it is inevitable that a localised reduction in the lobe plasma density on the newly-closed flux tubes, due e.g. to one or other of the above effects, will produce a localised channel of higher-speed earthward flow in the plasma sheet. From this standpoint, the high velocity of the plasma flowing out of the reconnection site does not stem from the value of the reconnection rate itself, but from the value of the Alfven velocity characterizing the plasma entering the reconnection region. The observations presented here show that the related reconnection rates also become enhanced, indicating an enhancement in the reconnection-associated cross-tail electric field E_y in the tail. Since the earthward contraction speed of the newly-closed flux tubes is given by $E_y/B_z \approx V_A$, where B_z is the field component threading through the current sheet, the implication is that $B_z \approx E_y/V_A$ would also become enhanced in a region where the increase of E_y would dominate that of V_A. Regions of high-speed low-density plasma threaded by a strong B_z are indeed the defining features of BBFs. Within this scenario, the interchange instability mechanism proposed by *Chen and Wolf* [1993, 1999] might operate in a later phase of flux-tube evolution, once the initial contraction following tail reconnection is over.

[11] SuperDARN radar data obtained above Northern Scandinavia between 2200 and 2202 UT reveal that the ionospheric convection was very low within the streamer, below 200 m s^{-1}. This reduced convection suggests that the strong auroral precipitation (responsible for the bright signatures in the IMAGE-FUV images) caused intense ionisation of the atmospheric gas thus favoring ionospheric field line tying [*Coroniti and Kennel*, 1973], which does not exclude strong flows from occurring along the same field line in the equator plane, and allows some decoupling between the magnetospheric and ionospheric plasma flows in mesoscale structures. A highly conductive ionosphere is

able to discharge efficiently the electric potentials of magnetospheric origin which can be considered as a cause for the decoupling. In-situ data from the tail (which are not available for the interval discussed here) would be necessary to rigorously establish that the observed streamer was actually related with a BBF.

[12] In order to consolidate the relation between flux closure and streamer formation on observational grounds, we analyzed the reconnection voltage of eleven other intervals with a north-south aligned arc, observed with IMAGE-FUV during winter 2000 on 10/02, 1109 UT; 10/03, 0339 UT; 10/07 0758 UT; 10/29, 0420 UT; 11/01, 0558 UT; 11/03, 2345 UT; 11/29, 0147 UT; 12/08, 0258 UT, 12/23, 0802 UT; 12/23, 1023 UT and 12/23, 1207UT. Despite the limited radar data coverage of some of these events, these intervals show a relation between streamers and flux closure. Higher closure voltages appear to favor the appearance of streamers: the closure voltage was found to range between ~-50 and ~-125 kV in all cases but one (11/03/2000). In this latter case, the voltage was only 22 kV, but the polar edge of the streamer was located in the MLT sector threaded by the field lines along which the flux closure takes place. Cases with higher closure voltages were found during an expansion phase, or shortly after during the recovery phase. Surprisingly, considering longer time scales, most of these streamers were observed during or following an interval of disturbed Dst index (8 cases with Dst < -30 nT, and up to Dst ~-127 nT).

[13] Observations of dipolarized field lines threading BBFs by *Angelopoulos et al.* [1992] indeed relate BBFs to magnetic flux closure. The time resolution of our method ($\sim$15 min) does not however allow us to fully resolve transient reconnection on these time scales, so that we may have missed a transient signature directly associated with the formation of the streamer. The time lag reported by *Angelopoulos et al.* [1992] between the BBF acceleration and the magnetic dipolarization may suggest that the plasma threaded by newly closed field lines evolve slowly uptail from the reconnection site until the conditions necessary for an additional acceleration mechanism are met, due to a specific topology of the electromagnetic field and of the current system. Possible candidates to accelerate the plasma bubble are again the $\vec{j} \times \vec{B}$ force, and the interchange instability proposed by *Chen and Wolf* [1993, 1999], for example. Another possibility may be that the onset of reconnection takes place under some conditions that differ from those favoring the formation of BBFs, so that a BBF will not form until other open flux tubes with the suitable properties will have reached the X-line, after the formation of the reconnection site.

[14] In this study, the ionospheric equivalent currents deduced from the MIRACLE-IMAGE and the SI12 boundary identification consistently indicate that the polar boundary moved poleward prior to the streamer development (Figure 2) indicating that flux closure started before the formation of the streamer. Indeed, the substorm expansion onset appeared in the FUV images $\sim$13 min before the streamer. However, a more extensive study including in-situ measurements in the tail is needed to fully verify the scenario proposed above. Note that the transition between the stretched tail and the dipolarized BBF can be idealized by a field changing orientation along a helix, with a curl parallel to the field implying field-aligned currents compatible with the usual current pattern of an auroral streamer.

4. Summary

[15] An auroral streamer was observed to develop in the midnight sector during a substorm expansion phase on 7 December 2000 between 2200 and 2206 UT using the MIRACLE-IMAGE magnetometer network, the FUV instruments onboard the IMAGE satellite, and the SuperDARN radar network. The open flux accumulated prior to onset was high, reaching $\sim$0.9 GWb. The flux closure voltage, oscillating with a period of $\sim$30 min, reached a maximum magnitude of $\sim$150 kV roughly at the time of the formation of the streamer. The reconnection rate also reached a maximum on field lines threading the poleward edge of the streamer. Ionospheric convection data suggest ionospheric field line tying and consequent decoupling of magnetospheric and ionospheric flows in the vicinity of the streamer. The closure voltage computed here is consistent with a BBF formed by the closure of plasma-depleted open flux tubes some time after the reconnection onset, with high plasma velocity at the exit of the reconnection site due to the $\vec{j} \times \vec{B}$ acceleration and possibly followed by the set up of an interchange instability. The relation linking flux closure and north-south aligned arcs is also found for eleven other cases observed with IMAGE-FUV.

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References

Amm, O., and K. Kauristie (2002), Ionospheric signatures of bursty bulk flows, *Surv. Geophys.*, *23*, 1.

Amm, O., and A. Viljanen (1999), Ionospheric disturbance magnetic field continuation from the ground to the ionosphere using spherical elementary current systems, *Earth Planet. Space*, *51*, 431.

Amm, O., A. Pajunpää, and U. Brandström (1999), Spatial distribution of conductances and currents associated with north-south auroral form during a multiple-substorm period, *Ann. Geophys.*, *17*, 1385.

Angelopoulos, V., W. Baumjohann, C. F. Kennel, F. V. Coroniti, M. G. Kivelson, R. Pellat, R. J. Walker, H. Lühr, and G. Paschmann (1992),Bursty bulk flows in the inner central plasmasheet, *J. Geophys. Res.*, *97*, 4027.

Chen, C. X., and R. A. Wolf (1993), Interpretation of high-speed flows in the plasma sheet, *J. Geophys. Res.*, *98*, 21,409.

Chen, C. X., and R. A. Wolf (1999), Theory of thin-filament motion in Earth's magnetotail and its application to bursty bulk flows, *J. Geophys. Res.*, *104*, 14,613.

Coroniti, F. V., and C. F. Kennel (1973), Can the ionosphere regulate magnetospheric convection?, *J. Geophys. Res.*, *78*, 2837.

Fairfield, D. H., et al. (1999), Earthward flow bursts in the inner magnetotail and their relation to auroral brightening, AKR intensifications, geosynchronous particle injections and magnetic activity, *J. Geophys. Res.*, *104*, 355.

Hubert, B., S. E. Milan, A. Grocott, S. W. H. Cowley, and J.-C. Gérard (2006a), Dayside and nightside reconnection rates inferred from IMAGE-FUV and SuperDARN data, *J. Geophys. Res.*, *111*, A03217, doi:10.1029/2005JA011140.

Hubert, B., M. Palmroth, T. V. Laitinen, P. Janhunen, S. E. Milan, A. Grocott, S. W. H. Cowley, T. Pulkkinen, and J.-C. Gérard (2006b), Compression of the Earth's magnetotail by interplanetary shocks directly drives transient magnetic flux closure, *Geophys. Res. Lett.*, *33*, L10105, doi:10.1029/2006GL026008.

Kauristie, K., V. A. Sergeev, O. Amm, M. V. Kubyshkina, J. Jussila, E. Donovan, and K. Liou (2003), Bursty bulk flow intrusion to the inner plasma sheet as inferred from auroral observations, *J. Geophys. Res.*, *108*(A1), 1040, doi:10.1029/2002JA009371.

Mende, S. B., et al. (2000), Far ultraviolet imaging from the IMAGE spacecraft: 3. Spectral imaging of Lyman alpha and OI 135.6 nm, *Space Sci. Rev.*, *91*, 287.

Mersmann, U., W. Baumjohann, F. Küppers, and K. Lange (1979), Analysis of an eastward electrojet by means of upward continuation of ground-based magnetometer data, *J. Geophys.*, *45*, 281–298.

Owen, C. J., and S. W. H. Cowley (1987), Simple models of time-dependent reconnection in a collision-free plasma with an application to substorms in the geomagnetic tail, *Planet. Space Sci.*, *35*, 451.

Ruohoniemi, J. M., and K. B. Baker (1998), Large scale imaging of high-latitude convection with Super Dual Auroral Radar Network HF radar observations, *J. Geophys. Res.*, *103*, 20,797.

Sergeev, V. A., K. Liou, P. T. Newell, S.-I. Otani, M. R. Hairson, and F. Rich (2004), Auroral streamers: Characteristics of associated precipitation, convection and field-aligned currents, *Ann. Geophys.*, *22*, 537.

Shiokawa, K., W. Baumjohann, and G. Haerendel (1997), Braking of high-speed flows in the near-Earth tail, *Geophys. Res. Lett.*, *24*, 1179.

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