Flow Vortex-Associated Downward Field-Aligned Current Retreating in the Near-Earth Plasma Sheet

Huanzhi Yuan1,2*, Hui Zhang2,3,4,5*, Jianyong Lu1*, Changbo Zhu6, and Ming Wang1*

1Institute of Space Weather, College of Math & Statistics, Nanjing University of Information Science & Technology, Nanjing, China, 2Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, 3Innovation Academy of Earth Science, Chinese Academy of Sciences, Beijing, China, 4Beijing National Observatory of Space Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, 6College of Earth Sciences, University of Chinese Academy of Sciences, Beijing, China, National Space Science Center, Chinese Academy of Sciences, Beijing, China

Abstract The formation of field-aligned currents (FACs) of a substorm current wedge is a key element of substorms. Conjunctive observations of a downward FAC during a substorm on 20 December 2007 were made in space by THEMIS satellites and on the ground by geomagnetic field and aurora stations, which provides a unique opportunity to investigate the generation of downward FAC. On the ground, AL index decreased significantly at 04:17:00 UT, denoting the onset of the substorm. The geomagnetic perturbations observed at the postmidnight station KUUJ show that the FAC of the substorm current wedge flowed into the ionosphere. Meanwhile, in space, two THEMIS satellites, THC and THB, the magnetic footprints of which were close to the postmidnight station KUUJ, were located in the near-Earth magnetotail and recorded the outside-in signatures of the plasma sheet thinning first and then the large-scale inside-out propagating plasma flow vortex inferred from the rotation of the flow vector. The magnitude of the FAC was estimated by using the bipolar $B_T$ perturbations associated with the flow vortex. It is found that this FAC was so strong that it cannot be produced by the time derivative of the vorticity and that the pressure gradient may act in this event. The upward flowing low-energy electrons are the possible carriers for this FAC.

1. Introduction

The formation of a substorm current wedge (SCW) characterizes a substorm. The SCW is a current system that consists of three parts: the cross-tail currents, the upward/downward field-aligned currents (FACs), and the westward electrojets in the ionosphere (McPherron et al., 1973). When a substorm occurs, the dawn-to-dusk cross-tail current in the near-Earth magnetotail is partially disrupted and turns to flow along field lines into the ionosphere, forming the downward FAC in the dawnside magnetosphere. This downward FAC diverts in the postmidnight ionosphere and flows to the premidnight, forming the westward electrojets. Finally, this current converges in the premidnight ionosphere and returns to the magnetotail along field lines and completes the closed circle of the SCW. Certainly, in the real case, the SCW and the FAC system could be very complicated (Birn & Hesse, 2014; Kepko et al., 2014; Sergeev et al., 2014).

Where and how the cross-tail current is disrupted and converted to be FAC is the key problem of substorm studies. There are two popular models, the near-Earth current disruption (NECD) model and the near-Earth neutral line (NENL) model, to interpret the formation of the SCW. The NECD model proposes that the current instabilities in the near-Earth tail ($\sim$8–10 RE) directly lead to the current disruption and trigger the substorm expansion phase, and the highly disturbed magnetic field and plasma are expected to be observed in this region (Baker et al., 1996; Lui, 1996; Ohtani et al., 1992). In the NENL model, however, the energy accumulated during substorm growth phase is thought to be released in the midtail ($\sim$20–25 RE) through magnetic reconnection (MR; Baumjohann, 2002; Nagai et al., 1998). The bursty bulk flows (BBFs) originating from the midtail transport energy and magnetic flux from the midtail to the near-Earth region (Angelopoulos et al., 1992; Angelopoulos et al., 1994). When encountering the boundary of the dipole-like field dominant and the tail-like field dominant regions in the near-Earth tail (typically $\sim$10 RE), the BBFs are braked and diverted (Baumjohann, 2002), the plasma pressure builds up (Birn et al., 1999), and the...
associated magnetic flux piles up (Zhang et al., 2007), which ultimately lead to a more dipolar tail configuration and, hence, is referred to as dipolarization.

The deceleration and diversion of the plasma flow and the buildup of the plasma pressure in the near-Earth region may all contribute to the formation of FACs, and debates are always present on what mechanism dominates. In ideal magnetohydrodynamic (MHD) regime, a clockwise flow vortex forms on the dawnside limited within the equatorial region because of the diversion and rebound of BBFs, and the decrease of the vorticity from the equatorial plane toward the ionosphere drives an FAC flowing downward to the ionosphere according to the Faraday's Law (Birn et al., 2004; Keiling et al., 2009; Paschmann et al., 2003). According to the force balance and current conservation in the MHD regime, an FAC can be theoretically decomposed into components arising from two sources, the flow inertial, that is, the time derivative of flow vorticity, and the pressure gradient (Hasegawa & Sato, 1979). Hasegawa and Sato (1979) scaled the two FAC components and theoretically inferred that the time derivative of the plasma vorticity dominates the FAC in a typical substorm, although, in their scenario, the vorticity is thought differently to derive from the flow shear between the diverted BBFs and the static inner magnetospheric plasma and the flow vortex rotates counterclockwise if seen from above the equator in the dawnside magnetotail. Because a large-scale flow vortex is hard to be identified for sure in the observations from two or even more satellites, in the literature, only a few flow vortex events have been reported (Keika et al., 2009; Keiling et al., 2009; Panov et al., 2010). The global MHD simulations show that, however, the inertial current is actually considerably small and should be ignored and that the pressure gradient term may dominate the FAC (Birn et al., 1999). In the near-Earth magnetotail, the distribution of plasma pressure in the central plasma sheet may exhibit different patterns: the pressure may dip near the midnight meridian forming a diverging pressure gradient pattern (Liu et al., 2013), or the pressure peaks near the midnight forming a converging pressure gradient pattern (Xing et al., 2011). Data from multiple satellites, that is, at least four satellites, are required to precisely estimate the pressure gradient (Paschmann & Daly, 2000). In practice, however, this requirement is usually not satisfied. Data from only two or three satellites may lead to significant errors in the estimation of the pressure gradients and the associated FACs.

The electric current carriers, including their particle types, the energies, and the fluxes, may provide more information to uncover the generation mechanism of FACs. It is observed that the upward going ions (Gombosi & Nagy, 1989) and the precipitating electrons (Korth et al., 2014) can both produce the upward FACs on the duskside of the near-Earth tail. The precipitating electrons can be further accelerated by the field-aligned potential drops in inverted-V structures or within kinetic Alfvén waves (Newell et al., 2009), and they finally collide with the neutral atmosphere and produce aurora in the ionosphere. The sudden aurora brightening in the premidnight sector is one of the main features of the substorm onset (Akasofu, 1964). On the dawnside, the upward going electrons from the ionosphere are thought to be the main carrier for the downward FACs. These upward moving electrons are frequently observed associated with the downward FAC in the region above aurora and their typical energies range from ~20 to ~200 eV, a little bit higher than their initial energies in the ionosphere (Burch et al., 1983). These electrons can be further accelerated by the potential drop along field lines (Cran-McGreehin & Wright, 2005) and when arriving at high altitudes their energies are typically much higher than their initial energies. The plasma and magnetic field observations from ISEE spacecraft shown by Frank et al. (1981) indicate that the electrons with energies less than 1 keV are the main carrier of the downward FACs. Cheng et al. (2016) reported that the high-speed electrons with energies above 500 eV are the main carriers but the contribution from ions cannot be ignored.

When a substorm occurs and FACs flow into the ionosphere, the associated magnetic perturbations can be measured on the ground. In the ionosphere, the FACs divert to be horizontal and the westward electrojets form (McPherron et al., 1973). The perturbations in the east component (D) of the geomagnetic field are typically attributed to the FACs, and the polarities of these perturbations depend on the directions of the FACs and the relative positions of the geomagnetic stations to these currents (Chu et al., 2014). The perturbations in the north component (H) are typically negative during substorms, and they are thought to be produced by the westward electrojets (Davis & Sugliura, 1966).

In this paper, a substorm event observed conjunctively in space and on the ground is reported. The substorm onset is at 04:17:00 UT on 20 December 2007, which can be clearly identified by AL index. Meanwhile, two satellites (THB and THC) of the Time History of Events and Macroscale Interactions (THEMIS) mission are
orbiting in the near-Earth tail, and their magnetic footprints are close to the postmidnight station: KUUJ (the geomagnetic longitude and latitude are 13.5° and 68.2°, respectively). The downward FAC in this event is found to form associated with a tailward retreating plasma flow vortex embedded within the near-Earth plasma sheet. In the next section, the instrumentation is briefly introduced. In section 3, the satellite and ground observations are presented. In section 4, the results are discussed and summarized.

2. Instrumentation

Data from the THEMIS mission (Angelopoulos, 2008) are used in this study. The magnetic field and plasma observations in space are provided by the Fluxgate Magnetometer (FGM; Auster et al., 2008) and the ElectroStatic Analyzer (ESA) plasma instrument onboard two THEMIS satellites, THC and THB (McFadden et al., 2008). All these data are used at a time resolution of 3 s. On the ground, the aurora data are provided by ASI of two THEMIS stations, KUUJ and SNKQ (the geomagnetic longitude and latitude are 385.2° and 66.3°, respectively), and the images are given at a time resolution of 3 s with pixels of 256x256 (Mende et al., 2008). The ground magnetic perturbations are recorded by the magnetometers at these two stations (Harris et al., 2008). The magnetic footprints of the observing satellites estimated by using the T01 magnetic field model (Tsyganenko, 2002a, 2002b) are close to these two stations. The solar wind and interplanetary magnetic field (IMF) conditions for the T01 model are the OMNI data with a time resolution of 1 min from the website of NASA’s Space Physics Data Facility: cdaweb.gsfc.nasa.gov, and the geomagnetic indices in the T01 model are obtained from the website of the World Data Center for Geomagnetism, Kyoto: http://wdc.kugi.kyoto-u.ac.jp.

3. Observations

The solar wind conditions and the geomagnetic perturbations during the substorm event on 20 December 2007 are shown in Figure 1. The IMF \( B_Z \) remains southward since 03:12:00 UT until it starts turning northward at 03:48:00 UT (Figure 1a, the red curve). AL index (Figure 1b, the blue curve) is observed to briefly decrease twice at 03:48:00 UT and at 04:05:00 UT (the first and second vertical lines) accompanied by two sudden aurora brightening observed at the premidnight station SNKQ (Figure 1c). These two perturbations can be identified as two sequential “pseudo-breakups” in the growth phase of this substorm. The AL index decreases significantly at 04:17:00 UT (the third vertical line). At the same time, in the northern most edge of the field of view of the SNKQ station, a new aurora arc forms and then it expands poleward out of the field of view of the station. The strongest geomagnetic perturbations at 04:17 UT indicate that a substorm onset occurs. Corresponding to the two pseudo-breakups and the major onset, the \( H \) components of the geomagnetic field recorded at these two stations all exhibit negative perturbations (Figure 1e), which suggests that the westward aurora electrojets form over these two stations. The perturbations of the \( D \) components at these two stations, however, show different characteristics. At the first pseudo-breakup, the \( D \) perturbation is negative at the postmidnight station KUUJ while positive at the premidnight station SNKQ, which indicates that a downward FAC and an upward FAC form to the north of KUUJ and SNKQ, respectively. For the second pseudo-breakup and the major onset, the \( D \) perturbations are both negative at the two stations indicating that a downward FAC is located to the north of these two stations.

Figure 2 shows the positions of the geomagnetic stations and the observing satellites (THB and THC), and the geometry of the magnetosphere. The magnetic field lines are depicted on the basis of the T01 magnetic field model (Tsyganenko, 2002a, 2002b), and the parameter input into the T01 model are obtained from the OMNI database. Two THEMIS satellites (THB and THC) are located at \([-13.3, -4.4, -4.9 \) \( R_E \) and at \([-11.5, -4.9, -4.3 \) \( R_E \) in the geocentric solar magnetospheric (GSM) coordinate system, on the downslope of the southern hemisphere of the magnetotail as marked by the red and black dots in Figure 2b. In this event, the dipole tilt angle of the Earth is \(-33°\), very close to its minimum value \(-34°\), and the central plasma sheet shifts southward significantly away from the \( Z=0 \) plane as seen in Figure 2b. That is why the observing satellites, THB and THC, are still very close to the central plasma sheet although they are far away from the \( Z=0 \) plane \((-4.5 \) \( R_E \)). The magnetic footprints of THB and THC in the ionosphere estimated by T01 model are marked by the red and black dots in Figure 2a. It is seen that these two footprints are located to the north and east of the postmidnight station KUUJ, where the downward FAC flows into the ionosphere as indicated by the geomagnetic data from KUUJ.
The first observational signature in space associated with this substorm event is the plasma sheet thinning. From ~03:30:00 UT, the magnetic field at THB is basically less than 5 nT and the plasma density is ~0.3 cm\(^{-3}\) as shown in Figures 3a1 and 3b1, indicating that THB is located in the central plasma sheet. The field magnitude, especially that of the \(B_X\) component, begins to increase, and the density begins to drop at ~03:50:00 UT, much earlier than the substorm onset. Both the enhancement in the field magnitude and the drop of the plasma density suggest that the plasma sheet is thinning and the observing satellite, THB, relatively leaves the central plasma sheet region due to this plasma sheet thinning. The plasma sheet thinning lasts for long at THB even after the substorm onset at 04:17:00 UT, and up to ~04:20:00 UT, the field magnitude becomes as large as 30 nT and the plasma density is ~0.1 cm\(^{-3}\). Seventeen minutes later at 04:07:00 UT, the same plasma sheet thinning signatures are detected by THC. This 17-min delay indicates that the thinning...
process proceeds earthward and/or flankward and the source region may be located tailward of these two observing satellites.

After THC detects the plasma sheet thinning, a dipolarization process initiates in the region earthward of THC and propagates tailward via THC and THB sequentially. At 04:25:00 UT, the magnitude of $B_Z$ component suddenly increases and that of the $B_X$ component suddenly drops at THC as shown in Figure 3a2, and the geomagnetic field changes to be more dipolar, that is, dipolarization. The same changes in $B_Z$ and $B_X$ occur at THB, the more tailward satellite, but 8 min later at 04:33:00 UT (Figure 3a1), which denotes that to the contrary of the plasma sheet thinning, the dipolarization propagates tailward.

Right at the front of the dipolarization, that is, the transition boundary between the dipole-like and the tail-like magnetic fields, a plasma flow vortex is observed to retreat tailward together with the dipolarization and pass by THC and THB sequentially. The plasma velocity at the inner satellite, THC, exhibits bipolar
variations in the components of \( V_X \) and \( V_Y \) in the GSM coordinate system as shown by the red and green curves between 04:18:00 UT and 04:30:00 UT in Figure 3c2. \( V_X \) changes its sign from negative to positive and \( V_Y \) from positive to negative at ~04:25:00 UT. The bipolar variations in the components of plasma velocity may indicate the occurrence of a flow vortex, although the observing features of the flow vortex may strongly depend on how the satellite traverses the vortex. As aforementioned, in this event, the plasma sheet is twisted significantly southward due to the large dipole tilt angle as shown in Figure 2b,
and it is thus necessary to examine and confirm the flow vortex structure in a local current sheet (CS) coordinate system (LMN). In this local CS coordinate system, the \( \vec{N} \) axis points northward along the normal of the local CS, the \( \vec{M} \) axis is determined by the \( \vec{M} = \langle \vec{B} \rangle \times \vec{N} / |\langle \vec{B} \rangle \times \vec{N}| \), where \( \langle \vec{B} \rangle \) is the direction of the local magnetic field, and \( \vec{L} \) completes the right-hand orthogonal coordinate system through \( \vec{L} = \vec{M} \times \vec{N} \). The minimum variable analysis (MVA) method (Sonnerup & Cahill, 1967) is adopted to determine the normal of the local CS, \( \vec{N} \). By using the data between the two vertical dashed lines (03:45:00 UT–03:55:00 UT) in the Figure 3a1, the MVA analysis gives \( \vec{N} = (-0.19, 0.35, 0.92) \) in GSM with the ratios among the three eigenvalues of \( \lambda_1 / \lambda_2 = 13.9 \) and \( \lambda_2 / \lambda_3 = 15.3 \). The direction of the local magnetic field is represented by the average field direction between 04:20:00 UT and 04:33:00 UT at THC, and thus, \( \langle \vec{B} \rangle \) is determined to be \((-0.91, 0.13, 0.39)\), and so \( \vec{M} = (-0.01, 0.93, -0.36) \) and \( \vec{L} = (0.98, 0.08, 0.18) \) in GSM. In this local CS coordinate system, the bipolar variations appear for all the three velocity components, and \( V_L \) changes its polarity from negative to positive, \( V_M \) from positive to negative, and \( V_N \) from positive to negative at 04:25:00 UT as shown in Figure 3e2. The bipolar variations in the three components suggest that the direction of the flow vorticity may not be purely along but oblique to the normal of the plasma sheet. Figure 4a zooms in the observed velocity at THC in the LMN coordinate system within the period from 04:20:00 UT to 04:30:00 UT, and Figure 4b shows the corresponding hodogram for the LM components of the plasma velocity during this period. It is seen that the velocity vector rotates clockwise. At THB, the plasma velocities observed around the dipolarization are much more complicated but do exhibit bipolar variations, and before the dipolarization (04:33:00 UT), \( V_L \) is basically negative and \( V_M \) and \( V_N \) are positive, while after the dipolarization, both \( V_L \) and \( V_M \) change their signs. The time delay of the flow vortex at THC and THB is about 8 min, the same as the time delay of the dipolarization, which indicates that the vortex is moving tailward accompanying the retreating dipolarization. The variation of \( V_M \) from positive to negative and the tailward motion of this vortex indicate that the plasma vortex rotates clockwise if looking down from the north hemisphere. The separation between the two satellites is 1.8 RE, and the 8-min time delay of the arrival of the flow vortex gives the tailward moving velocity of the structure at about 23.9 km/s. On the basis of this velocity, the scale of the flow vortex can be estimated to be 2.0 RE along the moving direction since it takes THC 9 min (04:20:00 UT–04:29:00 UT) to traverse the whole structure.

The magnetic fields are observed, both at THC and THB, to change significantly within the clockwise rotating flow vortex. In the local CS coordinate system, the \( B_M \) component is seen to change its polarity from positive to negative at THC at 04:26:00 UT (Figure 3d2), and the same variation occurs at THB 8 min later at 04:34:00 UT (Figure 3d3). These bipolar magnetic perturbations can be understood if a tailward retreating downward FAC system traverses the observing satellites. Although the \( B_M \) components change their signs, the magnitudes of \( B_M \) remain basically the same before and after the dipolarization, respectively.

The energy spectra and the pitch angle distributions of the electrons in this event are particularly examined to investigate the possible carriers for the FACs. The omnidirectional electron differential energy flux at THC is shown in Figure 3f3, and it is clearly seen that the energy flux of the thermal electrons (~keV) drops when THC leaves from the central plasma sheet during the plasma sheet thinning. The black curve on the bottom of Figure 3f1 is the potential of the satellite, which is about 14 eV. The dense and cold electrons are observed below the satellite potential curve, and these electrons are typically thought to be the contamination of the photoelectrons. After the plasma sheet thinning and around the dipolarization, the satellite potential increases from ~14 to ~40 eV and bumps at 04:25:00 UT because of the lower plasma density.
Escoubet et al., 1997), and correspondingly, the energies of the dense and cold photoelectrons increase up to ~40 eV as seen on the bottom of Figure 3f2. In Figure 3g2, the pitch angles of these low-energy (<40 eV) photoelectrons are particularly examined. It is found that from 04:17:00 UT to 04:26:00 UT, the low-energy electrons are moving along field lines and their pitch angles are mainly less than 90°.

4. Discussion and Summary

In the literature of substorm studies, either for the NENL model or for the NECD model, there are two regions in the magnetotail, which are critical to the initiation and the development of a substorm (Baumjohann, 2002; Lui, 1996). One is located in the midtail region at ~20–25 R_E, where the NENLs or MR prefer to occur and a huge amount of energy is released (Nagai et al., 1998). The other key region is the inner tail region at ~10 RE, where the high-speed flows originating from the midtail reconnection site decelerate, stop, or divert; the magnetic flux piles up; the magnetic field changes its configuration to be more dipolar; the cross-tail currents are disrupted, and the FACs finally form (Baumjohann, 2002).

In this substorm event, the two observing satellites, THB and THC, are located in the middle of the two aforementioned key regions. In this event, the substorm onset is at 04:17:00 UT, which can be clearly identified by the most significant decrease in the AL index (Figure 1b). Observations in space show that the
plasma sheet thinning may initially take place tailward of THB and THC, probably far downstream in the midtail, and it then gradually develops into the near-Earth region to THB and THC sequentially. The plasma sheet thinning signatures are detected at THB to begin at 03:50:00 UT, which is much earlier than the substorm onset and possibly during the growth phase. Seventeen minutes later, this plasma sheet thinning seems to proceed earthward to THC, which is closer to the Earth, and a significant thinning occurs at THC even after the major onset at 04:17 UT. During this event, both THB and THC are located in the near-Earth tail (X≈−11 RE), which is most likely on the earthward side of the midtail MR, but outside the central portion (Y≈−4 RE). The plasma sheet thinning after the major onset in the near-Earth tail but outside the central portion thus seems consistent with the scenario as proposed by Reeves et al. (1992) and Reeves et al. (1993). The plasma sheet thinning is one of the characteristic midtail features of the growth phase of a substorm, during which a huge amount of magnetic energy is stored in the tail lobe and the electric current in the central plasma sheet enhances. The plasma sheet thinning and the enhanced current density make a favorite condition for the breakup of MR in the midtail (McPherron et al., 1973). In this event, however, THB and THC miss the MR signature, that is, the high-speed earthward flows, due to their positions significantly bias to the dawnside of the plasma sheet. After the outside-in developing plasma sheet thinning, an inside-out propagating process, the dipolarization, passes by the observing satellites. The dipolarization is the global magnetic field response to the formation of SCW. Equivalently, the dipolarization process can be interpreted as a result of the magnetic flux pileup during the high-speed flow braking and/or diverting when they encounter the boundary between the dipolar and the tail-like fields. In this event, although neither THB nor THC are located within the high-speed flow channel, the flow vortices, inferred from the rotation of the local flow vector right at the transition region (the dipolarization front), are detected on the dawnside plasma sheet. The dipolarization associated with the flow vortex occurs first at THC, the inner observing satellite, and then at THB. The magnetic flux pileup may lead to the tailward retreating of the dipolarization front (Zhang et al., 2007).

The polarity changes in the \( B_M \) component in the CS coordinate system indicate the presence of FACs associated with the dipolarization front and the plasma flow vortex. Although the vorticity \( \Omega \) of a vortex cannot be measured from a single satellite, it can be roughly estimated to be \( 0.05 \) s\(^{-1}\) in this event by using the rotation of the local flow vector at THC through \( \Omega = \Delta V_M/S - \Delta V_L/S \), where \( \Delta V_M \) and \( \Delta V_L \) are the differences in \( V_M \) and \( V_L \) at the strongest flow regions on the opposite sides of the flow vortex (at \( \sim04:23:00 \) UT and \( \sim04:27:00 \) UT, respectively) and they are estimated to be \( 400 \) and \( -300 \) km/s, and \( S \) is the scale of the vortex, which is \( 2.0 \) RE since it takes the observing satellite THC 9 min to traverse through the vortex structure at a velocity of \( 23.9 \) km/s. The structure of the flow vortex has changed when it arrives at THB and the flow observations seem very different with that at THC, the vorticity \( \Omega \), however, is hard to be obtained because the plasma flow highly fluctuates during the crossing of THB. In this condition, the variation rate of the vorticity cannot be well estimated, but it could be \( 1 \times 10^4 \) s\(^{-2}\) if the vorticity at THB is as small as zero.

The magnitude of FAC can be estimated through the magnetic field observations. The current density can be written as the curlometer of magnetic field \( \mathbf{j} = \nabla \times \mathbf{B} / \mu_0 \) (here, \( \mu_0 \) is the magnetic permeability; Dunlop et al., 1988), which typically requires the magnetic field observations from four satellites. When the CS is one dimensional, observations from one satellite might be enough to estimate the current density if how the satellite traverses the CS is already known. In order to calculate the FAC in this event, a main magnetic field (MMF) coordinate system is adopted. In the MMF coordinate system, the \( \mathbf{\hat{Z}}_{\text{MMF}} \) axis is defined to point northward along the normal of the FAC sheet; the \( \mathbf{\hat{Y}}_{\text{MMF}} \) axis is determined by \( \mathbf{\hat{B}} \times \mathbf{\hat{Z}}_{\text{MMF}} / |\mathbf{\hat{B}} \times \mathbf{\hat{Z}}_{\text{MMF}}| \), where \( \mathbf{\hat{B}} \) is the average of the fields besides the dipolarization front at 04:20:00 UT and 04:33:00 UT in the LMN coordinate system; and \( \mathbf{\hat{X}}_{\text{MMF}} \) completes the right-hand orthogonal coordinate system through \( \mathbf{\hat{X}}_{\text{MMF}} = \mathbf{\hat{Y}}_{\text{MMF}} \times \mathbf{\hat{Z}}_{\text{MMF}} \), which is the direction of the main magnetic field. The normal of the FAC sheet is estimated to be \((0.67, 0.42, 0.59)\) in the LMN coordinate by using \( \mathbf{n} = \mathbf{\hat{B}}_1 \times \mathbf{\hat{B}}_2 / |\mathbf{\hat{B}}_1 \times \mathbf{\hat{B}}_2| \), where \( \mathbf{\hat{B}}_1 \) and \( \mathbf{\hat{B}}_2 \) are the magnetic fields at 04:25:56 UT and 04:29:08 UT (the vertical lines in Figure 5), respectively. \( \mathbf{\hat{B}} \) is determined to be \((−0.82, 0.0, 0.58)\), and so \( \mathbf{\hat{Y}}_{\text{MMF}} = (−0.13, 0.97, −0.19) \) and \( \mathbf{\hat{X}}_{\text{MMF}} = (0.55, −0.08, −0.83) \) in the LMN coordinate system. In this MMF coordinate system, the \( B_Y \) changes its polarity at the dipolarization front,
indicated that an FAC forms. Before the dipolarization (04:25:00 UT), $B_{Y,\text{MMF}}$ remains basically constant (about 10 nT). After the dipolarization $B_{Y,\text{MMF}}$ becomes negative and remains unchanged at $-3$ nT. The relatively constant values of $B_{Y,\text{MMF}}$ before and after the dipolarization show that a one-dimensional CS inclined to the plasma sheet may be a good representative for the FAC system in this event. The current density can thus be estimated by $j = \frac{\Delta B_{Y,\text{MMF}}}{\Delta Y_{\text{MMF}}}$, where $\Delta B_{Y,\text{MMF}}$ is the change of $B_{Y,\text{MMF}}$ between two neighbor measurements, $v$ is the velocity of the observing satellite traversing the FAC sheet along the normal direction, and $\Delta t$ is the time delay between two neighbor measurements. In practice, $v$ is estimated to be 18.6 km/s by taking the fact that the separation of THB and THC in the direction normal to the FAC direction, and $\Delta t$ is time resolved measurements, which is probably because of the flapping of the FAC sheet or the current filaments embedded within the FAC sheet. The total current density through the whole FAC sheet is calculated by conducting the spatial integral of the current density $j$ along the satellite path, which is about $-11.8$ mA/m as denoted by the red horizontal line in Figure 5d.

In this event, the separation of the two observing satellites (1.8 RE) is comparable to the scale of the flow vortex (2.0 RE), which may suggest that the thickness of the FAC sheet, which is embedded within the flow vortex, could be smaller than the satellite separation. In this situation the total current density may be estimated by using the simultaneous observations from THB and THC, $J_{\parallel} = \Delta B_{Y,\text{MMF}}/\mu_0$, where $\Delta B_{Y,\text{MMF}}$ is the difference of $B_{Y,\text{MMF}}$ of THC and THB. The calculated $J_{\parallel}$ is shown by the black curve in Figure 5d. It is seen that before the first vertical line, the $B_{Y,\text{MMF}}$ components at THB and THC are both positive and of the same magnitudes of $-10$ nT, which indicates that THB and THC are both located tailward of or beneath the downward FAC sheet. $B_{Y,\text{MMF}}$ at THC begins to decrease from about ~04:26:00 UT and becomes negative at ~04:29:00 UT, while at THB $B_{Y,\text{MMF}}$ remains positive and unchanged. The changes at THC indicate that THC gradually immerses into the FAC sheet, and during this time interval, the total current density $J_{\parallel}$ between THB and THC gradually decreases to $-12$ mA/m. After 04:29:00 UT but before 04:34:00 UT, $B_{Y,\text{MMF}}$ at THC remains negative and changes little and $B_{Y,\text{MMF}}$ at THB remains positive and unchanged. Within this time, THB is still located tailward of or beneath the downward FAC sheet, but THC is located earthward of or above the downward FAC (the whole FAC sheet is located thoroughly between THB and THC), and the total current density $J_{\parallel}$ reaches its minimum value of $-14$ mA/m, comparable with that estimated by using the single satellite data ($-11.8$ mA/m, as shown by the red horizontal line in Figure 5d) and also comparable with those calculated by Ohtani et al. (1988) in the other substorm events. From 04:33:30 UT $B_{Y,\text{MMF}}$ at THC begins to reduce, and after 04:36:00 UT $B_{Y,\text{MMF}}$ at THC reaches the level of that at THC. During this period, THB finally passes though the FAC and enters the region earthward of or above the FAC sheet, and the total current density $J_{\parallel}$ between THB and THC also gradually increases.

It should be noted that the current density is calculated by using the curlometer of the magnetic fields but not using the temporal as well as the spatial derivatives of the vorticity in the formulae of Hasegawa and Sato (1979) and Paschmann et al. (2003), because the vorticity cannot be evaluated as well as its variations in this substorm. In addition, only two satellites, THB and THC, are available in the concerned region, and the pressure gradient in this region cannot be well estimated through their observations. Therefore, it is difficult to distinguish the contributions to the build-up of FACs from the vorticity variations and the pressure gradient (Birn et al., 2004; Hasegawa & Sato, 1979; Keiling et al., 2009; Paschmann et al., 2003). The plasma flows observed by the two satellites are quite different at THB and THC, and the flows are well structured at THC but pretty fluctuate at THB. The durations of the vortex at THB and THC are also not the same, 9 min at THC and almost 20 min at THB. All these observations indicate that the vorticity of this vortex is evolving with time, which may contribute to the build-up of the FAC system. As mentioned earlier, the vorticity of the vortex at THC is estimated to be 0.05 s$^{-1}$. The flows at THB are very disturbed, and the variation in any component of these flows is not a well-structured bipolar variation. The vorticity of the flow vortex $\Omega$ at THB can be roughly estimated to be 0.02 s$^{-1}$ through $\Omega = \Delta V_M/S - \Delta V_I/S$, where $\Delta V_M$ and $\Delta V_I$ are estimated to be 300 and $-300$ km/s, and $S$ is estimated to be 4.5 RE since it takes the observing satellite THB 20 min (04:25:00 UT-04:45:00 UT) to traverse through the
vortex structure at a velocity of 23.9 km/s. Let us say, even if the flow vorticity at THB is as small as zero, the variation rate of the vorticity is just $1 \times 10^{-8} \text{s}^{-2}$ since it takes 8 min for the vortex to evolve from THC to THB, corresponding to an FAC density as weak as 0.012 nA/m$^2$ and a total current density of 0.16 mA/m according to Hasegawa and Sato (1979), which is 2 order less than the quantity obtained from the magnetic field curlometer calculation, ~12 mA/m. In this case, the contribution of the time derivative of the flow vorticity to the FAC can thus be ruled out, let alone the flow vortex in this event rotates clockwise on the dawnside magnetotail, opposite to the counter-clockwise direction proposed by Hasegawa and Sato (1979). The FAC in this event is thus not produced by the vortex but just accompanied by the vortex, and the pressure gradient term may dominate the FAC, although it is still hard to measure the pressure gradient by using the observations in this study.

The particle phase space distribution function can also be used to obtain the current density $j_{||} = \int ev_{||} f dv$, where $e$ is the unit electric charge, $v_{||}$ is the particle parallel velocity in the phase space, and $f$ is the particle phase distribution function. The calculation of $j_{||}$ shows that the current densities carried both by the higher energy electrons (> 40 eV; the blue curve in Figure 5c) and by the ions (the cyan curve in Figure 5c) are so small that they are impossible to contribute to the current density $j$, that is, that calculated by using the magnetic field data. This result may suggest that the low-energy electrons are probably not all photoelectron contamination and a portion of them may be the upward moving ionospheric electrons.

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Erratum

In the originally published version, several instances of text were typeset incorrectly. The errors have since been corrected, and this version may be considered the authoritative version of record.