Particle precipitation characteristics in the dayside four-sheet field-aligned current structure

Genta Ueno,1 Tomoyuki Higuchi,1 Shin-ichi Ohtani,2 and Patrick T. Newell2

Received 23 August 2006; revised 12 February 2007; accepted 1 March 2007; published 23 June 2007.

[1] We study the statistical characteristics of four-sheet structures of large scale field-aligned currents (FACs) with an emphasis on particle precipitation collocated with each FAC sheet observed in dayside using magnetic field and particle precipitation data from the Defense Meteorological Satellite Program (DMSP). A total of 3247 four-sheet events were identified by applying an automatic procedure to the magnetic field data. The occurrence frequency of the events was less than 10% in each magnetic local time (MLT) sector for both hemispheres. The selected events were classified into two groups (type W and type M) with respect to the polarity of FACs. The polarity of the most equatorward type W (type M) FAC sheet is upward (downward). Type W (type M) events are observed predominantly in the morning (evening) sector and display a clear interplanetary magnetic field (IMF) BY dependence. Type W (type M) events appear for negative (positive) IMF BY in the Northern Hemisphere with the opposite dependence in the Southern Hemisphere. For each FAC sheet for type W events, we examined the occurrence of different precipitation regions identified with another automatic procedure. The most equatorward FAC sheet is collocated predominantly with central plasma sheet precipitation except for the prenoon sector, where boundary plasma sheet (BPS) precipitation has the highest occurrence. For the second and the third equatorward sheets, boundary layer-like precipitation, BPS near dawn and low-latitude boundary layer near noon, is dominant. In the most poleward sheet, mantle precipitation was observed frequently near noon, while BPS precipitation was dominant at earlier MLTs. These results, especially precipitation characteristics near noon, are consistent with our interpretation of the four-sheet structures, which is based on IMF BY dependence of convection patterns consisting of lobe, merging, and viscous cells.


1. Introduction

[2] It is well known that there are three large-scale field-aligned current (FAC) systems, that is, region 2 (R2), region 1 (R1), and region 0 (R0) currents [Iijima and Potemra, 1976a, 1976b]. However, we occasionally observe four-sheet structures along satellite orbits across the dayside high-latitude region [Ohtani et al., 1995b; Ohtani and Higuchi, 2000; Eriksson et al., 2002]. This unique structure can be interpreted as an overlap of a low-latitude pair of conventional R2 and R1 currents and a high-latitude pair of midday R1 and R0 currents extending from either side of noon [Ohtani et al., 1995b; Ohtani and Higuchi, 2000]. The demarcation between the prenoon and postnoon midday FAC pairs moves as a function of the interplanetary magnetic field (IMF) BY [Iijima and Potemra, 1978; Erlandson et al., 1988]. For negative IMF BY, the postnoon-side pair, which consists of upward R1 and downward R0 currents, extends across the noon meridian in the Northern Hemisphere. If that pair extends further downward on the poleward side of a pair of conventional R2 and R1 currents, which flow upward and downward, respectively, the resultant latitudinal profile of FACs can be observed as a four-sheet structure. For positive IMF BY, the prenoon-side R1 and R0 pair extends duskward across the noon meridian, and accordingly, the four-sheet structure is observed in the postnoon sector, in which the polarity of each corresponding FAC is reversed. Thus, there are two types of the four-sheet structure in terms of the FAC polarity, and their occurrence depends on the combination of IMF BY and magnetic local time (MLT) [Ohtani and Higuchi, 2000].

[3] The polar distribution of large-scale FACs should be closely related to the ionospheric convection pattern [Potemra et al., 1984], which is often 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]. Figures 1a and 1b schematically illustrate northern (southern) polar convection patterns associated
with four-sheet structures for negative and positive (positive and negative) IMF $B_y$ [Ohtani and Higuchi, 2000]. The three types of ionospheric convection cells, namely, the merging cell (M), the viscous cell (V), and the lobe cell (L), are shown along with the corresponding distribution of FACs, which is inferred from the divergence/convergence of electric field.

[5] Two viscous cells, one in the morning sector and another in the evening sector, are inferred to be insensitive to the IMF $B_y$ component. The merging cell is driven by reconnection between the IMF and dayside closed field lines, and the lobe cell is driven by reconnection between the IMF and lobe field lines at the high-latitude magnetopause tailward of the dayside cusp [Maezawa, 1976; Dungey, 1963; Eriksson et al., 2005]. In contrast to the viscous cell, the characteristics of these reconnection-related cells, such as shape and flow direction, strongly depend on the IMF orientation [Burch et al., 1985; Reiff and Burch, 1985]. When IMF $B_y$ is negative (positive), the morning-(evening-)side cells become dominant in the Northern Hemisphere as shown in Figure 1a (Figure 1b). The polar cap is occupied by one lobe cell. Let us focus on the case of negative IMF $B_y$ (Figure 1a); the positive IMF $B_y$ case (Figure 1b) is basically its mirror image. In the prenoon sector, the convection flow is sunward, antisunward, and then sunward from equatorward to poleward. The lower latitude sunward flow is a return flow of the merging and viscous cells. The weakening flow (decreasing equatorward electric field) toward the equator corresponds to convergence of electric field and therefore to an upward FAC. In contrast, the flow reversal inside the viscous cell corresponds to divergence of electric field, which corresponds to a downward FAC. There exists another flow reversal, which is located between the antisunward flow of the viscous cell and the sunward flow of the lobe cell. The corresponding FAC is directed upward. Finally, this sunward convection of the lobe cell (equatorward electric field) weakens as it gets poleward corresponding to divergence of electric field and therefore to a downward FAC. Thus, we have four FACs, which flow upward, downward, upward, and downward from equatorward to poleward. In the afternoon sector, in contrast, there is a single convection reversal, and the latitudinal FAC structure has two or three FAC sheets. This idea can be supported by simultaneous observations of a four-sheet structure in the prenoon sector and a three-sheet structure in the postnoon sector [Ohtani et al., 1995b].

[6] The asymmetric spatial distribution of FACs indicates that four FACs preferentially appear either in the prenoon or in the afternoon sector. This situation can be supported by the MLT distribution of the occurrence of different types of four-sheet structures and the preferred sign of the IMF $B_y$ component for each type [Ohtani and Higuchi, 2000]. However, another independent test is to examine the characteristics of particle precipitation collocated with each FAC sheet and address whether the result is consistent with what is expected from the source region inferred from the model convection pattern. Such a comparison between FACs and particle precipitation should also allow us to readdress the conventional identification of particle precipitation using the locations of FACs relative to convection patterns as a guide of the field line mapping.

[7] In this study, we examine statistical characteristics of four-sheet FAC structures with an emphasis on particle precipitation collocated with each FAC sheet. We refer to each sheet as sheet A, B, C, and D from equatorward to poleward. Sheets A and B would correspond to conventional R2 and R1 currents, respectively. According to Figure 1a, sheets C and D exist only in the prenoon sector, which is based on the occurrence frequency of the four-sheet events [Ohtani and Higuchi, 2000], and are therefore considered as the midday R1 and R0 currents. From the interpretation in terms of the convection pattern, however, sheets C and D can still exist in the morning sector. Actually, R0 currents were also reported in the morning sector [Bythrow et al., 1988]. Sheets C and D may correspond to a current system that was previously identified as northward $B_z$ (NBZ) currents especially if one of the lobe convection cells dominates in the polar cap because of IMF $B_y$ [Iijima and Shibaji, 1987; Vennerstrom et al., 2002, 2005; Eriksson et al., 2005].

[8] In section 2, we briefly describe magnetic field and particle precipitation data from Defense Meteorological Satellite Program (DMSP) satellites, which we use for this study. After examining four events in detail in section 3, we statistically examine in section 4 the occurrence of particle precipitation regions for each FAC sheet as well as other
characteristics such as the MLT and IMF dependencies of occurrence. Results will be discussed and summarized in section 5.

2. Data and Automatic Identification

[8] DMSP-F7, 12, 13, 14, and 15 are sun-synchronous satellites with nearly circular polar orbit at altitudes around 840 km and of inclinations of 98.8°. DMSP-F7 ascends in the prenoon (premidnight) sector and descends in the premidnight (prenoon) sector in the Northern (Southern) Hemisphere. The DMSP-F12, 14, 15 satellites cover the local time similar to DMSP-F7, but the direction of their orbits are the opposite to that of DMSP-F7. They ascend in premidnight and descend in prenoon in the Northern Hemisphere, and vice versa in the Southern Hemisphere. Because of the different directions of the orbits, the orbital plane of DMSP-F7 is inclined at 8.8° toward the predawn sector in the Northern Hemisphere and toward the predusk sector in the Southern Hemisphere, while those of DMSP-F12, 14, and 15 are toward the predusk and the predawn sectors in the Northern and the Southern Hemispheres, respectively. On the other hand, the DMSP-F13 satellite crosses the northern (southern) polar region from dusk to dawn (from dawn to dusk). The plane of the orbit is inclined toward noon and midnight in the Northern and the Southern Hemispheres, respectively. We use data of December 1983 to January 1988 for DMSP-F7, September 1994 to October 2001 for DMSP-F12, March 1995 to July 2000 for DMSP-F13, December 1997 to October 2001 for DMSP-F14, and December 1999 to October 2001 for DMSP-F15. It is a matter of course that data are obtained along the satellites’ orbits, which are confined in the geographically fixed planes that are 8.8° away from the poles. However, in the magnetic coordinate, these orbits correspond to those having spatial coverage of a width of 16° and that of 30° in the north and the south polar regions, respectively. The wider coverage in the Southern Hemisphere comes from larger deviation of the magnetic pole from the geographic pole.

2.1. Magnetic Field and FAC Identification

[9] The magnetometer on board [Rich et al., 1985] measures three magnetic components every second. Data were provided in the form of the difference between the measured and model magnetic fields in the spacecraft coordinate system. In this system, the X axis is directed vertically downward, that is, it always points earthward. The Y axis is in the direction of the projection of the satellite orbital velocity onto the plane perpendicular to X, and the Z axis completes the right-hand orthogonal system.

[10] Since the magnetic field is approximately vertical in the high-latitude region, FACs cause magnetic perturbations in the Y and Z directions. Higuchi and Ohtani [2000] developed an automatic procedure to identify large-scale FAC systems from variations of the $B_Y$ and $B_Z$ magnetic components. The procedure first applies the minimum variance analysis to $B_Y$ and $B_Z$ perturbations for the interval when the satellite crossed FACs. The maximum variance orientation is then defined as the A axis, which is set positive in such a way that the angle from the positive Z direction is minimized. If FACs have an infinite current sheet structure, then the $B_A$ component is parallel to these FAC sheets.

[11] In nominal cases, the A axis approximately points in the Z direction which depends on the direction of the orbit, duskward for DMSP-F7, downward for DMSP-F12, 14, and 15, and antisunward for DMSP-F13. The A direction allows us to grasp the relationship between magnetic field deflections and FACs in a simple rule that is independent of the satellite trajectory. That is, we just need to remember that if $B_A$ increases (decreases) with time, the corresponding FAC flows downward (upward). This rule holds irrespective of hemisphere, local time, or the direction of the satellite motion. 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 the fitted segments. The number of node points, which determines the number of FAC sheets, is optimized for each orbit so that the Akaike information criterion [Akaike, 1974] is minimized.

2.2. Precipitating Particles and Regional Identification

[12] Electrons and ions are measured by the SSJ/4 instrument [Hardy et al., 1984], the detector of which always points vertically upward (−X direction). One complete electron and ion spectrum is obtained every second, which covers from 32 eV to 30 keV in 20 logarithmically spaced steps. With particle observations in the dayside high-latitude region, Newell et al. [1991] developed a scheme that automatically identifies different particle precipitation regions and addressed their source regions. A list of classified regions includes void, polar rain, mantle, cusp, open low-latitude boundary layer, closed low-latitude boundary layer (LLBL), boundary plasma sheet (BPS), and central plasma sheet (CPS). In addition, there can be a region labeled “unclassified,” where particle precipitation does not fit into any of the other regions’ criteria.

3. Case Study

[13] Figure 2 shows four examples of four-sheet FAC events. Two of them (Figures 2a and 2b) were observed in the prenoon sector (~10 MLT), and the other two events were observed in the dawn (Figure 2c, 6 MLT) and dusk sectors (Figure 2d, 18 MLT), respectively. Each panel consists of the $B_A$ component superposed by the resultant line segment fit, corresponding region of the magnetosphere, energy flux, averaged energy, and energy-time diagrams. Time interval is 5 min for all events. For poleward-to-equatorward passes (Figures 2a, 2c, and 2d), horizontal axes are inverted to plot the data from equatorward to poleward from the left to the right of the figure. In addition, the $B_A$ axes are inverted for these passes so that the same sense (increase/decrease) of slopes represents the same polarity (downward/upward) of FACs irrespective of the orbit direction. Relationship between the slopes and the FAC polarities is also independent of hemisphere. The FAC polarities are denoted by arrows.

[14] In Figure 2a, slopes A, B, C, and D in $B_A$ correspond to the FAC sheets having polarities of upward, downward, upward, and downward, respectively. From the shape of the $B_A$ plot, we refer to the structure as type W. Sheet A, the most equatorward sheet, coincided with CPS in its equatorward part and with BPS in its poleward part. The CPS
Figure 2. Four-sheet FAC structure events, (a) type W and (b) type M in the prenoon sector and (c) type W in the dawn sector and (d) type M in the dusk sector.
Figure 2. (continued)

DMSP-F13

Apr. 12, 1999

DMSP-F13

Oct. 25, 1997

D
The BPS precipitation was also observed in sheet B. The poleward two FAC sheets (sheets C and D) were collocated with the LLBL precipitation. No significant precipitation was observed farther poleward, and the region was classified as “void.”

Figure 2b also shows observations in the prenoon sector, but each corresponding FAC was flowing in the opposite direction compared with that in Figure 2a. That is, the FACs were flowing downward, upward, downward, and upward and the plot of the $B_A$ component reveals M-shaped variations; thus we call this structure type M. According to Figure 1b, type M events are expected to be observed in the postnoon sector, but this type M event was observed in the prenoon sector, where several type M events were detected (see statistics shown in Figure 4). As seen in the former event, CPS precipitation was observed both inside and equatorward outside of sheet A. From its downward polarity and CPS precipitation inside, sheet A could be an R2 current extended from the postnoon sector. The BPS precipitation appeared in sheet B. The majority of the next FAC, sheet C, was collocated with LLBL precipitation, which overlaps with the equatorward part of sheet D. Though, most of sheet D is collocated with the mantle precipitation. The mantle signature was extended farther poleward, but no significant FAC was observed there.

A dawnside event in Figure 2c shows $B_A$ variations of type W. The CPS precipitation started equatorward of sheet A close to, but noticeable equatorward of, the demarcation between sheet A and sheet B, where the BPS precipitation started, which was collocated all other FAC sheets (sheets B, C, and D) and extended farther poleward.

Figure 2d shows an M type structure observed in the dusk sector. The BPS precipitation appeared in the middle of the most equatorward sheet (sheet A) and extended up to the poleward boundary of the most poleward sheet (sheet D). In the equatorward half of sheet A, no significant precipitation was observed; thus the regions can be classified as void.

4. Statistical Study

4.1. Observation Site of Four-Sheet FAC Events

We applied the procedure [Higuchi and Ohtani, 2000] to the entire data set of magnetic field measurements (7069 days in total) made by the DMSP-F7, F12, F13, F14, and F15 satellites and identified at least one large-scale FAC system for 32,397 northern and 36,443 southern passes; see the work of Higuchi and Ohtani [2000] for details of selection criteria. In general, the MLT of the satellite position
changes as a DMSP 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 1376 (1871) out of 1981 (2847) northern (southern) passes we selected as four-sheet events, the satellite orbit was confined within 1 hour in MLT. All four-sheet FAC events were classified into either type W or type M (see section 3) with respect to the FAC polarity.

[19] Figures 3a and 3b show northern polar diagrams of satellite orbital segments along which, type W and type M events were observed, respectively. Observations in the Southern Hemisphere are displayed in Figures 3c and 3d. Irrespective of the hemispheres, FACs of type W tended to appear in the morning side while those of type M preferred the evening side.

[20] Larger number of events were observed in the Southern Hemisphere than in the Northern Hemisphere. It is due to the spatial coverage of the satellites that slightly differs for the Northern and the Southern Hemispheres (see section 2). For example, DMSP-F7 covers a prenoon-premidnight belt which is shifted to the predusk and to the predawn directions in the Northern and the Southern Hemispheres, respectively. DMSP-F12, 14, and 15 also cover prenoon-premidnight belts, but their belts are shifted oppositely to DMSP-F7. The number of events for each satellite is summarized in Table 1. DMSP-F7 detected larger number of type W events in the Northern Hemisphere than in the Southern Hemisphere, and vise versa for type M events. This tendency is just the opposite for DMSP-F12, 14, and 15 (except for type M events observed by DMSP-F14), which is consistent with their spatial coverage. Number of events observed by DMSP-F13 also differs for the Northern and the Southern Hemispheres. We infer that the difference also came from noon-shifted and midnight-shifted spatial coverage in the Northern and the Southern Hemispheres.

4.2. Occurrence Frequency

[21] Figure 4 shows occurrence frequencies 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 total number of orbits for which FACs were detected within 1 hour in MLT (the same condition for selecting four-sheet events). In other words, the occurrence frequency shown in Figure 4 represents the probability that FACs have a clear four-sheet structure if any FAC is observed. 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.

[22] For both hemispheres, the occurrence frequency was less than 10% even at its peak. Local time sector favorable for the occurrence of type W and type M events are clearly different. Irrespective of the hemispheres, type W and type M events preferred the morning and evening sectors, respectively. The transition of preferential types occurs not at noon and midnight but at earlier local times around MLT = 11 and MLT = 23.

4.3. IMF Dependence

[23] Figure 5 plots the IMF measurements in the GSM Y-Z plane during four-sheet FAC events in the dayside (MLT = 6–18). Among events observed by one of the DMSP satellites, we select ones for which IMP 8 was located at X > 10 R\(_E\) and \(\sqrt{Y^2 + Z^2} < 30\ R\_)\(_E\). We use 30-min averages of IMP 8 magnetometer data before events. Propagation time from the satellite position to the subsolar point at the magnetopause was taken into account. Table 2 summarizes the quartiles (25th, 50th, and 75th percentiles) of the distribution of IMF \(B_Y\) and \(B_Z\), respectively. For the Northern Hemisphere, type W and type M events tend to occur when IMF \(B_Y\) is negative and positive, respectively. For the Southern Hemisphere, the favorable sign is the opposite for each type. In contrast to Ohtani and Higuchi [2000], who analyzed a smaller number of events observed by DMSP-F7 alone, we could not find any clear preference for northward \(B_Z\), and it seems that the occurrence of four-sheet structures are controlled only by the IMF \(B_Y\) component. No preference for northward \(B_Z\) was reported on the basis of observations of ISEE 2 [Gosling et al., 1991] and FAST [Eriksson et al., 2002].

<table>
<thead>
<tr>
<th></th>
<th>F7</th>
<th>F12</th>
<th>F13</th>
<th>F14</th>
<th>F15</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>465</td>
<td>84</td>
<td>120</td>
<td>101</td>
<td>8</td>
<td>778</td>
</tr>
<tr>
<td>NM</td>
<td>215</td>
<td>165</td>
<td>96</td>
<td>103</td>
<td>19</td>
<td>598</td>
</tr>
<tr>
<td>SW</td>
<td>312</td>
<td>148</td>
<td>344</td>
<td>231</td>
<td>23</td>
<td>1058</td>
</tr>
<tr>
<td>SM</td>
<td>257</td>
<td>155</td>
<td>184</td>
<td>199</td>
<td>18</td>
<td>813</td>
</tr>
</tbody>
</table>

Figure 4. The occurrence frequency of type W (black) and type M (gray) events as a function of MLT (a) in the Northern Hemisphere and (b) in the Southern Hemisphere. MLTs with light gray bars represent small sampling number for statistics (less than 50).
4.4. Comparison of FAC and Regional Boundaries

We now compare boundaries of FAC sheets with those of particle precipitation regions. We refer to FAC sheets as sheet A, B, C, and D from equatorward to poleward, as did in the case study. For each sheet, we examine the occurrence ratio of different precipitation regions. As an example, let us look at the event shown in Figure 2a. Sheet A was collocated mostly with CPS precipitation, while BPS precipitation appeared near its poleward boundary. The CPS and BPS precipitation occupied 88 and 12% of the orbital segment corresponding to sheet A, respectively. As to the orbital segment for sheet B, 67% was collocated with BPS precipitation, and the remaining 33% was collocated with LLBL precipitation. The entire segment for sheet C was within the LLBL precipitation region, and the LLBL precipitation also occupied the equatorward 77% of the orbital segment for sheet D. For the rest 23% of sheet D, the precipitation is identified as void.

Figure 6 shows the occurrence ratios of precipitation regions in type W four-sheet FAC events as a function of MLT. We examine only type W events, since type M events were far less frequently observed in the morning sector because of the local time preference as shown above. This tendency is apparently consistent with what is expected from the IMF $B_Y$-dependent global convection pattern (Figure 1). Four panels are assigned for sheets D, C, B, and A in descending order, that is, FAC sheets from poleward to equatorward. The occurrence ratios of different precipitation regions are shown by different colors. For MLT = 12, we have less than five samples, and therefore the column is colored gray. For some columns, the total of the occurrence ratios is less than unity; this is because some events were unclassified (the flux levels are clearly significant but the precipitation did not fit the identification of any precipitation region). The CPS precipitation is dominant for sheet A at MLT 6–10, whereas the BPS precipitation is

Table 2. Quartiles of the IMF $B_Y$ and $B_Z$ Distribution Shown in Figure 5, Cases for NW, NM, SW, and SM

<table>
<thead>
<tr>
<th></th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_Y$</td>
<td>-3.9</td>
<td>-2.2</td>
<td>0.4</td>
</tr>
<tr>
<td>$B_Z$</td>
<td>-0.8</td>
<td>0.5</td>
<td>1.7</td>
</tr>
<tr>
<td>NM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_Y$</td>
<td>-0.5</td>
<td>0.8</td>
<td>3.3</td>
</tr>
<tr>
<td>$B_Z$</td>
<td>-1.1</td>
<td>-0.3</td>
<td>1.4</td>
</tr>
<tr>
<td>SW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_Y$</td>
<td>-0.8</td>
<td>1.4</td>
<td>3.7</td>
</tr>
<tr>
<td>$B_Z$</td>
<td>-1.3</td>
<td>0.0</td>
<td>1.3</td>
</tr>
<tr>
<td>SM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_Y$</td>
<td>-3.5</td>
<td>-1.7</td>
<td>0.2</td>
</tr>
<tr>
<td>$B_Z$</td>
<td>-1.4</td>
<td>-0.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>
most frequent at MLT = 11. For sheets B and C, the occurrence ratio of BPS precipitation increases toward dawn, whereas that of LLBL precipitation increases toward midday. For sheet D, the occurrence of mantle precipitation is noticeable for MLT 9–11, although it is still less than 50%. Farther toward dawn, BPS is the dominant precipitation region.

[26] We divide each FAC sheet into four areas with equal latitudinal width and identified for each area the precipitation region with maximum occurrence ratio. Figure 7 shows the result in the polar diagram. The number of orbits in each MLT sector is shown in parentheses. Sheet A is collocated mostly with CPS precipitation from 6 to 10 in MLT, but BPS has the highest occurrence ratio throughout the sheet at MLT = 11. BPS precipitation is most frequent for sheets B, C, and D at MLT = 6–9, but LLBL is dominant at MLT = 10–11. Mantle precipitation is most frequent in the poleward part of sheet D in the MLT 9–11 sectors.

5. Discussion and Summary

[27] In the previous section we statistically examined characteristics of four-FAC sheet events observed by DMSP satellites. We confirmed that type W events are observed predominantly in the morning sector, and type M events are observed in the evening sectors irrespective of hemisphere. In the Northern Hemisphere, type W and type M events are observed preferably when IMF $B_Y$ is negative and positive, respectively, and in the Southern Hemisphere, the favorable signs of IMF $B_Y$ are just the opposite. These results are consistent with our interpretation of the four-sheet structures, which is based on the geometry of three different types of convection cells, that is, viscous, merging, and lobe cells (Figure 1).

[28] We then statistically examined the occurrence of different precipitation regions in each FAC sheet. As will be discussed below, some features are consistent with our explanation of the formation of four-sheet FAC structures, whereas other features raise potentially important issues as to either the formation of four-sheet structures or the identification of particle precipitation. Let us address particle precipitation for each FAC sheet, from equatorward to poleward, in terms of the model convection pattern (Figure 1).

[29] It should be noted that the proposed convection pattern (Figure 1), which consists of three different types of convection cells, is not the unique explanation of four-sheet FAC events. In general, what is essential for the FAC distribution is the divergence of the electric field rather than the direction of the electric field itself. For the four-sheet structure, even if either the merging or viscous cell disappears, there would still be four FAC sheets as far as two sunward flow channels exist separated latitudinally. For one event reported by Ohtani et al. [1995b] (in plate 5), the latitudinal profile of the electric field is consistent with the...
three-cell pattern shown in Figure 1a including the poleward electric field in the middle. Note that such a poleward electric field, which corresponds to an antisunward flow, is a unique feature expected only in the presence of the viscous cell. In contrast, for the events shown in Figures 2c and 2d, the Special Sensor for Ions, Electrons, and Scintillation (SSIES) instrument onboard DMSP observed two separate sunward channels but not an antisunward flow between them (not shown). It is interesting to examine the convection pattern associated with the four-sheet structure using an antisunward zonal flow as a marker of the viscous cell, which is, however, the subject of a future study.

[30] The most equatorward FAC (sheet A) is collocated predominantly with CPS precipitation except for close to the noon meridian (MLT = 11). This is consistent with our interpretation that this is a conventional R2 current, which is mapped to the near-Earth equatorial region [Iijima et al., 1990], either the plasma sheet or ring current. The associated convection flow should be sunward, which can be regarded as a return flow of the viscous and/or merging convection. Near its poleward edge, CPS precipitation is often observed, which has been reported previously for individual events [de la Beaujardière et al., 1993; Ohtani et al., 1995a, 1995b]. One unexpected result is that the relative occurrence of CPS precipitation is significantly smaller (~25%) in the prenoon sector (MLT = 11) than in earlier MLT sectors (see Figure 6). Instead, BPS precipitation has the highest occurrence ratio there, and the occurrence of LLBL and cusp precipitation is also noticeable. Whereas we need to be cautious because the number of orbits is much smaller (28) in that sector, this apparent difference might reflect a certain magnetospheric condition preferable for the occurrence of four-sheet FAC structures. It is interesting to compare the present result with the general characteristics of particle precipitation for R2 currents, which will be the subject of a future study.

[31] For sheet B the occurrence ratios of BPS and LLBL precipitation are significantly higher than that for sheet A. The ratio of the occurrence of LLBL precipitation to that of BPS precipitation increases toward noon. CPS precipitation is occasionally observed especially at earlier MLTs, but its frequency is significantly lower than that for sheet A. According to our interpretation, this FAC is a conventional R1 current extending from night side, and it is located around the convection reversal inside the viscous cell or in the region in the merging cell where the sunward velocity decreases toward poleward. This region mapped along the magnetic field line to the equatorial plane is likely located between the plasma sheet and the low-latitude boundary layer, or to the inner part of the LLBL, where the convection is stagnant [Williams et al., 1985; Traver et al., 1991]. It is therefore reasonable that this current sheet is collocated mostly with particle precipitation with characteristics of the boundary layer, whether it is identified as BPS or LLBL. In the prenoon sector (MLT = 11), cusp precipitation is occasionally observed in this current sheet, which was reported before for the midday R1 current [Erlandson et al., 1988].

[32] In terms of the occurrence ratios of precipitation regions, sheet C has very similar characteristics to sheet B except that in sheet C, the occurrence ratio of CPS precipitation is even lower and that of mantle precipitation is still low (<20%) but noticeable near noon (Figure 6). In our interpretation, this current sheet is located between the antisunward convection of the viscous cell and the sunward convection of the lobe cell. Or in case when the viscous cell is absent, it is located just outside the lobe cell where the sunward velocity increases toward poleward. The current sheet may be identified as the midday R1 current or the NBZ current only because of IMF $B_y$ effects. Previous studies have found that the R1 current in the dayside sector have their source in the boundary layers [Bythrow et al., 1981; Potemra et al., 1987; Woch et al., 1993], except for local times around noon, where R1 currents are collocated with cusp particle precipitation [Erlandson et al., 1988]. In the NBZ current region, Eriksson et al. [2005] have observed boundary layer-like plasmas. Therefore we expected that cusp precipitation is observed frequently close to noon, while boundary layer-like precipitation becomes dominant for other local times. Our statistics showed BPS near dawn and LLBL near noon and cusp precipitation was not dominant for all local times we examined (MLT = 6–11). The result is consistent with the expectation and implies that cusp precipitation would preferentially appear in the very narrow sector around noon.

[33] Sheet D is identified as a midday R0 current extending from the midday sector along with sheet C or an NBZ-like current only because of the IMF $B_y$ effects, and it is located in the sunward convection region of the lobe cell. Frequent observation of mantle precipitation in sheets D near noon is consistent with this idea; the midday R0 current is collocated with mantle precipitation [Erlandson et al., 1988; Bythrow et al., 1988; Ohtani et al., 1995a]. Moreover, boundary layer-like precipitation was observed in the NBZ current [Eriksson et al., 2005]. It is, however, interesting to note that BPS precipitation is dominant at earlier MLTs. There are at least two possibilities. First, our interpretation may not be applicable to four-sheet structure events away from the midday sector. For example, at earlier MLTs, all four sheets may be extending from night side in association with geomagnetic activity; note the occurrence frequency of four-sheet structures has actually another peak on the night side. Second, the lobe cell is located (by definition) inside the polar cap, but because of active interaction between the solar wind and the magnetosphere, the associated precipitation may have similar characteristics to LLBL or BPS precipitation [e.g., Eriksson et al., 2002].

[34] In summary, the occurrence ratio of particle precipitation regions associated with four-sheet structures is generally consistent with our interpretation near noon. At earlier MLTs, however, boundary-type precipitation, especially BPS precipitation, is dominant for sheets B–D. This is actually reasonable in the sense that the occurrence of precipitation of magneto/sheath-origin particles decreases monotonically away from the midday sector, and in the absence of such particles, precipitation regions cannot be identified as LLBL, cusp, or mantle, but they are identified as either CPS or BPS. Thus the dominance of BPS precipitation away from noon should not be considered to be counter-evidence of our interpretation of four-sheet structures. However, it still needs to be understood how far toward dawn the midday R1 and R0 currents can extend. In the context of the NBZ-like currents, Eriksson et al. [2005] reported that the single lobe cell can indeed be located farther tailward than is often assumed. An alternative explanation is that four-sheet structures in the
dawn sector are a feature extending from night side. From that perspective, it is extremely intriguing to examine the formation/evolution of four-sheet structures in terms of global geomagnetic activity, which, however, is beyond the scope of the present study.

[35] Acknowledgments. Magnetometer data from the DMSP satellites were provided by F. J. Rich and the Air Force Research Laboratory. The IMP 8 magnetometer data were provided by R. P. Lepping and the National Space Science Data Center through the World Data Center-A for Rockets and Satellites. Software for calculating AACGM (PACE) coordinates was provided by S. Wing and K. B. Baker. The DMSP thermal plasma data were provided by the Center for Space Sciences at the University of Texas at Dallas and the US Air Force. Work at APL was supported by NSF grant ATM-0503065. This study was carried out under the ISM Cooperative Research Program (2006-ISM-CRP-2024).

[36] Wolfgang Baumjohann thanks Stefan Eriksson and another reviewer for their assistance in evaluating this paper.

References


Maezawa, K. (1976), Magnetospheric convection induced by the positive z component of the interplanetary magnetic field: Quantitative analysis using polar cap magnetic records, J. Geophys. Res., 81, 2289–2303.


T. Higuchi and G. Ueno, The Institute of Statistical Mathematics, Research Organization of Information and Systems, 4-6-7 Minami-Azabu, Minato-ku, Tokyo 106-8569, Japan. (gen@ism.ac.jp)

P. T. Newell and S. Ohtani, Applied Physics Laboratory, The Johns Hopkins University, 11100 Johns Hopkins Road, Laurel, MD 20723-6099, USA.