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Four-sheet structures of dayside field-aligned currents: Statistical study

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Abstract. The present study investigates the statistical characteristics of four-sheet structures of large-scale field-aligned currents (FACs) observed by the Defense Meteorological Satellite Program-F7 (DMSP-F7) satellite in the dayside high-latitude region. A total of 495 four-FAC-sheet events were selected from the entire set of DMSP-F7 magnetometer data. With respect to the polarity of FACs, the selected events are classified into two groups, which are named type M and type W after the shape of a plot of the azimuthal magnetic component. The polarity of the equatorward most FAC is downward for the type M structure, whereas it is upward for the type W structure. Type W and type M events tend to take place in the prenoon and postnoon sectors, respectively, but the transition takes place slightly before noon. The type W structure tends to be observed for negative and positive interplanetary magnetic field (IMF) B_Y in the Northern and Southern Hemispheres, respectively. For a given hemisphere, the favorable sign of IMF B_Y for the type M structure is opposite to that for the type W structure. It is also found that both types occur more often when the IMF B_Z is northward than when it is southward. The four-sheet structure can be interpreted in terms of two zonal ionospheric convection flows separated in latitude. The equatorward one is a part of the viscous cell and, possibly, also the merging cell, whereas the poleward one is a part of the lobe cell. The direction (of the major cell) of the lobe convection is determined by the sign of IMF B_Y and is different in different hemispheres, explaining the discovered IMF B_Y dependence. The preference for northward IMF B_Z is consistent with the required development of the lobe convection. It is inferred from the expected polar distribution of FACs that the four-sheet structure is a superposition of a pair of midday region 0 and region 1 currents and a pair of conventiqonal region 1 and region 2 currents.

1. Introduction

Dayside field-aligned currents (FACs) have been examined in terms of three large-scale systems. From equatorward to poleward they are the region 2, the region 1, and the (midday) region 0 systems [*Iijima and Potemra*, 1976a, b]; we propose to refer to the poleward most FAC system as the region 0 system, rather than the cusp or mantle current system, because this current system cannot be associated with a single precipitation region [*Ohtani et al.*, 1995a]. The region 2 current flows out of the ionosphere in the prenoon sector and into the ionosphere in the postnoon sector, and this current system is very weak or disappears in the noon sector. The region 1 current flows in the opposite direction to the region 2 current at a given local time. In the midday sector, however, the region 1 current is paired with the region 0, not the region 2, current, and the distribution and the polarity of these currents depend on the sign of the Y component of the interplanetary magnetic field (IMF) [e.g., *Erlandson et al.*, 1988]. In the Northern Hemisphere, the demarcation between the prenoon and postnoon currents shifts to later and earlier local times for positive and negative IMF B_Y, respectively. The IMF dependence of the FAC distribution can be explained in the framework of the antiparallel merging between the IMF and the magnetospheric field line [*Potemra et al.*, 1984; *Burch et al.*, 1985; *Cowley et al.*, 1991].

The four-sheet structure of dayside FACs is an extreme example of the distortion of the FAC distribution due to the IMF B_Y [*Taguchi et al.*, 1993; *Yamauchi et al.*, 1993; *Ohtani et al.*, 1995b (hereafter referred to as paper 1)]. Paper 1 reports four examples of such a structure observed in the prenoon sector in the Northern Hemisphere. Simultaneous observations in the postnoon sector reveal the standard three-sheet structure. For three out of the four events, IMF data were available, which show that the IMF B_Y was negative. However, because of the limited number of events, there remain several important questions to be addressed. A list of such questions includes (1) how often the four-FAC-sheet structure takes place; (2) how wide the structure is in local time; (3) whether or not a similar structure takes place on the postnoonside or in the Southern Hemisphere; (4) how the answers to the preceding questions depend on the IMF condition. In paper 1 the formation of the four-FAC-sheet structure is explained in terms of the combination of the

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merging, viscous, and lobe convection cells. The statistical study of this unique structure of FACs is expected to provide new insights about these convection cells and therefore about the solar wind-magnetosphere interaction.

In the present study we surveyed the entire set of the DMSP-F7 magnetic field measurement for four-FAC-sheet events. In section 2 we briefly describe the data and the event selection procedure. Selected events are statistically examined in section 3, and the result is discussed in section 4. Section 5 is a summary.

2. Data and Event Selection

DMSP-F7 is a Sun-synchronous satellite with a nearly circular polar orbit at an altitude of 835 km, with its ascending and descending nodes at 1030 and 2230 LT (local time), respectively. In this study we use three-component magnetic field measurements [*Rich et al.*, 1985] made throughout the entire interval of this satellite mission (December 1983 to January 1988). The time resolution of the data is 1 s.

We developed an automatic procedure to identify the structure of large-scale FAC systems from magnetic field measurements along a satellite track; see *Higuchi and Ohtani* [this issue] for details. The procedure applies the minimum variance analysis (also known as principal component analysis) to magnetic perturbations in the horizontal plane and determines the orientation of FAC sheets. Following *Higuchi and Ohtani* [this issue], we represent the horizontal magnetic components in the directions of the minimum and maximum variances as B_L and B_A, respectively. B_L is approximately in the latitudinal direction in the region of FACs and is positive in the direction of the satellite velocity. The satellite orbits from the Southern to the Northern Hemisphere on the dayside, and therefore B_L is positive poleward and equatorward in the dayside Northern and Southern Hemispheres, respectively. B_A is the component parallel to FAC sheets and is approximately in the azimuthal direction. The positive direction of the "*A*" axis is determined so that it completes a right-hand orthogonal system along with the vertical (positive downward) and "*L*" directions. Thus B_A is positive eastward on the dayside irrespective of the hemisphere. For the Northern Hemisphere, if B_A increases (decreases) as the satellite moves poleward, the corresponding FAC flows downward (upward). The corresponding FAC polarity is the opposite for the Southern Hemisphere. The procedure fits line segments to a sequential plot of B_A with variable node positions and determines the number of FAC sheets from the number of fitted segments.

We applied this procedure to the entire data set of dayside magnetic field measurements (1,339 days) made by the DMSP-F7 satellite and identified at least one large-scale FAC system for 6,359 northern and 4,965 southern passes. For a change in B_A to be regarded as a large-scale FAC sheet, its magnitude must be larger than 30% of the magnitude of the largest B_A slope; see *Higuchi and Ohtani* [this issue] for details. Four-FAC sheets were identified for 517 and 436 passes in the Northern and Southern Hemispheres, respectively. In general, the MLT of the satellite position changes as DMSP-F7 crosses FAC sheets. It is possible that the satellite samples portions of different FAC systems at different MLTs and observes a longitudinal rather than a latitudinal structure. In 280 (215) out of 517 (436) northern (southern) passes we selected, the satellite orbit was confined within 1 hour in MLT. We will focus on these passes in the following.

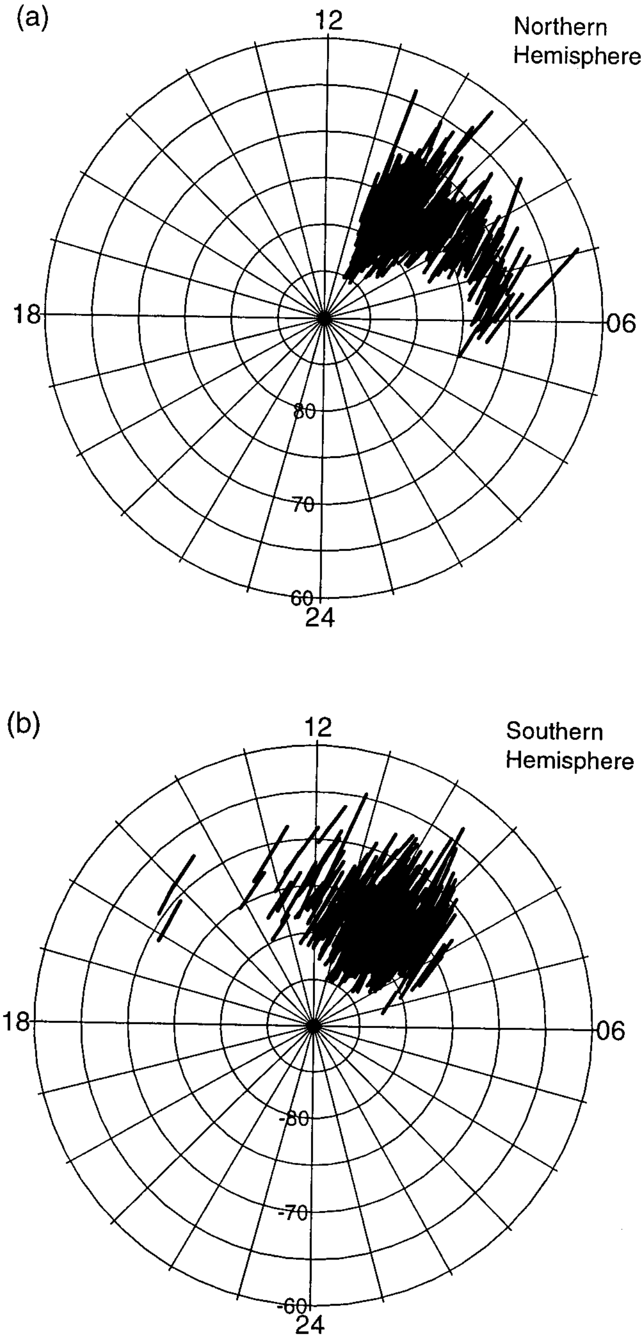

Figure 1. Orbital segments of the DMSP-F7 satellite along which four-FAC-sheet structures were observed in (a) the Northern and (b) the Southern Hemispheres.

Figure 1 shows the northern (Figure 1a) and southern (Figure 1b) polar diagrams of satellite orbital segments along which four-sheet events were observed. In the Northern Hemisphere, events are confined in the prenoon (MLT<11) sector, whereas in the Southern Hemisphere, the distribution shifts to later local times and several events were observed in the postnoon sector. This is due to the fact that the satellite orbit is Sun-synchronous and covers different ranges of MLT

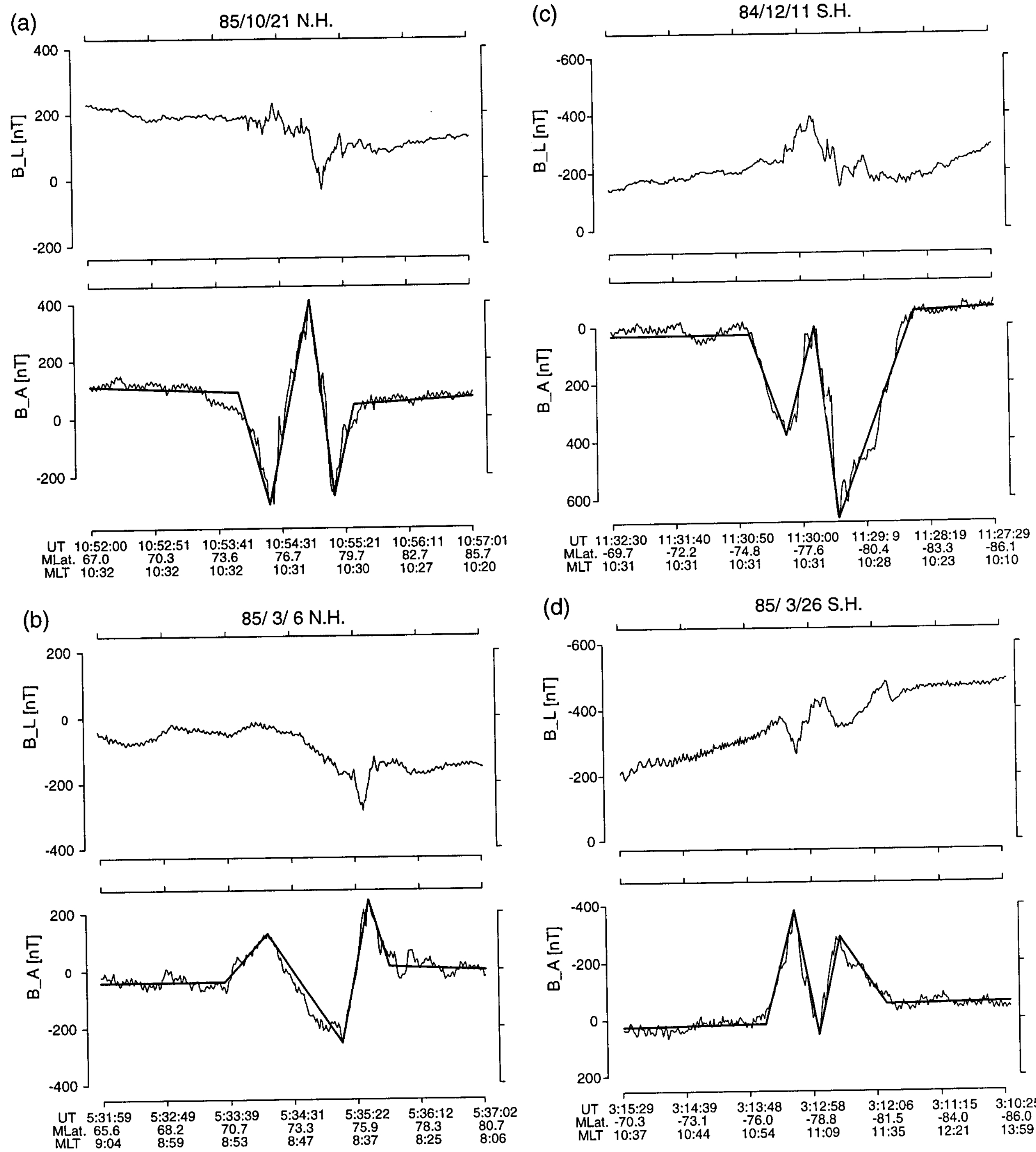

Figure 2. An example of (a) type NW, (b) type NM, (c) type SW, and (d) type SM events. In each set of plots, the latitudinal and azimuthal components are plotted in the top and bottom graphs, respectively, and the result of the line segment fit is superposed to the plot of B_A. Both vertical and horizontal axes are inverted for Figures 2c and 2d.

in the Northern and Southern Hemispheres. Normalized occurrence frequency will be examined later. Although the DMSP-F7 satellite explores even later magnetic local times in the Southern Hemisphere, many afternoon orbits skimmed, rather than cut through, FAC structures and therefore did not satisfy the criterion of the local time confinement mentioned previously.

3. Data Analysis

3.1. Event Classification

Figure 2 shows four examples of four-sheet structure events. Two of them (Figures 2a and 2b) were observed in the Northern Hemisphere, and the two other events (Figures 2c and 2d) were observed in the Southern Hemisphere. For those

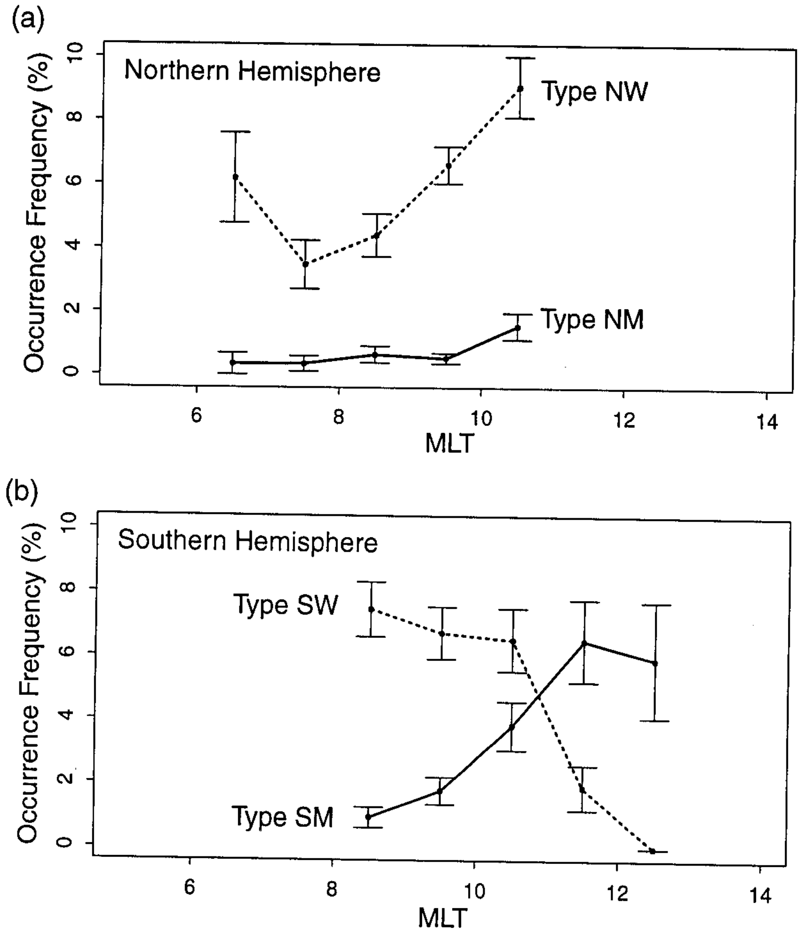

Figure 3. (a) The occurrence frequency of type NM (solid line) and type NW (dashed line) events as a function of MLT. (b) The same as Figure 3a panel except for type SM (solid line) and type SW (dashed line) events.

southern passes (Figures 2c and 2d) both vertical and horizontal axes are inverted so that the data are plotted from equatorward to poleward from the left to the right of the figure, and the same sense (increase/decrease) of slopes represents the same polarity (upward/downward) of FACs irrespective of the hemisphere. The result of the line segment fit is superposed to the plot of B_A. Four major slopes can be easily recognized in the plots of B_A, whereas the variation of B_L is much smaller.

The 280 northern and 215 southern events selected were classified into two groups with respect to the polarity of FACs. One is a structure with FACs flowing downward, upward, downward, and upward from equatorward to poleward, and the other is a structure with the opposite polarity for each corresponding FAC. In the former case the plot of B_A versus time (or latitude) begins with a decreasing slope, whereas in the latter case the initial slope is an increase; note that for the Southern Hemisphere, the vertical axis is inverted. From the shape of the plot, we refer to the former and latter structures as type W and type M, respectively. Events are further classified in terms of hemispheres (N; Northern Hemisphere; S; Southern Hemisphere) and are referred to NW, NM, SW, and SM in the following. Figures 2a to 2d are examples of type NW, NM, SW, and SM events, in that order.

3.2. Occurrence Frequency

Figure 3 shows the occurrence frequency of four-FAC-sheet events as a function of MLT for the Northern (top) and Southern (bottom) Hemispheres. The MLT is binned with a 1-hour increment. The occurrence frequency was calculated for each bin by dividing the number of events by the total number of orbits for which FACs were detected, whether or not their structure was identified by our procedure, and the start and end points of the FAC crossing were within 1 hour in MLT (the same condition for selecting four-sheet events). In other words, the occurrence frequency shown in Figure 3 represents the probability for which if FACs are observed, they have a clear four-sheet structure. The MLT of each satellite pass is defined as the average of the MLTs of the start and end points of the FAC sheet crossing.

For both hemispheres the occurrence frequency is less than 10% even at its peak. In the Northern Hemisphere, all orbits are confined in the prenoon sector, and the occurrence frequency of type W events dominates that of type M events. Events tend to be observed more frequently closer to noon. For the Southern Hemisphere, our data set extends toward afternoon, and four-FAC-sheet events were observed on both sides of the noon meridian. Local time sectors favorable for the occurrence of type W and type M events are clearly different. The occurrence frequency of type W events has its peak at 8 < MLT < 9, whereas that of type M events is maximum at 11 < MLT < 12. The transition of preferential types occurs not at noon, but at an earlier local time around MLT = 11.

3.3. IMF Dependence

In this section we examine the dependence of the occurrence of four-FAC-sheet events on the IMF orientation. We use 30-min averages of IMF 8 magnetometer data before events. Propagation time from the satellite position to the subsolar point was taken into account.

Table 1 lists the number of events of each type for three different ranges of IMF B_Y, that is, IMF $B_Y < -1$ nT, -1 nT < IMF $B_Y < +1$ nT, and $+1$ nT < IMF B_Y. For the Northern Hemisphere, type W and type M events tend to occur when the IMF B_Y is negative and positive, respectively. For the Southern Hemisphere, the favorable sign is the opposite for each type.

We made a subset of events for which the IMP 8 satellite was located at $X > 10\ R_E$ and $\sqrt{Y^2+Z^2} < 30\ R_E$; for this subset the measured IMF is more likely to be the one that actually interacted with the magnetosphere. The result for this subset was given in Table 2 in the same format as Table 1. The previously mentioned preference for the sign of IMF B_Y is even clearer for this subset. Since the occurrence of events is strongly controlled by the IMF orientation, we infer that the reconnection process between the IMF and the magnetospheric magnetic field plays an important role in the formation of the four-FAC-sheet structure.

Figure 4 plots the IMF measurements in the GSM Y–Z plane for the subset of each type. In addition to the preference for the sign of IMF B_Y, the figure suggests that four-FAC-sheet events tend to occur when the IMF B_Z is positive.

4. Discussion

Ionospheric convection can be addressed in terms of three kinds of convection cells, namely, the viscous cell, the merging cell, and the lobe cell [*Burch et al.*, 1985; *Reiff and Burch*, 1985]. There are two viscous cells in each hemisphere, one on the morningside and the other on the eveningside, and they are driven by the viscous interaction at the flanks of the magnetosphere. Each viscous cell consists of a crescent-shaped flow path, which is directed antisunward and sunward on the poleward and equatorward sides, respectively. The shape and size of the viscous cell are inferred to be relatively insensitive to the IMF B_Y. The merging cell is driven by the reconnection process between the IMF and dayside closed field lines. In contrast, the lobe cell is driven by the reconnection process between the IMF and lobe field lines at the high-latitude magnetopause tailward of the dayside cusp [*Maezawa*, 1976]. The shape and flow direction of these reconnection-driven convection cells, especially the flow direction in the open field line region, are determined by the IMF orientation.

Table 1. Number of Events for Different Ranges of IMF B_Y

Type	< −1 nT	−1 nT to +1 nT	> +1 nT
NW	90 (76%)	15 (13%)	14 (12%)
NM	0 (0%)	7 (54%)	6 (46%)
SW	17 (23%)	12 (16%)	45 (61%)
SM	14 (54%)	7 (27%)	5 (19%)

Table 2. Number of Events for Different Ranges of IMF B_Y in Which IMP 8 was Located at $X > 10\ R_E$ and $\sqrt{(Y^2+Z^2)} < 30\ R_E$

Type	< −1 nT	−1 nT to +1 nT	>+1 nT
NW	32 (91%)	2 (6%)	1 (3%)
NM	0 (0%)	4 (67%)	2 (33%)
SW	4 (16%)	7 (28%)	14 (56%)
SM	8 (73%)	1 (9%)	2 (18%)

Figure 5a schematically shows the ionospheric convection pattern and the FAC distribution in the Northern Hemisphere for negative IMF B_Y. Whereas the viscous cell (V) is relatively insensitive to the IMF orientation, the IMF B_Y plays an essential role in driving the merging cell (M) and the lobe cell (L). The figure assumes that all three convection cells coexist, although the merging cell is not essential for the formation of the four-FAC-sheet structure. It is also assumed that there is a single lobe cell in the polar cap; the coexistence of a minor lobe cell, which may occur when the northward IMF B_Z dominates the IMF B_Y ($B_Z > |B_Y|$), does not affect the following interpretation.

For negative IMF B_Y, the antiparallel merging hypothesis [*Crooker*, 1979] predicts that the field line merging takes place in the prenoon sector, and merged field lines are dragged eastward. The lobe cell fills the polar cap and circulates counterclockwise. The morningside merging cell dominates the eveningside merging cell and includes both morningside viscous cell and lobe cell in it.

We focus on the prenoon sector. There is a convection reversal inside the viscous cell. This convection reversal exists irrespective of the IMF orientation. The convection electric field is directed equatorward and poleward on its equatorward and poleward sides, respectively, and the associated divergence of the ionospheric Pedersen current requires a FAC to flow downward to this convection reversal. This FAC is regarded as a region 1 current. If the eastward convection of the viscous cell (and the merging cell) is confined in latitude, it is expected that there is an upward FAC on the equatorward side of the downward flowing FAC. This upward flowing current corresponds to a region 2 FAC.

There is another convection reversal, which is located between the viscous cell and the lobe cell. This convection reversal exists only in the prenoon sector. The lobe cell convection is directed eastward, whereas on its equatorward side, the viscous convection is directed westward. The convection electric field converges to this reversal, and the associated FAC is directed upward. If the eastward lobe cell convection is confined in latitude as depicted in Figure 5a, there should be a closure FAC, which flows downward, on the poleward side of this upward FAC. Thus we have four FAC systems. From the polarities of FACs, the structure is classified as type NW. This is consistent with the preference of the occurrence of this type for negative IMF B_Y. Such a latitudinal profile of the convection electric field was confirmed for one of the four type NW events reported in paper 1 (Plate 5 of paper 1).

From the antisymmetric configuration of the Earth's magnetic field, we infer that for the Southern Hemisphere, the pattern depicted in Figure 5a is attributed to positive IMF B_Y,

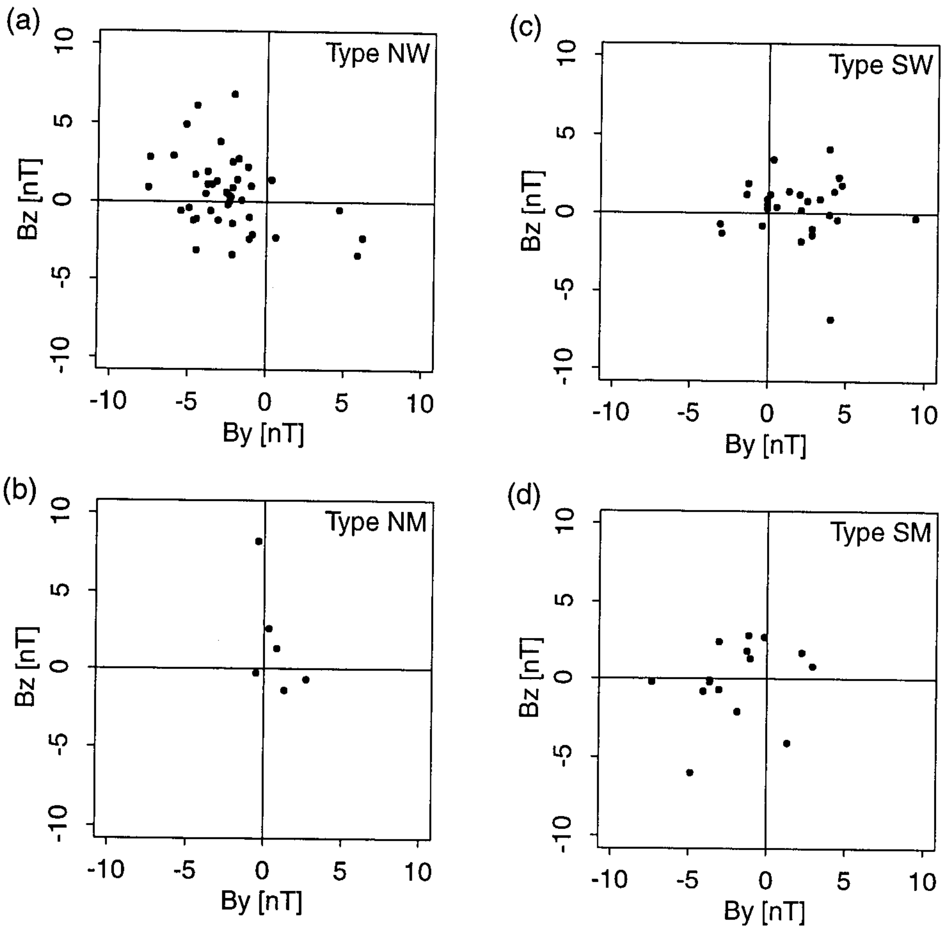

Figure 4. Interplanetary magnetic field (IMF) measurements in the GSM Y–Z plane before (a) type NW, (b) type NM, (c) type SW, and (d) type SM events. See text for the details.

which explains that type SW events tend to be observed when the IMF B_Y is positive (Tables 1 and 2).

The FAC distribution depicted in Figure 5a is inferred from the divergence/convergence of convection electric field. The four-sheet structure can be interpreted as the overlap of two pairs of FACs. One is a pair of conventional region 2 and region 1 FACs, which extend from the nightside. The other is a pair of midday region 1 and region 0 FACs, which extend from the noon sector. Note also that the four-FAC-sheet structure exists only in the prenoon sector, and in the postnoon sector there are only two or three FAC sheets along meridian, as reported in paper 1.

Figure 5b schematically shows the ionospheric convection pattern and the FAC distribution in the Northern Hemisphere for positive IMF B_Y. For the Southern Hemisphere, the depicted pattern is attributed to negative IMF B_Y. For positive IMF B_Y, the merging region is located in the postnoon sector, and the zonal convection sector is directed westward in the midday sector, which is associated with a pair of downward flowing region 1 and upward flowing region 0 FACs on the equatorward and poleward sides, respectively. Along with a pair of conventional region 1 and region 2 FACs extending from dusk, these midday FAC systems form a four-FAC-sheet structure in the postnoon sector. This is consistent with the preference of the occurrence of type NM (type SM) events for positive (negative) IMF B_Y.

One might expect that the pattern for positive IMF B_Y is simply a mirror image of the pattern for negative IMF B_Y (Figure 5a) with respect to the noon meridian except the polarities of FACs. However, Figure 3b suggests that the transition between the prenoonside and postnoonside FAC patterns takes place slightly before noon. Taking into account this point, both patterns shown in Figure 5 have a convection throat in the prenoon sector. Such an asymmetry is commonly found in convection patterns reported previously [e.g., *Heppner and Maynard*, 1987]. This asymmetry may be interpreted in terms of the corotation electric field. The corotation electric field is directed equatorward, that is, in the same direction as the electric field between region 1 and region 0 FACs in the postnoon sector but in the opposite direction to that in the prenoon sector. Thus even if a convection pattern driven by external sources is symmetric with respect to the noon meridian, the superposition of the corotation electric field makes the demarcation move toward an earlier local time. The asymmetry of FAC distribution may also be explained in terms of the latitudinal gradient of ionospheric conductance on the dayside. The dawn-to-dusk electric field drives a Hall ionospheric current to flow equatorward. The intensity of this Hall current increases equatorward, even if the electric field is homogeneous, since the conductance due to the solar illumination is higher at lower latitudes. Thus the current has a finite divergence and is

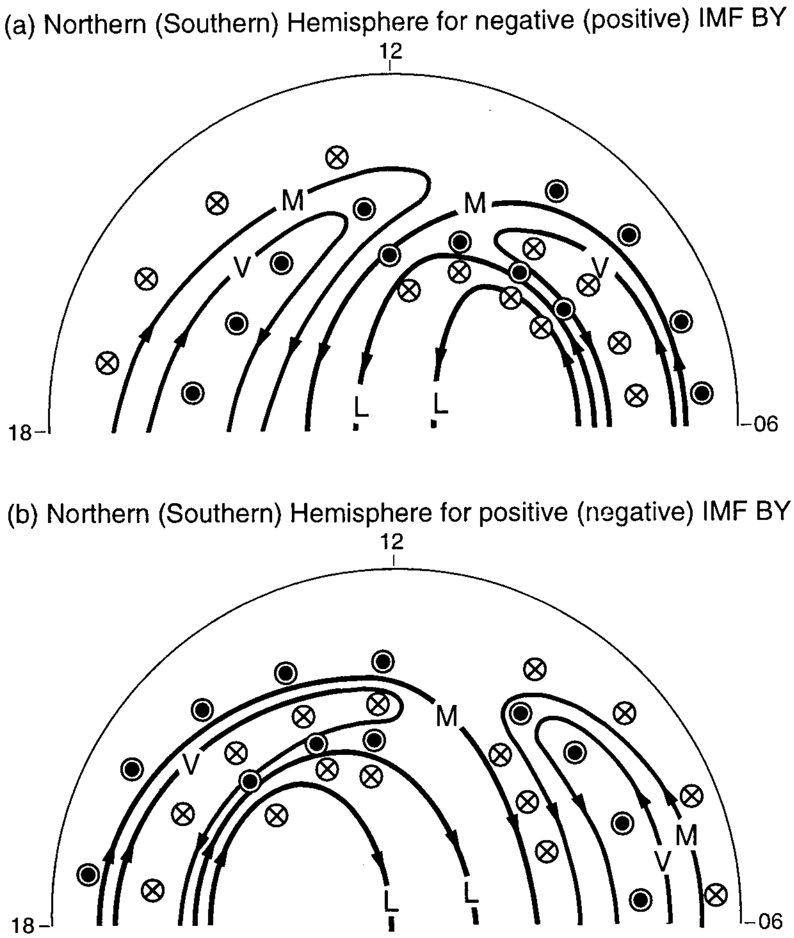

Figure 5. Schematic illustration of the three types of ionospheric convection cells, namely, the merging cell (M), the viscous cell (V), and the lobe cell (L), and the corresponding distribution of FACs in the Northern (Southern) Hemisphere for (a) negative (positive) and (b) positive (negative) IMF B_Y.

closed with an upward flowing FAC. The polarity of this FAC is the same as the postnoonside region 1 current, and therefore this additional FAC may cause an apparent dawnward shift of the demarcation between prenoon and postnoon FAC systems.

In closing, we emphasize that although the above explanation focuses on the convection reversal, what is essential for the formation of the four-sheet structure is the coexistence of two zonal convection flows separated in latitude. One is the sunward flow of the viscous (and merging) cell, and the other is associated with the lobe cell. Whereas the former exists irrespective of the IMF condition, the latter is driven by the field line merging on the poleward side of the dayside cusp and develops when the IMF B_Z is northward. This explains the discovered occurrence preference for northward IMF B_Z (Figure 4).

5. Summary

In the present study we examined the statistical characteristics of four-FAC-sheet structures observed in the dayside high-latitude region. Whereas paper 1 reported four type NW events, the present study confirmed the existence of three other types (NM, SM, and SW). It was found that type W and type M events tend to take place in the prenoon and postnoon sectors, respectively, but the transition takes place at a local time slightly earlier than noon. The type W structure tends to take place for negative and positive IMF B_Y in the Northern and Southern Hemispheres, respectively. The favorable sign of IMF B_Y is opposite for the type M structure. We also found that the four-FAC-sheet structure tends to occur when the IMF B_Z is northward. From the viewpoint of ionospheric convection, the four-FAC-sheet structure was explained in terms of two zonal convection flows separated in latitude. One is a part of the lobe convection, whereas the other is a part of the viscous (and merging) convection. The associated divergence/convergence of latitudinal Pedersen currents forms the four-FAC-sheet structure. The IMF B_Y dependence of the occurrence of each type, as well as the preference for northward IMF B_Z, can be explained in terms of the IMF dependence of the lobe convection. The four-sheet structure can be regarded as a superposition of a pair of midday region 0 and region 1 currents and a pair of conventional region 1 and region 2 currents.

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Correction to "Four-sheet structures of dayside field-aligned currents: Statistical study" by S. Ohtani and T. Higuchi

In the paper "Four-sheet structures of dayside field-aligned currents: Statistical study" by S. Ohtani and T. Higuchi (*Journal of Geophysical Research, 105*(A11), 25,317-25,324, 2000), Tables 1 and 2 were incorrect. The correct Tables 1 and 2 appear below.

Table 1. Number of Events for Different Ranges of IMF B_Y

Type	< −1 nT	−1 nT to +1 nT	> +1 nT
NW	92 (70%)	22 (17%)	18 (14%)
NM	2 (13%)	8 (53%)	5 (33%)
SW	17 (21%)	16 (20%)	49 (60%)
SM	21 (51%)	11 (27%)	9 (22%)

Table 2. Number of Events for Different Ranges of IMF B_Y in Which IMP 8 was Located at $X > 10\ R_E$ and $\sqrt{(Y^2+Z^2)} < 30\ R_E$

Type	< −1 nT	−1 nT to +1 nT	>+1 nT
NW	35 (83%)	4 (10%)	3 (7%)
NM	0 (0%)	4 (67%)	2 (33%)
SW	4 (14%)	8 (29%)	16 (57%)
SM	11 (73%)	1 (7%)	3 (20%)

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Correction to "Four-sheet structures of dayside field-aligned currents: Statistical study" by S. Ohtani and T. Higuchi

In the paper "Four-sheet structures of dayside field-aligned currents: Statistical study" by S. Ohtani and T. Higuchi (*Journal of Geophysical Research*, *105*(A11), 25,317-25,324, 2000), Figure 5 was incorrect. The correct Figure 5 appears below.

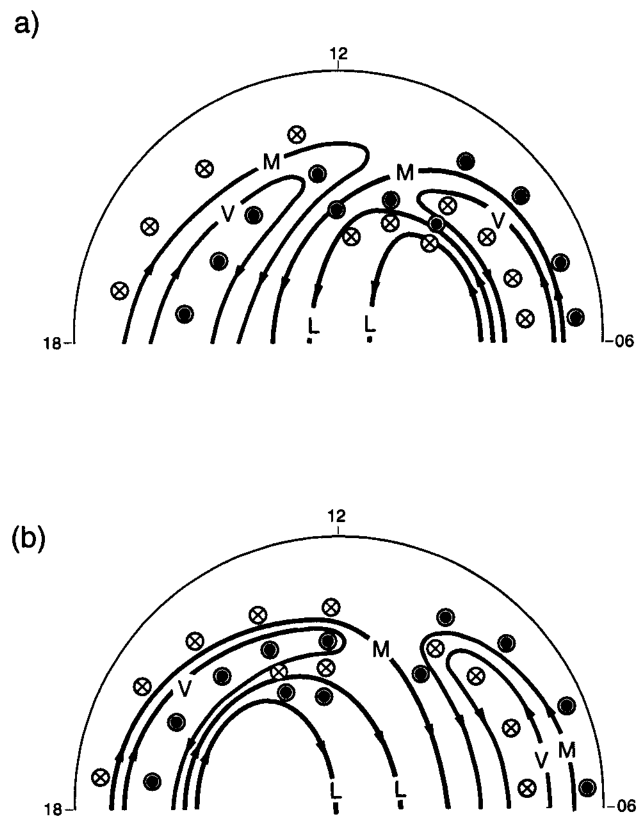

Figure 5. Schematic illustration of the three types of ionospheric convection cells, namely, the merging cell (M), the viscous cell (V), and the lobe cell (L), and the corresponding distribution of FACs in the Northern (Southern) Hemisphere for (a) negative (positive) and (b) positive (negative) IMF BY.