

# The substorm current wedge and midnight sector partial ring current near substorm onset: A synthesis based on a magnetotail magnetic field geometry model

George J Sofko<sup>\*</sup>, Kathryn A McWilliams & Chad R Bryant

Institute of Space & Atmospheric Studies, University of Saskatchewan, Saskatoon S7N 5E2, Canada

Received 28 August 2012; accepted 23 January 2013

**Abstract** The Substorm Current Wedge (SCW) occurrence in the late growth and onset phases of substorms was proposed as the current system which disrupts cross-tail current by diverting it to the ionosphere. The closure current for the SCW originally was suggested to be the strong westward auroral electrojet (WEJ). However, the SCW-WEJ system has no viable generator current. Similarly, the asymmetric or Partial Ring Current (PRC) increases in strength during the growth phase, and is sometimes associated with an enhanced Region 2 field-aligned current (FAC) closing to the ionosphere, but specifics of that closure have been lacking. Here we present a unifying picture which includes the SCW post- and pre-midnight (AM and PM, respectively) currents and a generator current in the midnight portion of the PRC system, with these currents based upon a model of the nightside magnetotail magnetic geometry. That geometry consists of open north and south lobe regions surrounding a plasmashet with two types of closed field line regions—stretched lines in the central part of the plasmashet (SPS) and dipolar lines (DPS) between the low latitude boundary layer (LLBL) regions and the SPS. There is also an important plasmashet transition region (TPS) in which the dipolar field near the plasmopause gradually transforms to stretched lines near the earthward edge of the SPS, and in which the midnight part of the PRC flows. We propose that our proposed near-onset current system consists of a central current which becomes part of the midnight sector PRC and which is the generator, to which are linked two three-part current systems, one on the dawnside and one on the duskside. The three-part systems consist of up and down FACs closing as Pedersen currents in the ionosphere. These 3-part systems are not activated until near-onset is reached, because of a lack of ionospheric conductivity in the appropriate locations where the Pedersen current closure occurs. The initial downward FAC of the 3-part dawnside system and the final upward FAC of the 3-part duskside system correspond to the AM and PM current segments, respectively, of the originally proposed SCW.

**Keywords** magnetotail, magnetic field model, auroral substorm, substorm current wedge, partial ring current, substorm onset

**Citation:** Sofko G J, McWilliams K A, Bryant C R. The substorm current wedge and midnight sector partial ring current near substorm onset: A synthesis based on a magnetotail magnetic field geometry model. *Adv Polar Sci*, 2013, 24:32-41, doi: 10.3724/SP.J.1085.2013.00032

## 1 Introduction

The processes causing a magnetic substorm have been the source of debate for decades, particularly after McPherron et al.<sup>[1]</sup> proposed that substorm onset was accompanied by a current system called the Substorm Current Wedge (SCW) that resulted from “Current Disruption” of the nightside

westward cross-tail current system. This led to the question: “What causes the Current Disruption?” In this paper, we hypothesize that the entire substorm sequence of growth, onset, and recovery phases follows quite naturally from the magnetic geometry of the magnetotail, in particular from the growth of the stretched field region in the middle of the plasmashet. We propose that the magnetotail plasmashet region consists of three main portions, namely: (i) a central “stretched” magnetic field located roughly at  $Y$ -values  $|Y| \leq 10-12R_E$  that results from reconnection of the stretched lobe lines at the DTNL (distant tail neutral line), as first

\* Corresponding author (email: george.sofko@usask.ca)

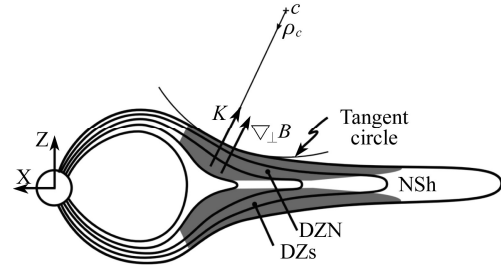
proposed by Dungey<sup>[2]</sup>, and that this region is made up of a central narrow neutral sheet bordered to the north and south by two “Disruption Zones” (DZs) that block the cross-tail current; (ii) two quasi-dipolar plasmasheet (DPS) regions that lie between the low-latitude boundary layers (LLBL) and the central SPS region; and (iii) a “transition plasmasheet region” (TPS) lying between the plasmasphere and the inner portion of the SPS. Our idea is that the life cycle of a substorm is principally the result of the life cycle of the SPS, and that the substorm onset is a direct result of dynamic processes within the earthward portion of the SPS when its growth has caused it to reach its nearest approach to the Earth, about  $8 R_E$  tailward near midnight. Here we will argue that the original idea of McPherron et al.<sup>[1]</sup> that the AM (post-midnight) downward SCW current and the PM (pre-midnight) upward SCW current are closed by the WEJ in the auroral zone is not consistent with the magnetotail field geometry. The AM and PM SCW currents result from the blockage of the cross-tail current by the SPS, which forces them to remain associated with the quasi-dipolar regions (DPS and TPS) rather than the SPS. A seven-part current system lying entirely on the quasi-dipolar field lines of the DPS and TPS regions is proposed. This system begins with the AM SCW downward current and ends with the PM SCW upward current, but contains five other portions whose central generator portion is in the TPS region where, near onset, it occupies a portion of the midnight-sector partial ring current (PRC). We shall, in a future paper, propose that the WEJ current is entirely associated with currents generated within the SPS, since it is the SPS that causes the principal substorm processes in the auroral zone. A combination of SuperDARN near-onset-phase convection pattern results and Polar UVI observations that supports our proposal is shown in Figure 4(D) of Bristow et al.<sup>[3]</sup>. In that figure, the near-onset strong auroral luminosity region, within which the SPS-associated WEJ would flow, is surrounded by two “detached” regions that we propose correspond to the DPS/TPS-associated SCW currents seen in the ionosphere on the AM and PM sides of the strong luminosity region.

## 2 The proposed magnetic geometry of the magnetotail

### 2.1 A noon-midnight meridian plane view of the magnetotail geometry

Figure 1 shows a cartoon of magnetotail field lines in the noon-midnight meridian plane. In the diagram, the field line shown nearest the Earth is dipolar and is meant to represent the outermost field line of the plasmasphere. The next line radially outward from the Earth is somewhat stretched. The region of transition from dipolar lines to somewhat stretched lines is denoted as the Transition Plasma Sheet (TPS). The region of closed central plasmasheet field lines beyond the TPS consists only of stretched field lines; we

define that region as the Stretched Plasma Sheet (SPS). Many authors have suggested that there is a region of stretched closed field lines in the midtail, as in Figure 8 of Haerendel<sup>[4]</sup>.



**Figure 1** A cartoon of the noon-midnight meridian plane view of the closed field line geometry in the tail, showing an inner dipole line to represent the DPS and four stretched lines to represent the SPS. The region between the dipole line and inner stretched line is the TPS. Also shown shaded are the SPS regions on the stretched that lie between the inflection points and that are characterized by outward curvature  $\bar{K}$  and outward gradient  $\nabla_{\perp} B$ . These are the DZs. The total current (curvature, gradient, and magnetization) in the DZs is eastward, which disrupts the westward cross-tail current that would have occurred there if the region had dipolar geometry.

When one examines the stretched field lines of the SPS shown in Figure 1, one of the features that is very prominent is the curvature vector  $\bar{K}$ . That curvature vector points roughly away from the neutral sheet (NSh), which is shown in white. That was confirmed by a minimum variance analysis of magnetometer measurements from the Cluster satellite mission<sup>[5]</sup>. As shown in their Figure 4, the radius of curvature in that SPS region is roughly  $5-10 R_E$ . One of the most important consequences of this curvature is that the curvature drift of the ions is eastward, while that of the electrons is westward.

Another important paper about magnetotail field geometry from satellites involved THEMIS observations by Saito et al.<sup>[6]</sup>. In that paper, the results revealed a deep minimum in the geomagnetic field magnitude at X distances beginning about  $-10 R_E$  and extending tailward for several  $R_E$ . The minimum occurred for up to about 20 min before substorm onset. An important consequence of this minimum is that the magnetic field gradient  $\nabla_{\perp} B$  points away from the minimum of  $B$ , such that, as shown in Figure 1, that gradient is roughly parallel to the curvature  $\bar{K}$ . This means that the gradient drift of the ions in the stretched field line region also is eastward. Therefore, the stretched geometry has a profound effect on particle drift, namely that the curvature-gradient (CG) drift of the ions and electrons is opposite to that which occurs in the dipolar field regions of the magnetotail. Not only is the CG ion drift eastward in the SPS region (the shaded regions in Figure 1), but so also is the net current, consisting of the curvature, gradient and magnetization current components.

Because the current is eastward in the shaded zones,

which lie between the inflection points on the stretched field lines, it is clear that any westward current trying to enter the shaded regions cannot do so. This important conclusion provides a ready explanation for one of the most striking early substorm observations by McPherron et al.<sup>[1]</sup>, namely that during the substorm onset, the westward cross-tail current is disrupted. Clearly, the geometry of Figure 1 supports this “Current Disruption”. It is for that reason that we call the shaded regions in Figure 1 the Disruption Zones (DZs), one (the DZN) being on the north side of the NSh and one (the DZS) on the southward side of the NSh. The DZs lie between the inflection points on the field lines. Each closed stretched field line has four inflection points, two on the north of the NSh, two on the south, and the roughly outward curvature  $K$  detected in the Cluster results<sup>[5]</sup> confirm the geometry. The Cluster results also confirmed the existence of the equatorial-centered neutral sheet (NSh) region and showed that, at the center of the NSh, the field lines have a strong earthward curvature  $K$  with a corresponding radius of curvature less than  $2 R_E$ .

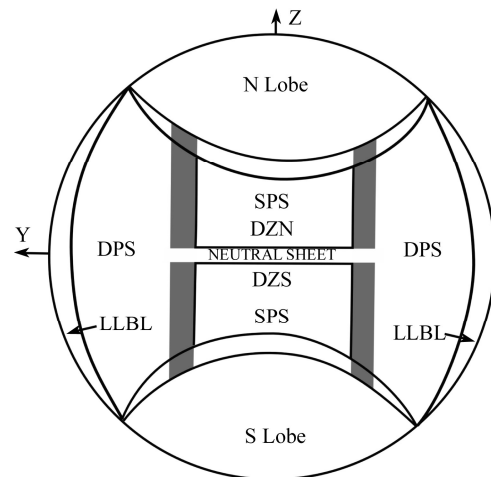
Shen et al.<sup>[5]</sup> interpreted the DZ regions as being part of the lobe, but we suggest here that their region of outward  $K$  is the part of the stretched closed field line region between inflection points. We agree with Shen et al.<sup>[5]</sup> that there is lobe field with outward  $K$ , but this would be located poleward of the DZs. In fact, the stretched closed field lines of the SPS are almost certainly the result of reconnection of the highly stretched lobe lines at the distant tail neutral line (DTNL), as suggested by Dungey<sup>[2]</sup> in 1961. It is no surprise that the curvature on the lobe lines becomes a part of the DZ lines after the reconnection, because the lobe lines are simply converted to stretched DZ closed lines at the time of the DTNL reconnection.

## 2.2 A YZ plane view of the Magnetotail at about $X = -15 R_E$

The next question concerns the shape of the magnetic field in the YZ plane. We show in Figure 2 a proposed cross-section of the tail in the YZ plane, nominally around  $15 R_E$  downtail. There the three parts of the SPS region in the midtail are shown, namely the central neutral sheet (NSh) portion, and the two DZ regions (DZN and DZS). McPherron et al.<sup>[1]</sup> estimated that the angular extent of the current disruption region was about 70 degrees, and that would place the current disruption region between  $Y = -8 R_E$  and  $Y = +8 R_E$  at a distance of about  $X = -12 R_E$ . On the dawn side and the dusk side of the SPS is a region of mainly dipolar field lines, called the Dipole Plasma Sheet (DPS).

One of the most important features of Figure 2 is the NSh itself. Early in the growth phase, the NSh is thick enough in the Z direction that much of the cross-tail current can flow westward through it. However, in the later growth phase when the NSh thins to about an ion gyroradius or less (Shen et al.<sup>[5]</sup> report a NSh half-thickness of  $0.12 R_E$ ), then most of the cross-tail current cannot flow through the NSh

and the cross-tail current is indeed “disrupted”. In the DPS regions, ions CG drift westward and electrons CG drift eastward. When the NSh is thick, say about  $4-5 R_E$ , the ions and electrons can travel through the NSh between the dawn and dusk regions. In this way, they form the normal cross-tail current. However, during the later growth phase, the NSh becomes so thin ( $\sim 0.5 R_E$ ) at X-distances  $\sim -9$  to  $-15 R_E$  that the cross-tail current is essentially “blocked” from flowing between dawn and dusk. The resulting flows and implications for the development of field-aligned currents (FACs) will be discussed in detail in Section 4.



**Figure 2** Typical cross-section of the magnetotail field at about  $X = -15 R_E$ . The NSh lies along the center of the tail, and the stretched SPS lines are located above and below the NSh. The DPS regions are found on the dawn and dusk flanks. The grey shaded regions represent the transition from stretched to dipolar magnetic field geometries.

Figure 2 also shows that, because there is westward cross-tail current outside of the SPS, the magnetic field in the region of westward current must be a quasi-dipolar part of the central plasmashet, which we name the DPS. There is DPS field on the dawnside between the dawn LLBL and the SPS, and also on the duskside between the dusk LLBL and the SPS. In their Finite Width Magnetotail Convection (FWMC) model, Spence and Kivelson<sup>[7]</sup> chose to use dipolar geometry for the whole tail between the LLBL regions, and they emphasized the key role played by the CG drifts of the particles. The stretched field line geometry of the SPS adds a totally new element to the picture because the ion CG drifts and the currents are eastward in the DZs, opposite to westward ion drifts and westward cross-tail current in the neighboring DPS regions on the dawn and dusk sides of the DZs.

The final magnetic regions in Figure 2 are the northern lobe (NL) and southern lobe (SL) bordering the SPS and DPS regions at higher latitudes where the open field lines from the polar cap extend down the tail. These lobe lines are essential to the formation of the SPS. The stretched lines of the SPS are created in nightside lobe reconnection

at the distant tail neutral line (DTNL), as first suggested by Dungey<sup>[2]</sup>. The subsequent growth of the SPS is caused by successive lobe-lobe reconnection events at the DTNL, and the earthward-directed reconnection jet for each such event leads to the filling of the SPS. We suggest here that the growth phase of the substorm is simply the creation of the SPS region, which takes about 60–90 min. It is only when that SPS region has filled inward so that the NSh reaches its most earthward location about 8–10  $R_E$  that substorm onset will occur. The filling time was confirmed by Zhou and Tsurutani<sup>[8]</sup> who showed that, even in the extreme case of an interplanetary shock, a substorm will not occur unless the tail has been filling for over an hour. Interplanetary shocks are very strong external triggers for substorms, but many substorms require no external trigger<sup>[9]</sup>. Once the SPS region has been filled, internal processes can lead to reconnection and to substorm onset. The near-Earth end of the SPS at about 8–10  $R_E$ , where the NSh thins substantially and where, at the NSh/DZ interface regions, reconnection can be driven by processes such as: (i) the Kelvin-Helmholtz instability due to the strong momentum shear<sup>[10-11]</sup> between the westward moving ions in the NSh and the eastward moving ions in the DZs; (ii) the sausage-mode current instability<sup>[12]</sup> caused by the strong current shear between the westward NSh current and the eastward DZ current.

We now summarize the important equations for the magnetotail geometry in Figures 1 and 2. In the DZs of the SPS, the ions drift eastward and the electrons westward, as given by the CG drift equation:

$$\mathbf{v}_{CG} = \frac{2W_{\parallel}}{qB} \hat{\mathbf{s}} \times \mathbf{K} + \frac{W_{\perp}}{qB} \hat{\mathbf{s}} \times \frac{\nabla_{\perp} B}{B}, \quad (1)$$

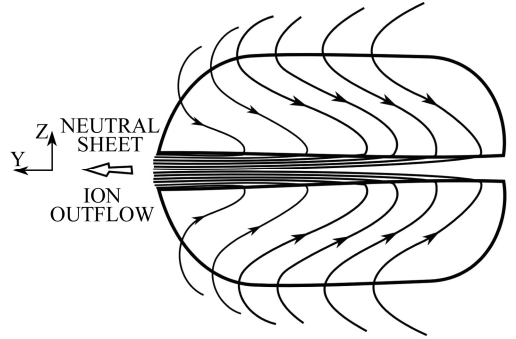
where  $\mathbf{v}_{CG}$  is the curvature-gradient drift,  $W_{\parallel}$  and  $W_{\perp}$  are the parallel and perpendicular energy,  $B$  is the magnetic field strength,  $\hat{\mathbf{s}}$  is the magnetic field unit vector, and  $q$  is the unit proton or electron charge. If the sum of the curvature, gradient and the magnetization currents of the ions and electrons is evaluated (e.g., Parks<sup>[13]</sup>), the current in the DZs is also eastward, as given below, first in terms of the total parallel and perpendicular pressures  $p$  of the ions and electrons (of concentration  $n$ ) and secondly in terms of the energies  $W$ .

$$\begin{aligned} \mathbf{J} &= \frac{p_{\parallel} - p_{\perp}}{B} \hat{\mathbf{s}} \times \mathbf{K} + \frac{\hat{\mathbf{s}} \times \nabla p_{\perp}}{B} \\ &= \frac{n(2W_{\parallel} - W_{\perp})}{B} \hat{\mathbf{s}} \times \mathbf{K} + \frac{\hat{\mathbf{s}} \times \nabla(nW_{\perp})}{B} \end{aligned} \quad (2)$$

It is this eastward current in the DZs that is the most likely cause of the Current Disruption proposed by McPherron et al.<sup>[1]</sup>. The current disruption thus is a simple consequence of the stretched line geometry, not of any plasma instability.

Figure 3 is a cartoon of the ion drift in a magnetotail YZ-plane, and it is a cross-sectional view looking toward the Earth from the deep tail. The CG ion (electron) drifts are eastward (westward) in the DZN and the DZS. It should

be noted that, during the late growth phase in the near-Earth portion of the central NSh at tail distances of about 10–15  $R_E$ , the NSh ions are essentially unmagnetized because the thickness of the NSh is less than the ion gyro-diameter. As a result, the NSh ions have neither CG drift nor  $\mathbf{E} \times \mathbf{B}$  drift in the NSh. Instead, the NSh ions “free-stream” westward in the direction of the dawn-dusk electric field  $\mathbf{E}_{dd}$ . The electrons in the NSh, on the other hand, have a small gyro-radius and remain magnetized, so they have a strong eastward curvature drift because of the small radius (large curvature) of the field lines which cross the NSh in the +Z direction. This westward electron drift is therefore one of the main reasons for the westward current in the NSh region, as opposed to the eastward currents in the neighbouring DZs to the north and south of the NSh.



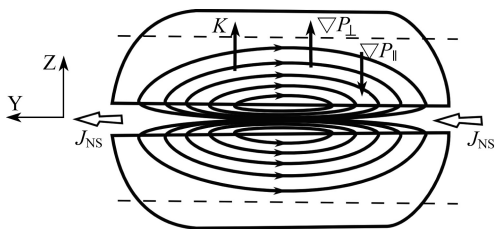
**Figure 3** Ion curvature and gradient flows in the DZs are eastward while the  $\mathbf{E} \times \mathbf{B}$  convective drift causes the motion toward the NSh from both the DZN (top) and the DZS (bottom) regions.

From Figure 3, it can be seen that, in the DZs, not only do the ions CG drift eastward, but they also  $\mathbf{E} \times \mathbf{B}$  drift toward the NSh as a result of  $\mathbf{E}_{dd}$ . They then turn westward in the dawn-to-dusk electric field within the NSh. There are also (not shown) cross-tail current ions that come into the NSh from the morning (–Y) DPS and then go out to the DPS on the dusk (+Y) side. The diagram purposely stresses the motions of the ions that remain in the SPS (i.e. the NSh and DZs), because these motions produce eastward current in the DZs. Of course, the magnetization current must be added to the curvature and gradient current to obtain (2).

### 3 The double-solenoidal current system

If there is stretched field line geometry in the SPS, there must be currents flowing that are consistent with that non-dipolar field geometry. That this self-consistency is the case is illustrated in Figure 4. Again, this is a cross-sectional view of the magnetotail, as viewed from the deep tail, similar to the region shown in Figure 3. The currents that support the tailward/sunward geomagnetic field lines in the SPS are two solenoidal current loops made up of the eastward currents in the DZs that close as westward currents in the NSh. The currents are joined together by the

ion-driven  $\vec{E}_{da} \times \vec{B}$  current from the DZ to the NSh on the east side of each DZ and by electron-driven  $\vec{E}_{ad} \times \vec{B}$  current from the NSh to the DZ on the west side of each DZ. Note that  $\vec{E} \times \vec{B}$  drift normally does not cause a current, but the eastward ion CG drift causes a tendency toward a surplus of ions on the east side of the DZ and, similarly, the westward electron CG drift causes a surplus of electrons on the west side. These surpluses are removed by the  $\vec{E}_{da} \times \vec{B}$  motions of the “surplus ions” on the east and of the “surplus electrons” on the west toward the NSh. In summary, the CG drift of the ions (electrons) drives them to the dawn (dusk) side of the DZ, where the  $\vec{E}_{ad} \times \vec{B}$  drift directs them from the DZs to the NSh, leading to the closure of the two current loops that are formed between the NSh and the DZs.



**Figure 4** A cartoon showing the double-solenoidal current system. This is a cross-section of the magnetotail, as viewed towards Earth from the deep tail. The top solenoid has +X vorticity and produces magnetic flux in the +X direction to enhance the stretching of the NH field lines along the +X direction. The bottom vortex has -X vorticity and produces magnetic flux in the -X direction to enhance the stretching of the SH field lines along the -X direction. This picture is the basis of a self-consistent model of the currents and the stretched field line geometry of the SPS. The extra flux from the double solenoidal system also exerts magnetic pressure on the NSh, leading to the thinning of the latter.

As shown in Figure 4, the resulting double-solenoidal NSh/DZ system is such that the solenoidal current on the northern side has +X vorticity and thus produces magnetic flux in the +X direction, thereby contributing to the stretching of the field in the +X direction, while the SH solenoidal current has -X vorticity that produces flux pointing in the -X-direction, leading to the stretching of the -X field on the south side of the NSh. But more than that, this extra magnetic flux near the DZ/NSh interface regions exerts extra magnetic pressure on the NSh, and is an important factor in the thinning of the NSh.

In the Cluster results by Shen et al.<sup>[5]</sup>, there is a region of large radius of curvature (a quasi-linear region) between the NSh and the DZ (which they called “lobe” but which we contend are closed SPS field lines). It is now clear from the double-solenoidal current why this large radius occurs. The linear flux along the axis of the two solenoidal currents is the cause, and thus the Cluster results can be looked at as a confirmation of the double-solenoidal system.

Note that there are pressure gradients as shown. The perpendicular pressure is low in the NSh, because measurements by both the Cluster and THEMIS missions show a

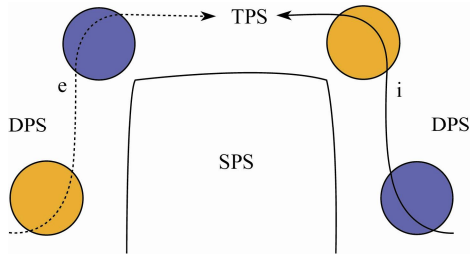
“deep minimum” in  $|\vec{B}|$  in the NSh. As a result, the first adiabatic invariant requires that the perpendicular energy  $W_{\perp}$  be small there. On the other hand, the second adiabatic invariant requires that, because the length of the stretched field lines becomes successively shorter in the earthward direction, the parallel momentum and the parallel pressure will increase toward the NSh, thereby leading to a corresponding gradient of the parallel pressure toward the NSh. Thus there are oppositely directed pressure gradients. The current in the DZs, particularly the inner part of the DZs, is thus eastward, and that is in keeping with both terms on the right side of the current equation (2).

#### 4 The A–H current system near substorm onset

The thinning of the NSh has a profound effect on the cross-tail current and the particle flow during the late growth and onset phases. When the NSh thins, the stretching of the SPS is enhanced, and the DZs increase in size. Figure 5 represents an XY slice through either the DZS or the DZN, below or above the NSh, respectively. In the midtail in the NSh region where the NSh is thin, most of the ions from the dawn side LLBL and the electrons from the duskside LLBL can no longer easily move through the NSh to go between the dawn and dusk DPS regions. They are effectively blocked by the SPS DZs, and as such must turn earthward in the  $\vec{E}_{da} \times \vec{B}$  direction, as shown by the lower left orange and lower right blue circles in Figure 5. The blockage of the ions (electrons) at the blue AM (orange PM) circles in Figure 5 re-directs their flows to the TPS region, where they contribute to the midnight sector partial ring current (PRC).

Finally, near onset, the ionospheric regions magnetically conjugate to the blue and orange circles acquire sufficient Pedersen conductivity to permit FACs to flow, downward from the AM blue circle, upward to the PM orange circle. As a result of the blockage of the westward CG ion drift in the DPS region on the dawnside, the ions must turn along the solid-line path through the blue circle on the bottom right of Figure 5. The streamlines then go to the TPS as shown. However, when the ionospheric conductivity is sufficient, the vorticity associated with the turning of the ions in the bottom right blue region (-Z vorticity) and of the electrons in the bottom left orange region (+Z vorticity) cause FACs downward to the ionosphere from the blue circle and upward from the ionosphere to the orange circle. This does not happen until some minutes before onset because the ionospheric conductivity, particularly on the morning side which has been in darkness for many hours, is simply too small. However, near onset, the magnetosphere-ionosphere feedback instability is activated, because an FAC begins to form, causing associated ionization, which in turn allows more current to flow, enhancing the conductivity, and so on. The flow vorticities then lead to the downward SCW FAC on the dawnside and the upward

SCW FAC from the duskside ionosphere.

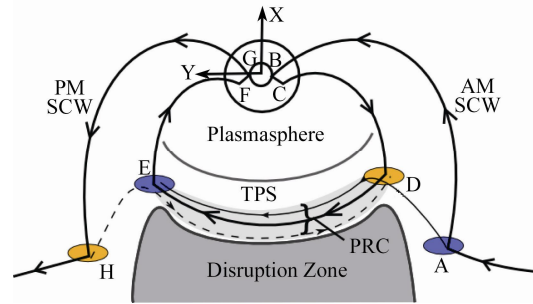


**Figure 5** A cartoon of the XY plane viewed from the +Z direction. The plane lies about an  $R_E$  above (or below) the equatorial plane of the NSH. The diagram illustrates that the SPS DZs block the entry into the SPS region of the dawnside ions, which turn with  $-Z$  vorticity at the blue circle, bottom right, and of the duskside electrons, which turn with  $+Z$  vorticity at the orange circle, bottom left. The ions (solid line) and electrons (dashed line) flow to the TPS where they can continue their original westward and eastward CG drifts, respectively, and contribute to the buildup of the midnight portion of the PRC. However, as the onset time is approached, the  $-Z$  vorticity of the ions at the blue AM circle causes the ions to flow as FAC, namely the AM SCW current, down to the ionosphere, where the conductivity has reached a high enough level to support the required ionosphere Pedersen closure current. Similarly, at near onset times, the  $+Z$  vorticity of the electrons at the orange PM circle allows them to flow as down to the ionosphere, leading to the upward FAC that is the PM SCW current.

Figure 6 illustrates the complete A–H current system that results from the development of the DZs in the SPS, which lead to the SCW FACs whose source vorticities are illustrated by the lower left orange and lower right blue circles in Figure 5. Figure 6 is a three-dimensional wedge cut of the magnetotail, looking at a cross-section above the NSH at Z-positions within the DZN. The magnetosphere-ionosphere (MI) coupling current system begins on the dawnside, again because the DZs in the SPS regions block the cross-tail current and cause it to be diverted to the ionosphere when the ionospheric conductivity is sufficient. That diversion begins at the blue circle at A in Figure 6, which matches the bottom right blue circle in Figure 5. Then there is downward FAC to the ionosphere from A to location B. Since the electric field in the dawnside ionosphere is equatorward near B (where the convective flow is sunward in the dawn cell of the two-cell convection pattern), the field aligned current AB will close as Pedersen current from the higher latitude location B to the lower latitude location C. At C, the current will become upward FAC to the TPS at location D, which is therefore a region of negative charge. The positive ions at D can then resume their dawn-to-dusk CG drift by flowing westward across the TPS region to region E, denoted by a blue circle.

Now let us consider the duskside electrons that resulted in upward current out of the ionosphere to the orange circle in the lower left-hand corner of Figure 5. This current

is shown near H (orange) in Figure 6. That FAC comes from the point G at higher latitude in the duskside ionosphere, where the electric field is poleward because G is in the sunward flow of the duskside cell of the two-cell convection pattern. The closure current in the ionosphere is thus the Pedersen current poleward from F to G. At F, that Pedersen current is fed by the downward FAC EF from the TPS region.



**Figure 6** The ABCDEFGH (A–H) system that includes: **a**, The outer currents of the originally proposed SCW (section AB of downward current on the AM side, and GH of upward current on the PM side); **b**, A part of the asymmetric ring current or PRC (section DE) in the TPS region between the inner edge of the SPS Disruption Zone and the Plasmapause. The thin line from A to D to E represents ion CG drift motion prior to the near-onset time. Near onset, the ions are diverted down from A to B because the ionospheric conductivity has increased enough that Pedersen closure current along BC becomes operative. The dashed line from H to E to D represents electron CG drift motion prior to onset. Near onset, the electrons are diverted down from H to G because Pedersen link FG has become activated by the enhanced ionospheric conductivity. Note that the A–H system lies entirely within the DPS/TPS quasi-dipolar magnetotail geometry, which does NOT include the westward electrojet (WEJ), because the latter is associated with the SPS stretched-field geometry. Hence the WEJ is not seen in the above picture.

We next turn our attention to the TPS region itself, which is located at the earthward limit of the NSH. In the TPS, the ions from the dawnside flow westward along DE while the electrons from the duskside flow eastward along ED. This of course results in a westward TPS current from D to E. This current is consistent with the asymmetric ring current (or PRC). It is enhanced near onset because of: (a) the strong blockage of the ions near A, which ultimately leads to the negatively charged flux tube along the upward FAC from C to D, at the end of the dawnside current system ABCD; and (b) the strong blockage of the electrons at H, which ultimately leads to the positively charged flux tube EF, at the beginning of the duskside current system EFGH. The result is that the center section DE of the A–H system lies in the midnight sector PRC, with current  $J_{D-E}$  flowing westward in a region where the associated electric field  $E_{E-D}$  goes eastward from the positive charge pool on the flux tubes at E to the negative charge pool on the flux tubes at D. Therefore, in that part of the PRC, the condition

$\int_{D-E} \mathbf{v} \cdot \mathbf{E}_{E-D} < 0$  holds, which shows that the PRC is the generator current for the entire circuit ABCDEFGH, or current system A–H for brevity. The A–H current system thus provides a natural answer to the question that has been an issue for the originally proposed SCW<sup>[1]</sup>. The closure for the SCW currents AB and GH is not through the westward electrojet, which is a dissipative current, but through the DE section of the midnight sector PRC, which is a generator current.

## 5 Discussion

Let us consider again the issue of the west-to-east electric field from E to D during the enhanced PRC flow near substorm onset in the TPS region. It is natural to ask what became of the “normal” dawn-to-dusk electric field in the outer TPS region where the PRC flows. One possible answer is that the curvature of the outer TPS, as seen in Figure 6, leads to the shielding of the curved outer TPS by the dawn and dusk “wings” of the inner SPS, thereby preventing the dawn-to-dusk field from freely accessing the outer TPS region. There is support for the eastward direction of the electric field from CRRES satellite observations and ground-based magnetometer data analyzed by Erickson et al.<sup>[14]</sup>. In that work, it was reported that there were oscillations of the electric field in the TPS region, but that the oscillation immediately preceding LEXO (local explosive onset) were always eastward. Thus the eastward oscillation just before onset was called a “trigger wave”. These eastward oscillations at CRRES lasted about 60–90 s. It is quite natural that there will be oscillations in the outer TPS and the inner SPS regions, because the FACs in the A–H system are carried by Alfvén waves, but the issue of the waves is beyond the scope of the present paper.

In the TPS region, the PRC has been strengthening during the growth phase. In the early growth phase, the blockage of the cross-tail current by the developing DZs in the SPS leads to the diversion of particles into the PRC region, as shown in cartoon form in Figure 5. During this time, it is likely that the diverted particles and the current flowing into the bottom blue and orange regions in Figure 5 would tend to be located in a broad (not circular but elongated along the tailward direction) portion of the DPS through which the cross-tail current flows. As the SPS and its DZ regions are growing during that time, there area for blockage of the cross-tail current becomes larger and more current is diverted earthward so that it can flow through the TPS from dawn to dusk. Therefore, the PRC in the TPS would be increasing through the growth phase, as observed in the detailed PRC study by Newell and Gjerloev<sup>[15]</sup>. Figure 6 shows the above scenario as a direct route from A to D for the ions and from H to E for the electrons. However, as near-onset conditions are reached, the ionospheric conductivity will increase, so an alternate route from A to the TPS region will become available, namely downward FAC AB followed by ionospheric Pedersen closure current BC followed by upward FAC CD. Since the parallel conductiv-

ity along the field-aligned portions AB and CD is very high, the ionospheric conductivity along BC is the key to the viability of this path ABCD. Is there any confirmation that an increased conductivity might be the case? The MSP results acquired in a 6–7 June 1989 substorm study by Kadokura et al.<sup>[16]</sup> at Asuka and Syowa stations, where combined meridian scanning photometer (MSP) and SuperDARN data were acquired, are shown in their Figure 13. Kadokura et al.<sup>[16]</sup> show that, about 15 min before onset, the FEM (fast equatorward moving) electron arc appears and, at the same time, the broad proton emission region in the ionospheric TPS changes significantly, in that the broad proton emission weakens and, most significantly, changes in breadth to a rather narrow emission at the equatorward edge of the previously-broad emission region. The FEM electron arc and the narrowed proton emission region could be an indication that the conductivity has “turned on” in two ionospheric regions, the auroral zone region where the FEM electron arc occurs and the subauroral region where the proton arc exists. If that happens, the observed shift of the proton emissions to lower latitude is in agreement with the development of path ABCD for the dawnside current, because the link BC is an equatorward Pedersen current that takes the current to lower latitudes so that, when it comes back to D as upward FAC AD, it would appear in the TPS at a lower latitude (nearer the Earth) than it previously did along direct route AD. These changes in ionospheric conductivity are consistent with the magnetospheric-ionospheric feedback instability, in that the downward field-aligned current AB (which is about to become the AM SCW current) or more likely the upward current CD can produce a small amount of conductivity along BC which permits a small current to flow, leading to more current and higher conductivity, and so on until the route ABCD becomes preferred as compared to the direct route AD.

Prior to the activation of the A–H current loop by the ionospheric conductivity increase, the dawnside ions go directly from the dawn DPS region A to D on the morning side of the TPS and the duskside electrons go directly from the dusk DPS region H to E on the duskside of the TPS. As mentioned above, that likely would lead to a shear in the westward drift of the ions in the TPS because the bulk of the TPS flow from these direct paths AD and HE would be preferentially in the outer TPS region. The resulting shear between higher speed flows in the outer TPS and lower speed flows in the inner TPS near the plasmopause would cause to a downward ( $-Z$ ) shear vorticity of the flow in the TPS. Such downward ( $-Z$ ) vorticity is associated with a downward FAC to the ionosphere. This is consistent with the observed proton emission in the subauroral region, which last for many minutes (up to an hour) preceding substorm onset. It is also important to note that, as shown by Figure 13 of Kadokura et al.<sup>[16]</sup>, the broad proton emissions at 486.1 nm are on the very equatorward edge of the electron emissions at 630.0 nm. Why is this? It is likely that, since the protons are more massive, their inertia prevents them from turning quickly into the TPS region as they reach

region D. They would then swing around into a more earthward part of the TPS than will the electrons coming from H to E. With smaller mass and lower inertia, the electrons would tend to make a sharper turn at E and thus would flow at higher latitudes in the TPS than the ions, and lead to an ionospheric subauroral signature at higher latitudes than the protons, as is clear in the Kadokura et al.<sup>[16]</sup> picture.

The proton “aurora” (which we are arguing is not in the auroral zone but rather in the ionospheric subauroral region) is one of the most prominent growth phase signatures. Our substorm model leads naturally to the conclusion that the ion and electron flows in the TPS result from the blockage by the DZs of the cross-tail current and its subsequent diversion into the TPS region. With that explanation, the resulting proton “aurora” region seen in the ionosphere becomes a very good indicator of the development of the DZs during the growth phase. The growing westward current in the TPS region is simply a part of the buildup of the PRC in the midnight sector. The latter is called the SMR-00 sector in the recent detailed study by Newell and Gjerloev<sup>[15]</sup> based on the SuperMAG results from some 98 magnetometer stations. There is considerable asymmetry in the PRC, with the SMR-18 sector having the highest values, but the SMR-00 sector also shows a depressed Dst value (in Figure 11, Newell and Gjerloev<sup>[15]</sup> show pre-onset values of about  $-88$  nT for SMR-18 and  $-70$  nT for SMR-00). During most of the early to middle growth phase, the ionospheric conductivity, particularly on the morning side where the ionosphere has been in darkness for many hours, is so low that the Pedersen closure current BC of the A–H system does not flow, and the entire A–H system does not occur. Only near onset, when the Pedersen conductivity has increased, does the A–H system spring into action.

However, as shown by Newell and Gjerloev<sup>[15]</sup>, there is a definite positive shift of  $10$ – $15$  nT in the SMR-00 Dst value starting at onset. This is also in agreement with our model of the SPS, because the inner edge of the SPS moves tailward, after reconnection begins at onset at the VNENL location at about  $8 R_E$ , to about  $20 R_E$  during the “expansion” or “dipolarization” period in the  $5$ – $10$  min interval after onset. The resulting large increase in width of about  $12 R_E$  of the quasi-dipolar field in the TPS leads to the weakening of the midnight sector PRC and hence to the  $+10$ – $15$  nT shift in the Dst value.

Of course, the enhanced westward PRC in the TPS region leads to downward ( $-Z$ ) magnetic field on the earthward side. This reduces the magnetic field on the earthward side of the TPS and in the region just inside the plasmopause. This weakening of the field at the plasmopause causes it to move toward the Earth during the growth phase. As the plasmopause moves earthward, the outer plasmaspheric particles are released from the plasmasphere to the inner TPS region, where they join the two-cell convection pattern. They are no longer driven by the plasmaspheric radially inward electric field that causes eastward drift. Instead, they become a part of the global two-cell magneto-

spheric convection pattern and the associated ionospheric convection pattern. The question of what happens to the dense low-energy plasmaspheric particle patches that are released to the TPS from the earthward-moving plasmasphere is very interesting because, although injected into the inner TPS near midnight, they must ultimately flow to the dayside where dayside reconnection occurs. It is possible that these patches of dense low-energy particles play an important role in the formation of the polar cap patches.

In the A–H system (Figure 6), it is clear that the first stage (AB) and the last stage (GH) have the exact senses of the FACs of the SCW that was originally proposed<sup>[1]</sup>. However, these two outer portions of the SCW were originally assumed to close as WEJ in the ionosphere. There has always been a major problem with WEJ closure for the SCW, because neither the SCW FACs nor the WEJ is a generator current. Although not shown here, the late growth phase convection pattern measured by the SuperDARN radars shows that the westward flowing WEJ is an ionospheric Pedersen current flowing parallel to the westward electric field in that region, and as such is dissipative. There is also a topological problem, again not discussed in detail here. Suffice it to say that the WEJ is the result of a current system generated in the NSh of the SPS. In other words, the WEJ flows across magnetic field lines which map to the SPS. On the other hand, the SCW FACs, which we argue originate and end in the DPS region, do not map to the SPS. Topologically, the entire A–H system lies on DPS/TPS quasi-dipolar field lines, whereas the WEJ lies on field lines which originate from the SPS.

The enhanced SMR-00 PRC which reaches its most negative Dst value just prior to onset not only produces a decrease of the magnetic field at the earthward edge of the TPS region but also creates an upward field near the SPS side of the TPS. This latter upward ( $+Z$ ) field contributes to the dipolarization of the TPS in its outer region at  $\sim 7$ – $8 R_E$ . It is interesting that there are many advocates of the idea that the substorm is caused directly by dipolarization. Although not discussed in detail here, suffice it to say that, if the onset-associated reconnection begins near the earthward edge of the NSh at a VNENL (Very Near Earth Neutral Line) location of  $8 R_E$ , then ongoing reconnection causes the VNENL to move tailward in about the  $5$ – $10$  min expansive phase to about  $20$ – $25 R_E$ , the latter being the more traditional location attributed to the NENL. Therefore, the dipole field on the earthward side of the reconnection site also moves tailward as a dipolarization front, which has been observed by satellite observations.

Just before onset, the enhanced upward ( $+Z$ ) field caused by the PRC at its tailward side in the  $7$ – $8 R_E$  region could also contribute to the onset of the dipolarization. Just tailward of that is the earthward edge of the SPS, where the conditions in the neighborhood of the thin NSh near the VNENL are ideal for reconnection, such as by the onset of the Kelvin-Helmholtz instability sausage mode in the ion momentum shear at the NSh/DZ interface or by the current shear there that can produce a sausage-mode current insta-



bility<sup>[12]</sup>. Of course, the reconnection directly leads to depolarization on the earthward side, adjacent to the +Z field of the PRC. It is possible that the two processes—dipolarization due to VNENL reconnection near the inner NSh/DZ interface regions and the tendency toward dipolarization in the outer PRC—are mutual contributors to the onset. The thin NSh and the wide DZs that block the cross-tail current and lead to the A–H system, thereby enhancing the PRC, occur at the same time and are directly related to the inner SPS magnetic geometry that leads to, across the NSh/DZ interfaces, the ion momentum shear and current shear which can cause the onset reconnection. These two causes of dipolarization might work in concert at substorm onset.

## 6 Summary

(1) A model of the magnetotail magnetic field geometry during the growth phase of a substorm has been presented. It consists of the dipolar plasmasphere, the transition region between dipolar and stretched field lines (TPS), the stretched field lines (SPS) of the central plasmasheet, the dipolar field lines (DPS) of the plasmasheet between the SPS edges and the LLBL dawn and dusk regions, and finally, at higher latitudes (or large  $|Z|$  values), the lobe lines that result from dayside reconnection and which are subsequently dragged back into the magnetotail by the solar wind. The SPS results from the lobe-lobe reconnection at the nightside DTNL, and the growth phase of the substorm is essentially the result of the growth of the SPS region, with the filling from the tail DTNL taking about 60–90 min. The SPS has a three-part structure, consisting of the central NSh region surrounded to the north and south by Disruption Zones (DZs). Because the DZs are between the inflection points on the stretched field lines, and because there is a minimum in  $B$  near the center of the NSh, the CG drifts of the ions and electrons result in eastward current in the DZs which is opposite to the cross-tail westward current that occurs in the DPS where the field geometry is quasi-dipolar. In the early stages of the SPS growth, the NSh itself is wide enough to allow the cross-tail current to flow from the dawnside to the duskside of the SPS. However, as the SPS grows, the particles in the DZs are driven into the NSh by convection caused by the dawn-to-dusk electric field into the NSh. The resulting increase in NSh particle pressure leads to a decrease in the magnetic pressure, consistent with the observed small magnetic field at the NSh minimum of  $B$ . This leads to an outward gradient of  $B$  from the NSh into the DZs, and that gradient then contributes to the eastward (westward) gradient drift of the ions (electrons) in the DZs.

(2) The DZs become very important in the late growth phase of the substorm, because the eastward current in the DZs closes with the westward current in the NSh, leading to a double-solenoidal current structure as seen in Figure 4. This double current produces extra magnetic flux in the  $-Z$  direction in the inner DZN and in the  $+Z$  direction in the inner DZS. This extra “linear” flux leads to increased

magnetic pressure that compresses the NSh and is likely an important factor leading to the NSh thinning.

(3) The resulting diversion of flow of dawnside ions and duskside electrons into the TPS leads to the enhancement of the midnight-sector PRC. However, due to the larger ion than electron inertia, the ions tend to cross the PRC TPS region a little closer to the earth than do the electrons. Near the plasmopause, the particle flows weaken in the TPS. Hence there is a shear vorticity between the faster flows a little more tailward and the weaker flows closer to the plasmopause. This leads to downward vorticity and to downward FAC, which produces the proton emissions seen in the ionospheric subauroral region for at least an hour before the substorm onset. Thus the broad (but weak, only about 50 Rayleighs) proton emission in the ionosphere is actually the signal that the SPS and its DZs are growing during the growth phase, thereby blocking the cross-tail current and diverting it to the region of the midnight-sector PRC. As such the proton emissions become a key signature of the magnetotail magnetic geometry reconfiguration that leads to substorm onset.

(4) The NSh thinning and the accompanying growth of the DZs have a profound effect on the cross-tail current, because the majority of that current is thereby blocked from direct passage from the dusk to the dawn side of the tail. Figure 5 shows that the blockage and the resulting curvature of the flow streamlines, which flow directly to the TPS region where they contribute to the intensification of the midnight-sector PRC. Figure 6 shows that these streamlines to the TPS go along direct paths AD and HE.

(5) When, near substorm onset, the ionospheric conductivity has reached a sufficiently high value, the A–H current system (Figure 6) is activated. Then the first and last sections of the A–H system, namely AB and GH sections, correspond to the originally-proposed<sup>[1]</sup> downward and upward field-aligned SCW currents. These currents close as Pedersen currents in the ionosphere, and then return as FACs to the region of the asymmetric or partial ring current. The resulting 7-part current A–H system illustrated in Figure 6 shows that the PRC is not only an important part of the A–H system, but also that it acts as the generator current for the A–H system. The dawn side of the midnight sector PRC is located where the upward current CD flows from the ionosphere to the TPS, and this is associated with negatively charged flux tubes. From the dusk side of the PRC at E, downward FAC EF flows from the TPS to the ionosphere and is associated with positively charged flux tubes. Thus there is a dusk-to-dawn electric field along the earthward portion of the midnight sector PRC current DE. Westward current DE flows opposite to the electric field and is therefore a generator current. This happens only near onset, and is consistent with the CRRES observations of a “trigger” eastward electric field reported by Erickson et al.<sup>[14]</sup>

(6) The A–H system provides a synthesis of the SCW and PRC systems. The enhanced midnight sector PRC so clearly described by Newell and Gjerloev<sup>[15]</sup> also provides a

possible close link with the magnetic reconnection at substorm onset. The dipolarization that results from the onset of reconnection near the earthward edge of the SPS is supported by the contribution to dipolarization from the westward midnight-sector PRC current in the outer TPS. Whether these two dipolarizations form a positive feedback system at onset is an interesting hypothesis that can be resolved only by more detailed satellite measurements near the TPS-SPS interface region.

(7) The proposed magnetospheric geometry of SPS, DPS and TPS systems is the basis for a comprehensive substorm model which provides a framework that is consistent with many of the key observed satellite and ground-based substorm observations in the roughly hour-long interval from the early growth phase to onset.

## References

- 1 McPherron R L, Russell C T, Aubry M P. Satellite studies of magnetospheric substorms on August 15, 1968: 9. Phenomenological model for substorms. *J Geophys Res*, 1973, 78(16): 3131-3149, doi:10.1029/JA078i016p03131.
- 2 Dungey J W. Interplanetary magnetic field and the auroral zones. *Phys Rev Lett*, 1961, 6(2): 47-48, doi:10.1103/PhysRevLett.6.47.
- 3 Bristow W A, Sofko G J, Stenbaek-Nielsen H C, et al. Detailed analysis of substorm observations using SuperDARN, UVI, ground-based magnetometers, and all-sky imagers. *J Geophys Res*, 2003, 108(A3): 1124, doi:10.1029/2002JA009242.
- 4 Haerendel G. Equatorward moving arcs and substorm onset. *J Geophys Res*, 2010, 115(A7), A07212, doi:10.1029/2009JA015117.
- 5 Shen C, Li X, Dunlop M, et al. Analyses on the geometrical structure of magnetic field in the current sheet based on Cluster measurements. *J Geophys Res*, 2003, 108, 1168(A5), doi:10.1029/2002JA009612.
- 6 Saito M H, Hau L N, Hung C C, et al. Spatial profile of magnetic field in the near-Earth plasma sheet prior to dipolarization by THEMIS: Feature of minimum B. *Geophys Res Lett*, 2010, 37(8), L08106, doi:10.1029/2010GL042813.
- 7 Spence H E, Kivelson M G. Contributions of the low-latitude boundary layer to the finite width magnetotail convection model. *J Geophys Res*, 1993, 98(A9): 15487-15496, doi:10.1029/93JA01531.
- 8 Zhou X Y, Tsurutani B T. Interplanetary shock triggering of nightside geomagnetic activity: Substorms, pseudobreakups, and quiescent events. *J Geophys Res*, 2001, 106(A9): 18957-18967, doi:10.1029/2000JA003028.
- 9 Morley S K, Freeman M P. On the association between northward turnings of the interplanetary magnetic field and substorm onsets. *Geophys Res Lett*, 2007, 34(8), L08104, doi:10.1029/2006GL028891.
- 10 Lee L C, Albano R K, Kan J R. Kelvin-Helmholtz Instability in the magnetopause-boundary layer region. *J Geophys Res*, 1981, 86(A1): 54-58, doi:10.1029/JA086iA01p00054.
- 11 Nakagawa T, Nishida A. Southward magnetic field in the neutral sheet produced by wavy motions propagating in the dawn-dusk direction. *Geophys Res Lett*, 1989, 16(11): 1265, doi:10.1029/GL016i011p01265.
- 12 Büchner J, Kuska J P. Sausage mode instability of thin current sheets as a cause of magnetospheric substorms. *Ann Geophys*, 1999, 17(5): 604-612, doi:10.1007/s00585-999-0604-5.
- 13 Parks G K. *Physics of Space Plasmas: An Introduction*, 2nd edn. Boulder, Colorado: Westview Press, 2004: 278-280.
- 14 Erickson G M, Maynard N C, Burke W J, et al. Electromagnetics of substorm onsets in the near-geosynchronous plasma sheet. *J Geophys Res*, 2000, 105(A11): 25265-25290, doi:10.1029/1999JA000424.
- 15 Newell P T, Gjerloev J W. SuperMAG-based partial ring current indices. *J Geophys Res*, 2012, 117(A5), A05215, doi:10.1029/2012JA017586.
- 16 Kadokura A, Yukimatu A S, Ejiri M, et al. Detailed analysis of a substorm event on 6 and 7 June 1989, 1, Growth phase evolution of nightside auroral activities and ionospheric convection toward expansion phase onset. *J Geophys Res*, 2002, 107(A12): 1479, doi:10.1029/2001JA009127.