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A statistical study of flux transfer event signatures in the dayside aurora: The IMF B_y -related prenoon-postnoon asymmetry

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Abstract. Theoretical and experimental studies suggest four main classes of magnetopause/boundary layer processes to explain how particles, momentum and energy transport from the solar wind into the magnetosphere-ionosphere system. Assuming that the IMF B_y-related prenoon-postnoon asymmetry of plasma convection is specific to the magnetic merging coupling mode, we determine statistically the local time distribution of transient auroral events as a function of the IMF B_y polarity. This is based on concurrent observations of the interplanetary magnetic field components B_z and B_y and optical auroral observations of cusp/cleft activities within approximately 1000-1400 magnetic local time (MLT) and 71°-81° magnetic latitudes. Intervals of negative IMF B_z and nonzero B_y are selected for this study. Earlier case studies have shown that transient auroral events moving eastward or westward in the midday sector, depending on the IMF B_y polarity, are candidate ionospheric signature of magnetopause flux transfer events (FTEs). An example of this auroral event sequence, illustrating some main characteristics of the expected ionospheric footprints of FTEs, is presented. The statistical study reported here shows an asymmetric prenoon-postnoon auroral occurrence distribution which depends on IMF B_y, consistent with the predictions of the reconnection model within a 95% level of confidence. This result confirms the previously existing evidence in favor of an FTE-related interpretation of the actual auroral phenomenon.

Introduction

A large number of ground-based and satellite observations over the last 2 decades have been undertaken in order to explore the interaction between the solar wind and the Earth's magnetosphere. Understanding how particles, momentum, and energy are extracted from the solar wind and transferred into the magnetosphere-ionosphere system is a fundamental problem of magnetospheric physics. The cusp/cleft ionosphere is a key region for understanding the physics of the magnetopause and the adjacent boundary layers.

Theoretical and experimental studies so far suggest four main classes of transient magnetopause/boundary layer processes: Flux transfer events (FTEs) [*Russell and Elphic*, 1978, 1979; *Cowley et al.*, 1991], impulsive plasma penetration events (PTEs) [*Lemaire and Roth*, 1978], solar wind pressure variations [*Sibeck*, 1990], and Kelvin-Helmholz instabilities [*Wei et al.*, 1990]. Some of these coupling mechanisms may give similar auroral signatures and their relative importance is not yet fully understood. In addition, it has been documented that IMF directional discontinuities (DDs) give rise to transient ionospheric events including discrete auroral signatures (P. E. Sandholt et al., Cusp/cleft auroral forms and activities in relation to ionospheric convection: Responses to specific changes in solar wind and IMF conditions, submitted to *Journal of Geophysical Research*, 1995).

Kelvin-Helmholz instabilities may occur on the flanks of the low-latitude boundary layer (LLBL) where there is a velocity shear across the boundary. The bulk velocity of the plasma flow is of the order of 100-300 km/s in the magnetosheath, while the flow is nearly zero or in the opposite direction in the inner magnetosphere. A flow reversal boundary usually occurs near the inner edge of the LLBL. The probability of Kelvin-Helmholz instabilities developing peaks at this flow reversal. Instabilities may occur, however, wherever there is a shear in the flow, for example, at the outer edge of the LLBL [*Wei and Lee*, 1993]. Because of this velocity difference combined with a diffusion flux across the magnetopause, vortices are generated in the boundary layer flanks giving rise to currents going into (out of) the ionosphere in the prenoon (postnoon) sector. In the postnoon sector this vorticity is associated with precipitation

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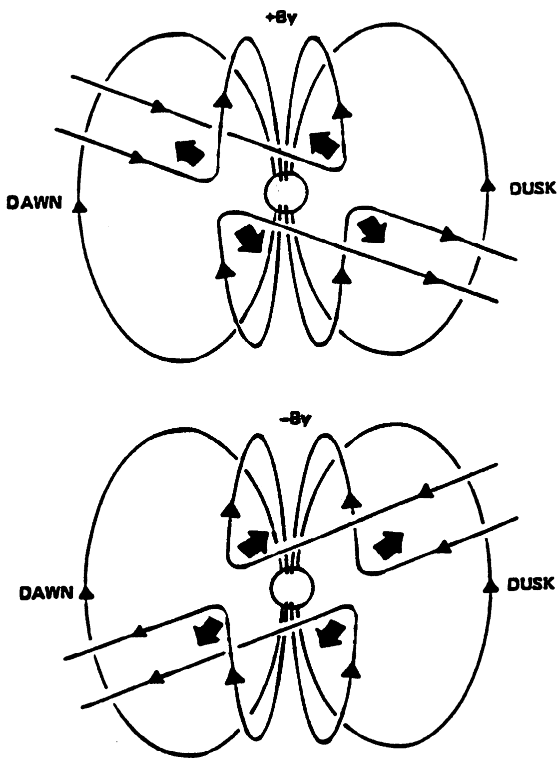

Figure 1. Schematic drawings of reconnection geometries at the dayside magnetopause as viewed from the Sun [from *Gosling et al.*, 1990b]. The large arrows indicate the direction of the forces associated with magnetic tension on recently reconnected field lines. When IMF B_y is positive (upper drawing), these forces pull the recently reconnected field lines towards dawn in the northern hemisphere. Similarly, when IMF B_y is negative (lower drawing), the reconnected field lines are pulled toward the duskside of the northern polar cap.

of accelerated electrons and therefore increased auroral activity, including "bright spots" and auroral spiral forms observed between 1400 and 1600 MLT from the Viking satellite [*Lui et al.*, 1989; *Elphinstone et al.*, 1993].

Dynamic pressure variations of the solar wind drive large-amplitude magnetopause motions, giving rise to a partial compression or relaxation of the magnetosphere. *Glassmeier and Heppner* [1992] proposed that the perturbation δj_{MP} in the Chapman-Ferraro current closes by field-aligned currents giving a twin-vortex system in the auroral ionosphere. As a solar wind discontinuity sweeps over the dayside magnetosphere, both the morning and evening parts of the magnetopause are affected. The ionospheric signatures produced should appear as auroral events in both the postnoon and the prenoon sectors [*Sibeck*, 1990].

Lemaire and Roth [1978] proposed that plasma irregularities in the solar wind with excess momentum density may, under certain conditions, penetrate into the magnetosphere. Later observations support this hypothesis. *Ma et al.* [1991] used a computer simulation to show a filament in the magnetosheath penetrating into the magnetosphere if the magnetic fields in the magnetosheath and magnetosphere are parallel or antiparallel, or if the filament's kinetic energy is sufficiently large. If the LLBL is penetrated the ionospheric signatures would be on closed field lines, and the motion of ionospheric footprints should be equatorward. According to statistical results by *Woch and Lundin* [1992], IMF B_y negative conditions favor the prenoon sector, and IMF B_y positive conditions favor the postnoon sector. This is due to the draping of the magnetosheath flux tubes around the magnetopause and the fact that antiparallel field orientation favors plasma penetration.

Dungey [1961] suggested that the primary solar wind-magnetosphere coupling mechanism is magnetic merging between the interplanetary magnetic field and the Earth's magnetic field. The merged field lines will then behave like a flux tube, transporting magnetosheath particles down to the polar ionosphere and giving antisunward flow. Merging can be steady or operate as a series of characteristic bursts. The merging bursts are called "flux transfer events" (FTEs), and on the dayside magnetopause they occur roughly every 8 min when the IMF is directed southward and disappear when the IMF points northward [*Cowley*, 1991]. Schematic drawings of merging at the dayside magnetopause are shown in Figure 1. The auroral signature of an FTE would be an optical event separating from the cusp/cleft aurora associated with its northward motion. Because of the asymmetry of the reconnection geometry depending on the IMF B_y component the auroral events are expected to move into the prenoon sector for positive IMF B_y and into the postnoon sector for negative B_y [*Cowley*, 1991; *Sandholt et al.*, 1993]. Using data from the ISEE 2 satellite, *Gosling et al.* [1990b] have observed a number of reconnection events at the low-latitude magnetopause. Their plasma flow observations indicated such an IMF B_y dependence. The corresponding motion of the auroral events is indicated in Figure 2. The detailed brightening history of poleward moving auroral forms has been documented by *Fasel et al.* [1992]. They proposed an explanation in terms of patchy multiple X-line reconnection [*Fasel et al.*, 1993].

All the above mentioned solar wind-magnetosphere coupling processes are expected to be associated with different auroral signatures and are, in principle, distinguishable. The Kelvin-Helmholz instability signatures should appear mainly in the 1400-1600 MLT region ("bright spots") [*Wei and Lee*, 1993]. PTEs, FTEs, and solar wind pressure variations can all give signatures in the noon sector. The PTE mode and the FTE mode both have IMF B_y dependencies. The PTE mode is associated with particle precipitation events in the prenoon sector for IMF B_y less than 0 and in the postnoon sector for IMF B_y greater than 0 [*Woch and Lundin*, 1992], while ionospheric FTE signatures are expected to occur predominantly in the prenoon sector for IMF B_y greater than 0 and in the postnoon sector for IMF B_y less than 0 [*Cowley et al.*, 1991]. In addition, PTEs move equatorward as they penetrate to lower magnetic L shells, while FTEs move into the polar cap. A factor of complication is that PTEs may enter at high latitudes, poleward of the cusp, giving northward moving ionospheric signatures similar to the FTE signatures [*Yamauchi and Lundin*, 1994]. The northward motion of PTE signatures will, however, in many cases differ from that of a typical FTE signature, as the northward motion will stop at a maximum latitude and not move into the polar cap [*Jacobsen et al.*, 1995]. In addition, the IMF B_y asymmetry will still be opposite for PTEs and FTEs, and also for PTEs penetrating at high latitudes, that is, a specific signature seems to exist. A solar wind pressure variation may also give northward moving signatures, but they may occur in both sectors independent of the IMF B_y polarity [*Sibeck*, 1990].

Based on considerations as indicated above, plausible signatures of FTEs in the dayside aurora have been identified [*Sandholt et al.*, 1986, 1990, 1993a]. The purpose of this study is to examine statistically the occurrence of FTE-associated auroral signatures compared with other modes. The most significant difference between the open and closed field line modes of interaction is the IMF B_y dependence. The lifetime of the optical events is typically approximately 10 min. This estimate refers to both observations [e.g., *Sandholt et al.*, 1993b] and theoretical considerations of the duration of precipitation along tailward convecting open flux tubes [*Weiss et al.*, 1995]. Thus a prenoon-postnoon asymmetry of the occurrence rate associated with the east-west motion is expected, since the B_y-related cusp displacement is moderate [*Newell et al.*, 1989]. Related to this it is noted that during large, positive IMF B_y conditions the fading phase of the auroral events is observed in the approximately 0800-0900 MLT sector [*Sandholt et al.*, 1993a].

Different models of excitation of transient ionospheric events on open field lines have been proposed. One model involves IMF B_y variability as an essential criterion [*Newell and Sibeck*, 1993]. According to this model B_y variations give rise to flow shears and associated field aligned currents (FACs) and auroral transients in the cusp region. This model implies a similar prenoon-postnoon asymmetry as the FTE model. As opposed to the Newell and Sibeck model, the FTEs are considered to be a spontaneous process, largely independent of B_y and dynamic pressure variability [*Kuo et al.*, 1995].

Because of our limited field of view it may be difficult to determine if individual northward moving events, observed in either the prenoon or the postnoon sector, is a reconnection or a pressure pulse effect. If the event is reconnection related it will preferentially show up in one of the sectors, depending on the IMF B_y polarity. Optical events caused by pressure variations should be equally distributed in both sectors. One solution is concurrent observations in the prenoon and the postnoon sectors. Unfortunately a large database of such observations does not exist. By the use of statistics, however, we are able to determine the distribution of northward moving events in the prenoon and postnoon sectors for a large number of IMF observations from the IMP 8 satellite, and in this way determine the occurrence rate of the reconnection-related signatures relative to the other modes. A single ground station is sufficient for such observations. If the reconnection mode is a frequent mode, there will be a preference of optical events in the prenoon sector when IMF B_y is greater than 0, and in the postnoon sector when IMF B_y is less than 0. We should restrict the statistical study to the time interval 1000-1400 MLT to avoid mixing events caused by reconnection or pressure variations with Kelvin-Helmholz instability events and events connected to nightside auroral activity. The statistical study of *Newell and Meng* [1992] showed that the nightside boundary plasma sheet (BPS) particle precipitation maps to the area outside the 1000-1400 MLT region. In addition, we shall restrict the study to intervals of negative IMF B_z, because this is the preferred condition for magnetic merging to happen at the dayside magnetopause. This study is an attempt to identify auroral signatures of reconnection and statistically determine the occurrence rate in the 1000-1400 MLT region when IMF B_z is less than 0 compared to the other modes and their associated auroral signatures. This is done by correlating IMF B_y with optical data from Svalbard, assuming that the IMF B_y - related prenoon-postnoon asymmetry is specific to the reconnection process.

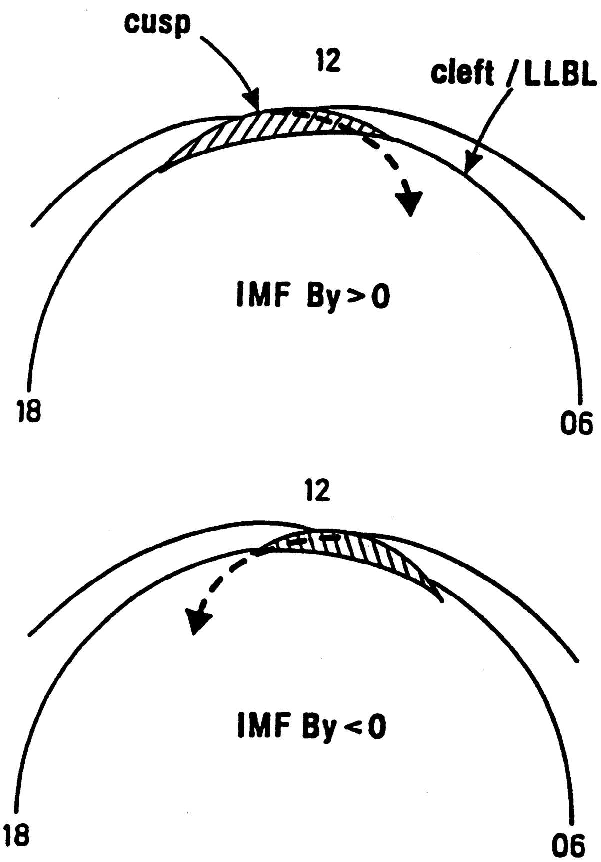

Figure 2. Expected motion of the auroral events in the polar ionosphere following a reconnection event at the low latitude magnetopause. When the IMF B_y component is positive, the event is pulled towards the duskside (upper panel) and, similarly, the event is pulled towards the dawnside for an IMF B_y negative situation (lower panel). After *Sandholt et al.* [1993].

Instrumentation and Observations

Certain requirements should be met by the observation site for optical observations of the dayside aurora. It should be situated at a high geographic latitude to avoid scattered sunlight, and it should pass under the dayside auroral oval. One of the few accessible locations satisfying these criteria is Svalbard. Our auroral observations were obtained at the station in Ny Ålesund, (geographic coordinates, 78.9°N, 11.9 °E; corrected geomagnetic latitude, 75.7°) during the polar night seasons 1988-1994. The "meridian scanning photometer" (MSP) is an instrument designed for measuring line-of-sight intensities of auroral emissions as a function of zenith angle along the magnetic meridian. In this paper we are using observations of the auroral red (630.0 nm) and

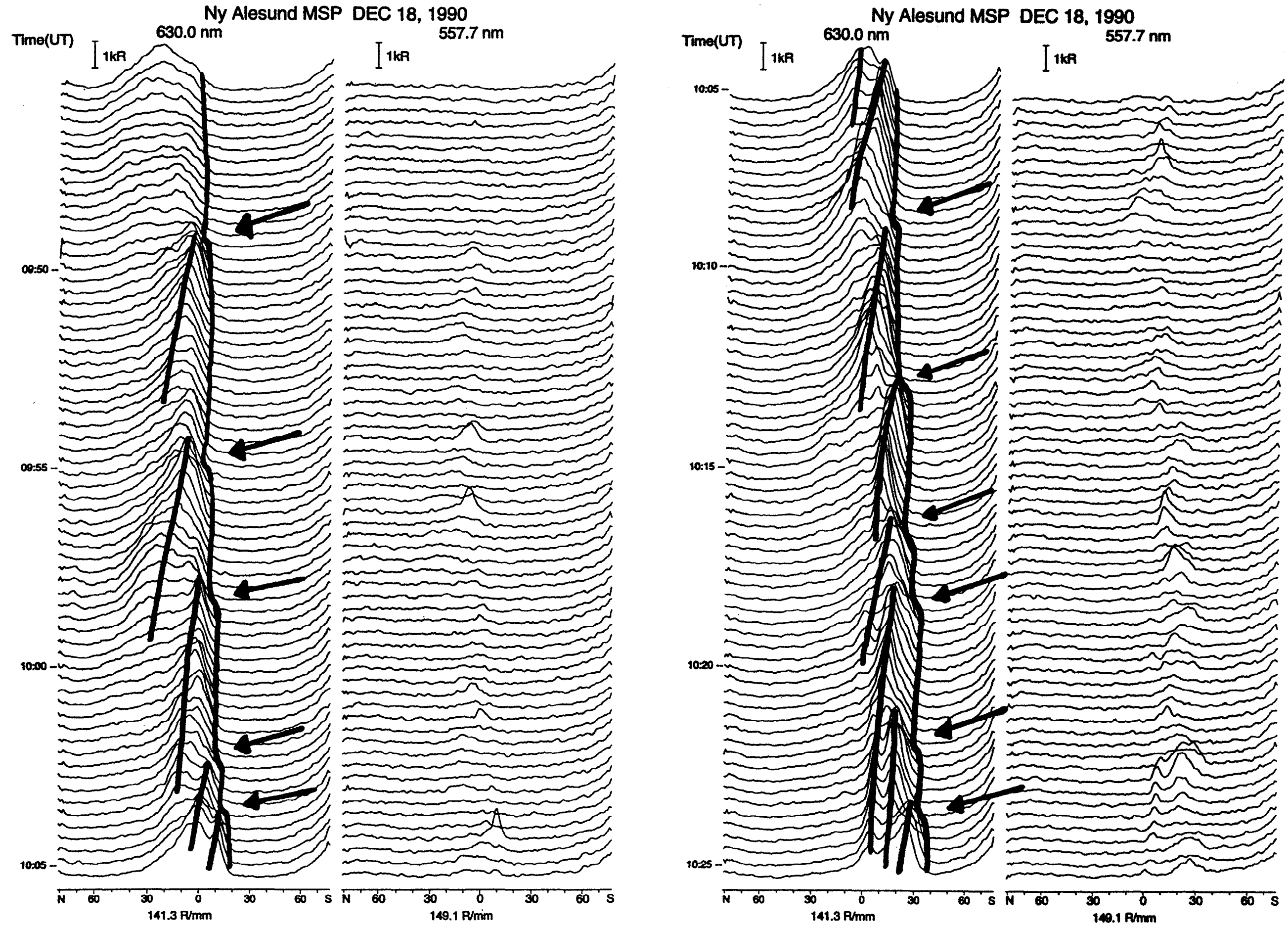

Figure 3. Photometer meridian scans (line-of-sight intensity versus zenith angle) at 630.0 nm and 557.7 nm for (a) 0945-1005 UT, (b) 1005-1025 UT, and (c) 1025-1045 UT. Intensity scales are indicated. The equatorward edge of the 630.0-nm emissions is marked by the solid line in the left panels. The onsets of the identified auroral events are indicated by arrows.

green (557.7 nm) lines of atomic oxygen. The red emission, corresponding to the transition $O^1D \rightarrow O^3P$, represents the F layer dayside auroral band caused by soft precipitation, while the green emission ($O^1S \rightarrow O^1D$) is more sensitive to structures of higher energy electron precipitation. Assuming that the red line emission layer peaks near 250 km, the MSP at 630.0 nm surveys the latitude range from approximately 71° to approximately 81° invariant latitude (ILAT). Magnetic noon at the station in Ny Ålesund is around 0850 UT. Thus the region of main interest for this study from 1000 to 1400 MLT corresponds to approximately 0650-1050 UT. In addition to the MSP, which is able to observe the north-south motion of the auroral structures, the instrumentation in Ny Ålesund also includes an all-sky TV camera. This gives us the possibility to observe east-west motion of auroral activity.

IMF and solar wind velocity data with 1-min resolution were obtained from the IMP 8 satellite while it was located in the solar wind beyond the bow shock. The solar wind velocity is needed for the calculation of delay times between a signal recorded by the satellite and associated signatures observed by ground-based instruments.

This total time delay may be written as the following sum:

$$T_{tot} = T_{sb} + T_{bm} + T_{mi} + T_{is} \qquad (1)$$

where T_{sb} is the lag between the satellite and the subsolar bow shock, T_{bm} is the propagation delay between the bow shock and the subsolar magnetopause, T_{mi} is the communication time between the magnetopause and the cusp/cleft ionosphere, and T_{is} is the ionospheric propagation time for the signal to reach the optical site. A simplified formula for T_{tot} reads [*Lockwood et al.*, 1989]

$$T_{tot} = (X_s - 1.3X_m - (Y_s \tfrac{B_x}{B_y}) + 2.6X_m)v_{sw}^{-1} + T_{is} + 120 \text{ s} \qquad (2)$$

B_x and B_y are the components of the IMF, X_s and Y_s are the geocentric solar ecliptic (GSE) coordinates for the satellite, and X_m is the coordinate of the subsolar magnetopause. The magnetopause distance (X_m) is set to its typical value of 10 R_E. The magnetopause position depends on the solar wind dynamic pressure. However, even a factor 2 increase in the dynamic pressure only decreases X_m by 12% (approximately 1 R_E). Hence the use of 10 R_E is reasonable. T_{is} is neglected here ($T_{is} \approx 0$), since we assume that the initial brightening of the auroral event is within the field of view of the optical instruments. This is not always the case, however. This effect can represent an uncertainty in the determination of the onset of the auroral event which amounts to 2-3 min or less.

When computing T_{tot} from (2) we use average values for the IMF components and the solar wind velocity over each

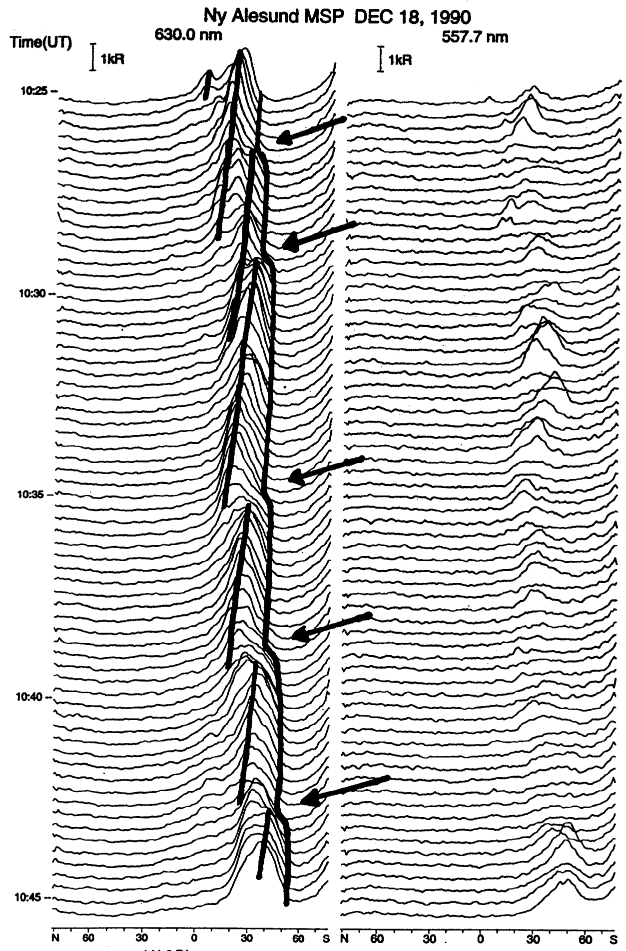

Figure 3. (continued)

time period observed. A good approximation to the real time delay between the satellite and the observed optical event is then obtained. The method has been tested by observing the response of the persistent cusp/cleft aurora to a sudden northward or southward turn of the IMF B_z component. The estimated time delay between the change in the IMF and the associated north-south movement of the background aurora agrees within a few (5 or less) minutes with the observed values. As explained later in this chapter we only use time intervals of negative IMF B_z and with the B_y component either positive or negative for a continuous time period longer than 20 min. Thus the correspondence between the ground-based MSP data and the satellite data is sufficiently accurate.

This study statistically examines the occurrence of FTE associated auroral signatures within the 1000-1400 MLT sector. Candidate signatures of FTEs in the dayside ionosphere appear as northward moving auroral structures with an east-west motion that depends upon IMF B_y. The counting of events is done manually according to certain criteria. In this study an event is identified from the MSP records as an auroral brightening form appearing inside the background cusp/cleft aurora or at its poleward edge, followed by propagation in the poleward direction. Thus the auroral form separates from the background aurora and fades within the polar cap.

The time intervals studied are selected from the available IMP 8 data, based on IMF orientation, that is, intervals of negative IMF B_z component and with the B_y component either positive or negative for a continuous time period longer than 20 min. The last condition is applied since using shorter intervals could introduce an error associated with the propagation delay between the satellite and the auroral ionosphere. The time delay given by (2) is taken into account when the auroral events are matched with the IMF data.

Despite our large total observation time of optical auroral data from the last six winter campaigns, there are only about 50 days left which fulfill the criteria of clear sky and IMF information. To prepare for this statistical study, the 1000-1400 MLT interval is divided into eight "bins", each a unit of 30 min duration. An auroral event is counted in the bin where it starts to separate from the background aurora. This procedure gave us a total of 2263 min of observation time and 161 auroral events, which should be sufficient for a statistical treatment.

An example of the auroral phenomenon under investigation is given in Figure 3. The MSP data from December 18, 1990, show a sequence of auroral events between 0945 and 1045 UT. The B_z (approximately -4 nT) and B_y (approximately -2 nT) components of the IMF were both negative in the time interval 0913-1043 UT. This corresponds to approximately 0920-1050 UT (1230-1400 MLT) along the Ny Ålesund meridian, accounting for an estimated time delay of 7 min (2). A typical auroral event appears as an auroral brightening at the equatorward edge of the background aurora followed by a subsequent poleward motion. This is as predicted by, for example, *Cowley et al.* [1991] for FTE footprints. Field-aligned electron fluxes along the newly reconnected flux tubes at the magnetopause [cf. *Gosling et al.*, 1990a] are expected to cause an auroral brightening at the equatorward boundary of the preexisting cusp/cleft aurora, as observed. Subsequently the flux tubes are pulled away from the reconnection site and into the tail (north-south and east-west) under the influence of the magnetic field tension and the magnetosheath flow, giving rise to a poleward motion of the precipitation signature. Fourteen auroral events are observed in the time interval 0950-1045 UT. This gives a mean recurrence time of 4-5 min between each event. The cusp/cleft aurora is located around zenith in Ny Ålesund (75.7° ILAT) at the beginning of the time interval, before moving rapidly equatorward between approximately 0950 and 1045 UT. The equatorward motion is stepwise. Each auroral event is associated with an equatorward shift of the luminosity. The net result is a rapid equatorward motion of the cusp/cleft aurora, from approximately 75.7 to approximately 73.5° ILAT, during the 0950-1045 UT interval.

Statistical Results

One hundred sixty-one events belonging to the category of candidate FTE-associated auroral signature have been studied in the 1000-1400 MLT interval. The auroral events and their location in MLT are summarized in Figure 4 and in Table 1. The 1000-1400 MLT interval is divided into eight bins in MLT, each of 30 min duration. The total observation time in each bin is given in Table 1. It also shows that there are between six and 29 events in each bin, and the total observation time is 2263 min. Figure 4 shows the average number of auroral events per 30 min of observation time as a function of MLT. The average number of auroral events per 30 min of observation time is between one and three.

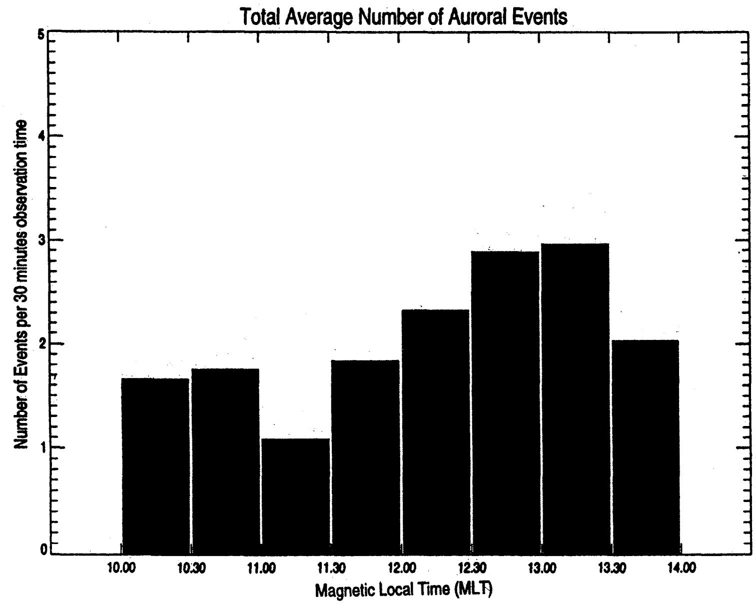

Figure 4. The average number of auroral events per 30 min of observation time as a function of magnetic local time (MLT).

The local time distribution of event occurrence as a function of IMF B_y polarity is investigated. Figure 5 shows the number of events per 30 min observation time for each of the eight bins between 1000 and 1400 MLT for positive IMF B_y, and Figure 6 shows the corresponding distribution for negative IMF B_y. The observations show a considerably higher event occurrence in the prenoon sector for positive IMF B_y and considerably more events in the postnoon sector for negative IMF B_y.

Due to different circumstances related to the observation site, we have a longer observation time in the postnoon sector than in the prenoon sector. One hundred four events are observed in the postnoon sector and only 57 events in the prenoon sector. But even after data normalization done in Figures 4, 5, and 6, we have a significant difference in the event distribution, with a higher occurrence rate of events in the postnoon sector. As a matter of fact, there is a higher probability for observing B_y negative than B_y positive in the solar wind [e.g., *Rich and Hairston*, 1994]. In our set of data we have 1357 min of observation time with B_y negative and 906 min of observation time with B_y positive, giving a higher probability for observing an auroral event during an interval of negative B_y.

To determine with a certain level of confidence whether the above results are statistically significant, we must apply statistical concepts and methods. Although the observations show a considerably higher event occurrence in the prenoon sector for positive IMF *By*, and considerably more events in the postnoon sector for negative IMF B_y (cf. Figures 5 and 6), we cannot from the figures decide how strongly the observations support any of the proposed classes of magnetopause/boundary layer processes. Using generalized linear models (GLMs), taking into account that the data consist of measurements with varying lengths of observation time, and assuming that the occurrence of auroral events is random, we find that the effect found in our observations is statistically significant within a 95% level of confidence. For further details on the statistical procedure used in this study, the reader is referred to the Appendix.

We also examined if the event occurrence statistics is influenced by the strengths of the IMF B_z and B_y components. Using a similar concept to that described above, we examined whether the occurrence of auroral events and the IMF B_y-related prenoon-postnoon asymmetry depends on the strength of the IMF B_z and/or B_y component. None of those approaches gave significantly better fits to the data than the first model, which only divided the data set into subgroups of IMF B_y positive and negative and belonging to the prenoon and postnoon sectors. Effects of the strength of the IMF components could not be observed. However, the reason for this may be that our sample of observations is too small when the data set is divided into subgroups according to the strengths of the IMF components. Thus we cannot say if the strength of the IMF B_z and B_y have an influence on the auroral event distribution.

To summarize, the results of the statistical investigation outlined above shows that there is a prenoon-postnoon asymmetry of auroral event occurrence depending on IMF B_y within a 95% level of confidence.

Table 1. Number of Auroral Events and Total Observation Time for Each Half Hour Bin Between 1000 and 1400 MLT

Bin	Events	Observation time, min
1	17	306
2	15	256
3	6	165
4	19	309
5	29	373
6	29	301
7	27	273
8	19	280
Total	161	2263

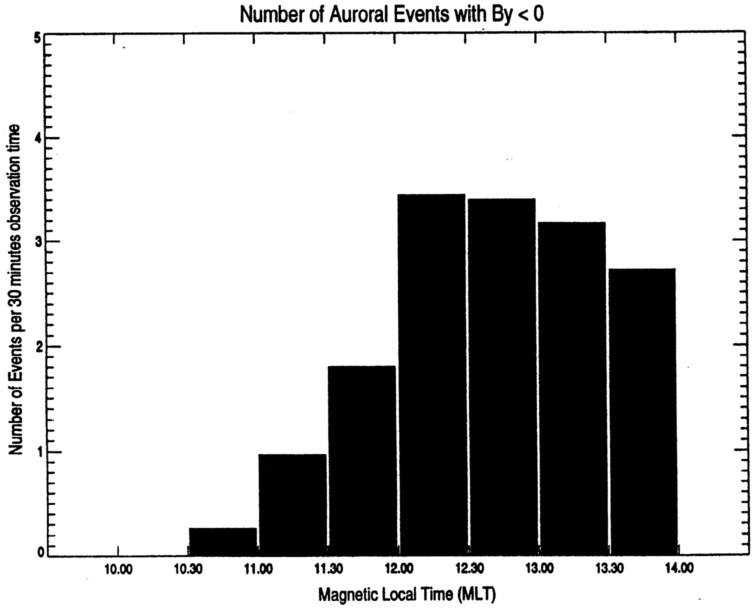

Figure 5. The average number of auroral events per 30 min of observation time as a function of MLT for negative IMF B_y.

Discussion and Conclusions

Poleward moving auroral events separating from the cusp/cleft aurora, moving northward and fading out at polar cap latitudes are candidate ionospheric footprints of pulsed reconnection. Several case studies have attempted to show that these events move eastward or westward in the midday sector depending on the polarity of IMF B_y. The detailed characteristics of the auroral events, that is, their spatial and temporal scales, repetition period, association with plasma convection events, particle precipitation characteristics, and field-aligned current structures strongly indicate a close relationship with transient magnetopause reconnection [*Sandholt et al.*, 1986, 1989, 1990, 1993a, 1994]. The IMF B_y-related east-west motion in the noon region is an essential feature of newly reconnected flux tubes [cf. *Jørgensen et al.*, 1972; *Cowley,* 1981]. The aim of this work is to find out if this particular IMF B_y effect is a prominent feature of the local time distribution of the actual auroral events. This is done by examining a large number of events in order to statistically determine the occurrence distribution of this category of auroral events in the local time window from 1000 to 1400 MLT as a function of IMF B_y.

An auroral event sequence is exemplified in Figure 3, in which the IMF B_z and B_y components are negative. The individual auroral event typically starts as a brightening at the

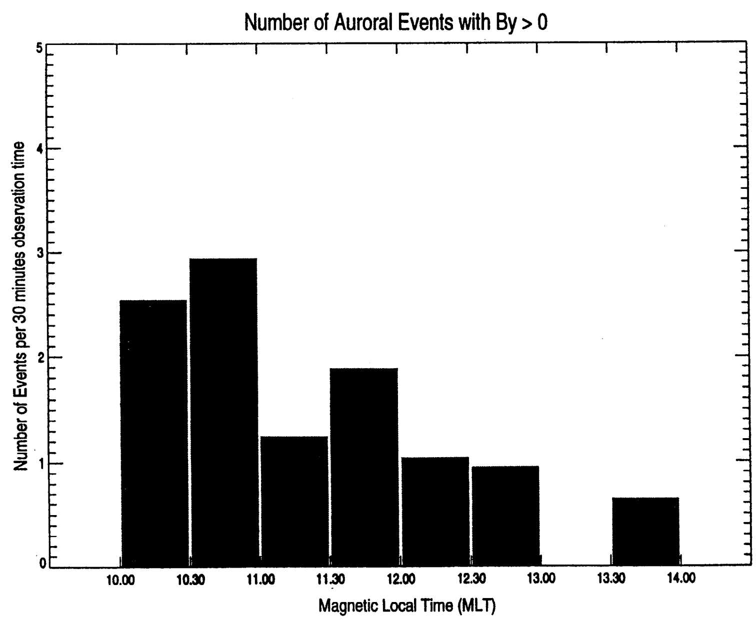

Figure 6. The average number of auroral events per 30 min of observation time as a function of MLT for positive IMF B_y.

equatorward edge of the preexisting aurora followed by a subsequent poleward motion. Each auroral event is associated with an equatorward shift of the luminosity. The cusp/cleft aurora is located around zenith in Ny Ålesund at the beginning of the time interval, before a stepwise equatorward motion takes place.

This stepwise equatorward shift of the cusp/cleft aurora is an expected signature of an erosion of the dayside magnetopause. The process is consistent with the empirical models of ionospheric FTE signatures described by *Smith and Lockwood* [1990] and *Cowley et al.* [1991], who discussed the concept of a "stepped" cusp [cf. *Newell and Meng*, 1991]. An FTE produces a patch of open flux which is added to the earlier open flux in the polar cap. The initial brightening of the aurora equatorward of the preexisting cusp/cleft emission is the expected signature of a burst of reconnection and associated particle injection from the magnetosheath through the subsolar magnetopause. A result of this process is that the open/closed field line boundary shifts southward after each event. Each FTE may excite precipitation and auroral events which have a longer lifetime than the mean time between the reconnection pulses at the magnetopause (approximately 8 min). At any given time auroral luminosity may be maintained by one or two FTEs. The observations in Figure 3 are in accordance with these theoretical predictions. This example illustrates the main characteristics which are considered to be associated with FTE footprints in the ionosphere. However, not all of the observations taken into account in the statistical study show such a regular sequence of auroral events. Due to possible similarities between the ionospheric signatures of different coupling modes (see the introduction), more than one mode may be included in the statistics.

The observations are summarized in Figures 5 and 6. The event distribution shows a clear IMF B_y-related prenoon-postnoon asymmetry, consistent with the motion pattern of reconnected flux tubes. The observed prenoon events for negative B_y and postnoon events for positive B_y can be explained by a corresponding displacement in cusp particle precipitation away from noon as observed by *Newell et al.* [1989]. The cusp (peak probability) shifts eastward, towards the postnoon side by approximately 1.5 hours when IMF B_y is positive and westward, towards the prenoon side by approximately 0.5 hour when B_y is negative (see Figure 2). A closer examination of Figures 5 and 6 shows that most of the events observed in the opposite MLT sector are located in the bins close to noon. Another factor which may contribute to this feature is the lack of accuracy in our assumption of the universal time corresponding to magnetic noon. We have used 0850 UT as our estimate of magnetic noon in Ny Ålesund. One way of investigating this problem is to use the all-sky TV images in addition to the MSP data to determine the direction of motion of the events. This is important information for the event identification, independent of the cusp location. Such a procedure is not implemented in this study. The interpretation of the auroral motion from the all-sky TV images includes some difficulties, partly due to limited resolution in the images. In addition, such a procedure would include an assumption about the movement of the auroral event which is not valid for all the four classes of magnetopause/boundary layer processes.

Despite the evidence provided by previous case studies, an unambiguous determination of the existence of FTE-related signatures in the aurora has been difficult to obtain. This is due to the multitude of possible modes of coupling between the variable solar wind and the magnetosphere-ionosphere system. The statistical study reported here shows that the auroral event occurrence distribution in the 1000-1400 MLT sector depends on IMF B_y, consistent with the predictions of the reconnection model to within a 95% level of confidence. By using the present technique the problem of distinguishing between different reconnection-related models (e.g., the *Newell and Sibeck* [1993] model versus FTEs) is recognized. However, one of our selection criteria is that IMF B_y does not change polarity during each of the observation intervals. This criterion does not exclude some variability of IMF B_y, but IMF directional discontinuities are excluded. It is noted that the post-noon auroral event sequence presented in Figure 3 (0945-1045 UT, December 18, 1990) occurred during an interval of relatively stable, quiet solar wind and IMF conditions (B_z less than 0; B_y greater than 0). In conclusion, the present results are considered to be in favor of an FTE-related interpretation of the actual auroral phenomenon.

Appendix

Generalized linear models (GLMs) are statistical models for counted data and are suitable for our study, since in a GLM we can take into account that the data consist of measurements with varying lengths of observation time.

The value we want to estimate here (with expected value μ_i) is the number of auroral events in a certain MLT sector for IMF B_y positive or negative. It is reasonable to assume that the occurrence of auroral events is random and thus follows a Poisson distribution. A GLM is then given by the following three components [*McCullagh and Nelder*, 1989]: (1) The random component (from the Poisson distribution):

$$\mu_i = \exp(\beta_0 x_{i0} + ... + \beta_p x_{ip}) \quad \text{(A1)}$$

(2) the systematic component (a linear predictor):

$$\log(\mu_i) = \beta_0 x_{i0} + \beta_1 x_{i1} + ... + \beta_p x_{ip} \quad \text{(A2)}$$

(3) the link function which relates the linear predictor to the expected value μ_i. For a Poisson distribution, as used in this study, the most frequently used link is the following:

$$g(\mu_i) = \log(\mu_i)$$

Y_{ij} is then the number of auroral events with IMF B_y value i (positive or negative) and MLT sector j (prenoon or postnoon).

We use a model with multinomial response, giving the following expression:

$$\mu_{ij} = E(Y_{ij}) = n_{ij} \varphi_i \theta_j$$

where μ_{ij} is the expected value for auroral events Y_{ij}, n_{ij} are the lengths of the observation intervals, and φ_i takes into account IMF B_y positive or negative; including θ_j introduces the MLT sector.

To fit our model to a GLM we substitute the following expressions into (A1) to make the random component linear:

$$x_{ij} = \log n_{ij}, \alpha_i = \log \varphi_i, \beta_j = \log \theta_j$$

Table A1. Estimated *t* Values

	Value	Standard Error	*t* Value
IMF $B_y < 0$	-2.60	0.10	-25.12
IMF $B_y > 0$	-2.81	0.14	-20.50
Postnoon sector	0.19	0.08	2.24

The table shows the result of the fit for the model chosen in this study. The fourth level, the prenoon sector, is determined by the three others.

giving the following expression for μ_{ij}:

$$\mu_{ij} = \exp(x_{ij_0} + \alpha_i + \beta_i)$$

We are now in the position of testing the statistical significance of the data presented in Figures 5 and 6. We want to test if $\alpha_1 = \alpha_2$ for β_1 or β_2, that is, if the sign of the IMF B_y values really make a difference in this context.

The deviance is minus twice the maximized log likelihood, up to a constant. We use the difference in deviance to compare two fitted models. This difference has a chi-square distribution, with degrees of freedom equal to the difference in degrees of freedom for the two models. This test method was used in the analysis. The *t* test was used to see whether the covariates are significant in the model. The limits for the *t* distribution for a 95% level of confidence and 102° of freedom would be t_{upper} = 1.66 and t_{lower} = -1.66. If the estimated *t* values falls between t_{upper} and t_{lower} then one would conclude that the covariates are not significant in the model. However, the estimated *t* values (Table A1) show that this is not the case, and the covariates are significant.

Residuals can be used to explore the adequacy of fit of a model in respect of choice of variance function, link function and terms in the linear predictor. We used the Pearson residual for this purpose and found that our statistical model gave a satisfactory reproduction of the data [*McCullagh and Nelder*, 1989].

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