Adv. Polar Upper Atmos. Res., **16**, 136–145, 2002

New model of plasma convection during transpolar arc events

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Abstract: A transpolar arc (TPA) event occurred on December 10, 1996, is examined using auroral images from the Polar UVI. Before the appearance of the TPA, the total pressure of the magnetotail observed at $X \sim -24$ R_E had been increasing for about three hours. Since the IMF B_z was strongly positive during this period, the viscous-like interaction probably contributed to the increase in the total pressure of the magnetotail. A clear TPA appeared in association with fluctuations in the IMF B_y component. A subsequent decrease in the IMF B_z component caused a significant equatorward shift of the dawnside auroral oval, probably resulting in the duskward movement of the TPA. The nightside termination of the TPA, however, was fixed at around local midnight of the auroral oval. This observation indicates that a quasi-stable structure existed in the magnetospheric convection pattern. To account for the present observations, a new model for the formation of TPAs is proposed. The model assumes that the interactions between the viscous convection cells and the merging cell occur in the magnetotail, and predicts that the TPA is mapped along magnetic field lines onto a plasma flow channel that branches off from the earthward plasma convection toward the flank of the magnetotail.

1. Introduction

A narrow-band arc with a rather faint luminosity can be occasionally observed extending from dayside to nightside, through the polar cap. The main characteristics of transpolar arcs (TPAs) described by previous studies can be summarized as follows (Frank *et al.*, 1986): (1) TPAs are confined to the region occupied by sunward-convecting, closed field lines; (2) TPAs tend to appear in association with a southward turning and/or change in the polarity of the interplanetary magnetic field (IMF) after a prolonged period of northward IMF; (3) TPAs move duskward (dawnward) when the B_y component of the IMF is positive (negative) and; (4) small auroral breakups are sometimes observed at the same time as TPAs.

TPAs usually remain in the polar cap for more than one hour. This indicates that a quasi-stable structure must exist in the magnetosphere. Frank *et al.* (1986) hypothesized that TPAs can be mapped along magnetic field lines to a thin plasma structure that bifurcates the tail lobe. If this is the case, a steady, narrow, tailward plasma convection must exist in the neutral sheet region during TPA events (Kan and Burke, 1985). However, as shown in the present study, an intense earthward convection can exist in the magnetotail during TPA events. The relationship between the narrow band of the tailward flow mapped to the TPA and the earthward convection is not clear at present. Furthermore, the stability of the narrow tailward flow surrounded by the earthward convection may be difficult to prove.

In this study, we investigated a TPA event, from its appearance to its disappearance, observed on December 10, 1996. Auroral images obtained by imaging systems onboard the Polar spacecraft and data from the Geotail satellite, the Defense Meteorological Satellite Program (DMSP), the Fast Auroral Snapshot (FAST) satellite, and the Wind satellite were analyzed. A brief description of our observations is presented, and a new model for the formation of TPAs is proposed.

2. Overview of the event

Auroral images obtained by the UVI instrument on Polar (Torr *et al*., 1995) were inspected to examine the formation and variation of a TPA event occurred between 1430 UT and 1800 UT on December 10, 1996. Data from Wind were used to examine the external conditions during this period (Fig. 1). The propagation time, calculated on the basis of the distance along the X coordinate, was approximately 14 min. However, the variations in the B_x and B_y components show that Wind was mostly in the away sector during the period of this event. Assuming the garden-hose spiral structure of the IMF, the propagation time is estimated to be approximately 6 min. Data points in Fig. 1 are plotted using the latter time lag. The solar wind speed (540–560 km/s; data not shown) and the dynamic pressure (2.2–3.2 nPa) around the present event were relatively stable. Variations in the total pressure and the magnetic pressure measured by Geotail in the magnetotail are shown in Fig. 2 (Kokubun *et al*., 1994; Mukai *et al*., 1994). The total pressure (P_{20}) scaled at $R=20\ R_E$ is plotted in the second panel from the top, assuming that the total pressure is proportional to $R^{-2.40}$ (Nakai and Kamide, 1994). The inclination of the magnetic field is represented by the ratio of B_z to B_{tot} in the bottom panel. Geotail was traveling from $(-21.6, 5.2, -3.5)$ to $(-26.1, -0.2, -2.6)\ R_E$ during the time span shown in the figure. The total pressure of the magnetotail continued to increase between 1400 UT and 1555 UT; the elevation angle of the magnetic field decreased during this period, indicating that the magnetotail was recovering from the reduction in the total pressure at ~1200 UT. The IMF B_z component was continuously positive during this interval (Fig. 1). The values of $\varepsilon(=VB_T^2/\mu_0 \sin^4(\theta/2))$ were nearly zero during this period except for small enhancements.

The TPA first became visible in an auroral image obtained at 1536 UT. The arc became progressively evident by 1551 UT (upper panel of Fig. 3). While the IMF B_z component was continuously positive for a few hours before 1600 UT, except for several brief southward excursions, the IMF B_y component was negative with considerable fluctuations between 1510 UT and 1550 UT. Chang *et al*. (1998) suggested that these changes in the IMF B_y component may be responsible for the appearance of the TPA (see also Watanabe *et al*., 2000).

While the B_z component was nearly zero between 1600 UT and 1640 UT, the B_y

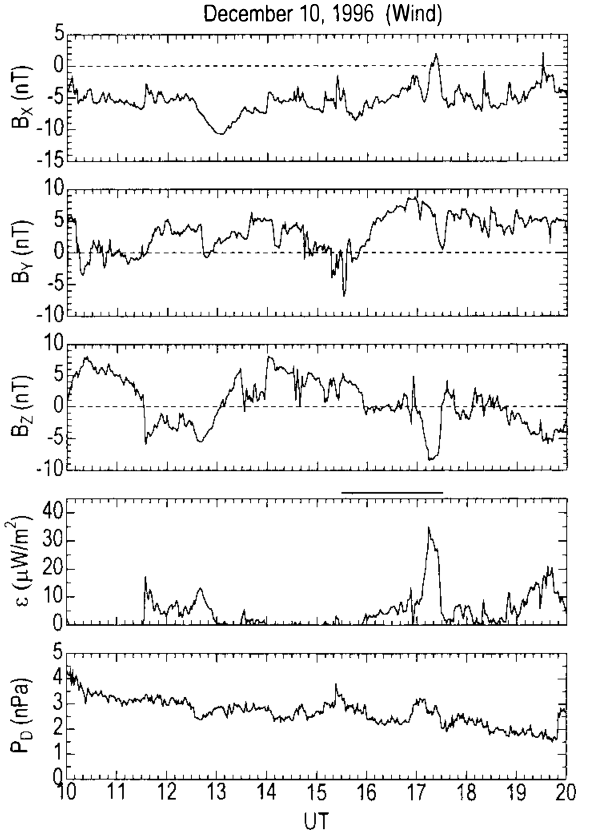

Fig. 1. Variations in the IMF and solar wind parameters between 1000 UT and 2000 UT on December 10, 1996. The three components of the IMF in GSM coordinates, the ε parameter, and the solar wind dynamic pressure are plotted from top to bottom. See the text for the definition of ε.

component increased and became steadily positive after 1600 UT, resulting in a gradual increase in the ε parameter from 3.0 $\mu W/m^2$ (at 1600 UT) to 9.4 $\mu W/m^2$ (at 1700 UT) (Fig. 1). A series of auroral images from Polar show that the nightside portion of the TPA brightened from 1603 UT to 1619 UT (data not shown). Spann *et al.* (1998) reported a similar auroral activation during a TPA event. They found that an active region appeared to tear away from the oval and move poleward along the TPA. After 1619 UT, our TPA moved duskward, and disappeared at ~1734 UT.

In Fig. 3 auroral UVI images obtained at 1551 UT and 1706 UT are shown with the geomagnetic latitude and magnetic local time coordinates superimposed. The original images were displayed using a false color scale. In this figure, however, the images have been reversed and converted to a gray scale for convenience. The auroral oval and the transpolar arcs at 1551 UT and 1706 UT are delineated by solid and dashed lines, respectively. The solid outline of the 1551 UT image was then overlaid on the 1706 UT image. It is important to note that the nightside termination of the TPA did not move between these two time points, although the central portion of the TPA moved considerably

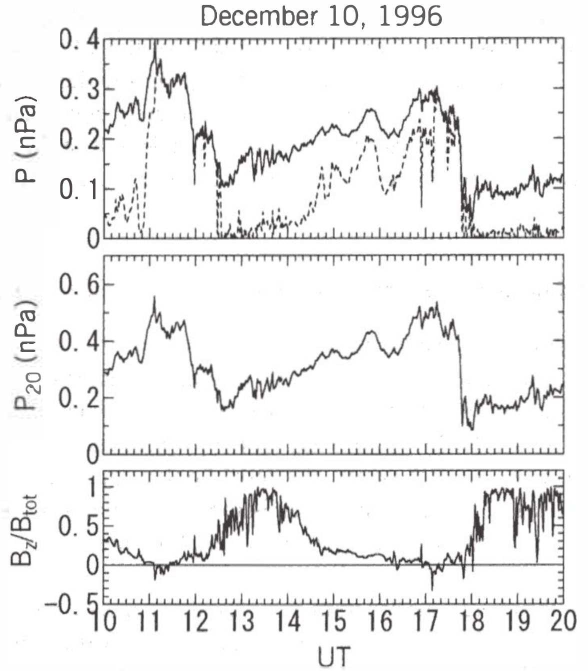

Fig. 2. *Variations in pressure and magnetic field measured in the magnetotail by Geotail. The solid and dashed lines in the top panel represent the total and magnetic field pressures, respectively. In the second panel, P_{20} denotes the total pressure scaled at $R=20\ R_E$. The ratio of the B_z component to the magnetic field magnitude B_{tot} is plotted in the bottom panel. Geotail traveled from $(-21.6, 5.2, -3.5)$ to $(-26.1, -0.2, -2.6)\ R_E$ during the time span shown in the figure.*

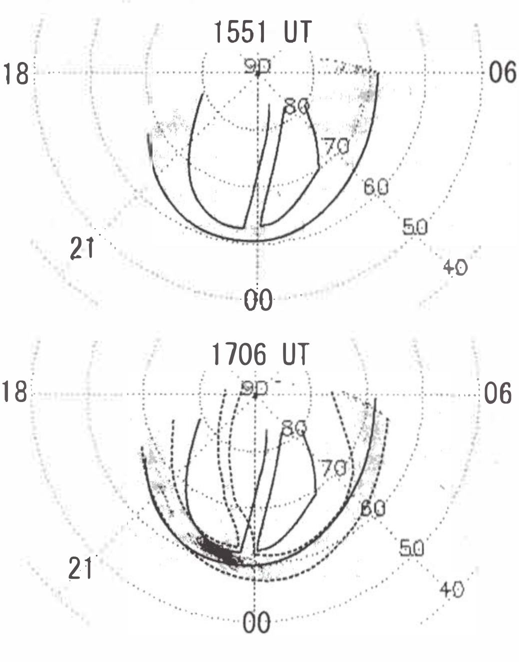

Fig. 3. *Auroral UV images obtained at 1551 UT and 1706 UT in geomagnetic latitude/geomagnetic local time coordinates. The false color scale has been reversed and converted to a gray scale for convenience. Regions with intense auroral luminosity are outlined by solid and dashed lines for the 1551 UT and 1706 UT images, respectively. The outline of the 1706 UT image is superposed on the 1551 UT image to illustrate the changes in the distribution of the aurora between these two time points.*

duskward. The nightside termination, however, eventually moved duskward after 1706 UT (data not shown). Because of the duskward shift of the TPA and the equatorward expansion of the dawnside auroral oval, the polar cap on the dawnside of the TPA was extensively enlarged. Since the ε parameter was moderately enhanced between 1600 UT and 1650 UT (see Fig. 1), this enlargement in the dawnside half of the polar cap probably resulted from the growth of the merging cell, consistent with the positive condition of IMF B_y.

3. Convection patterns and open/closed magnetic field configurations

Energy spectrograms of precipitating ions and electrons in the polar cap obtained by the DMSP satellites were examined in detail to evaluate whether the magnetic field lines were open or closed along the orbit of the spacecraft. Data from northern and southern polar-cap crossings by the DMSP F10, F12, and F13 satellites were used in the present study (data not shown). In this paper, the term "polar cap" denotes the ionospheric region located poleward of the auroral UV emissions constituting the auroral oval. The ionospheric regions occupied by closed (or open) field lines are termed as closed (or open) regions hereafter.

On the basis of the energy spectrogram analyses, the magnetic field configurations and the convection pattern in the ionosphere for the periods between ~1600 UT and ~1700 UT are schematically illustrated in Fig. 4. The gray ring indicates the auroral oval. The TPAs are also colored dark gray, representing the horse-collar auroral pattern. The dotted regions corresponds with the regions near the dawn or dusk flank of the magnetotail, or the "boundary plasma sheet" in traditional terminology. The resultant region, which is shaped like orchid's petals, indicates the open region. The open region between the TPAs indicates the polar cap portion of the merging cell, which corresponds to the region that expanded between 1551 UT and 1706 UT, as discussed in Fig. 3. On the other hand, the open region between the TPA and the morning (afternoon) auroral oval corresponds to the dawnside (duskside) lobe cell. Since the IMF B_y component was strongly positive during the period of concern, the dawnside patterns (*i.e.*, the dawnside TPA and the dawnside open region) might be severely compressed, making them invisible in the Polar images. The present open/closed patterns are quite similar to those obtained by Henderson *et al.* (see their Fig. 8). In agreement with them, the dusk- and dawn-side open regions are

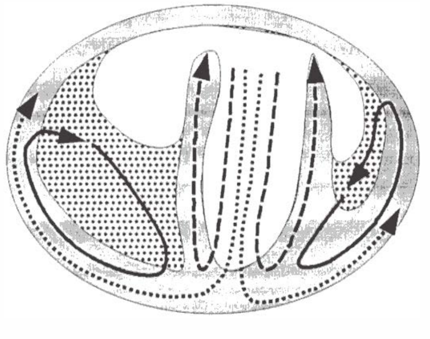

Fig. 4. Schematic convection patterns and open/closed magnetic field configurations in the polar region during TPA events. The gray zone indicates the auroral oval and the TPAs. The dotted region is assumed to correspond to the boundary plasma sheet. The white region in the polar cap is the open region. The lines with arrows show the convection patterns. The solid lines indicate the viscous cells. The short-dashed lines are the merging cell. The branches of the merging cell convecting within the TPAs are shown by the long-dashed lines.

assumed not to extend all the way across to the nightside oval.

In Fig. 4, the solid and dotted lines indicate the viscous and merging cells, respectively (Burch *et al*., 1985). The branches of the merging cell that convect sunward within the TPAs are shown by the dashed lines. Anti-sunward flows of the merging cell are assumed to diverge from the nozzle between the TPAs in the post-midnight sector. Assuming that the IMF B_y component is moderately positive, the convection lines in Fig. 4 have been drawn so that the merging cell is displaced somewhat dawnward. Whether or not the nozzle is confined between the TPAs is an important issue in the model of the convection pattern in Fig. 4. Since magnetometer data for the midnight sector are, unfortunately, not available for the time period being examined, the position of the nozzle cannot be confirmed. Pellinen *et al*. (1990), however, examined active auroras appearing to the west of the nightside termination of a TPA and found that the ion drift velocities were directed eastward near the western edge of the active auroras and westward in the region equatorward of the auroras. Consistent with our model, their results indicate that the region to the west of the TPA's termination is a portion of the duskside convection cell.

Since the IMF B_x was negative during the present event, the lobe magnetic field may reconnect with the IMF at the northern magnetopause. Henderson *et al*. assumed that the lobe field lines which have reconnected with the IMF at high latitudes are convected into the lobe-cell open regions and reconnect at the nightside open/closed boundaries. However, the northern and southern field lines in the lobe cells probably cannot reconnect with each other in the magnetotail, since the lobe cell does not expand to the nightside auroral oval. Therefore, the lobe-cell convection does not significantly influence the nightside convection patterns. The lobe-cell convection patterns are not shown in Fig. 4 for this reason.

Watanabe *et al*. (2000) suggested that the merged magnetic flux tends to drift along both sides of a TPA, pushing the TPA tailward. In our observations, however, only the polar-cap region between the TPA and the dawnside auroral oval was observed to expand in association with an increase in the dayside reconnection rate (Fig. 3).

4. Interpretations and discussions

Burch *et al*. (1985) suggested that the plasma convection in the polar region consists of viscous cells, lobe cells, and merging cells. They defined these cells in the following manner. (1) Two "merging" cells, in which closed magnetospheric flux tubes open by merging with solar-wind field lines at the day-side magnetopause, flow anti-sunward across the polar cap, reconnect on the nightside, and return at lower latitudes (the traditional two-cell system). (2) A "lobe" cell is driven by magnetic merging on the polar magnetopause, tailward of the cusp. This cell does not involve a transfer of magnetic flux from the dayside to the night side, but only a stirring and shortening of magnetotail field lines. (3) Two "viscous" cells, one on each side of the polar cap, are driven by a quasi-viscous process on the flanks of the magnetosphere. In this section, we will discuss our observations using this nomenclature.

The IMF B_z component was continuously positive between 1400 UT and 1555 UT (Fig. 1). The values of ε were nearly zero during this period, except for small, brief enhancements, while the total pressure of the magnetotail continued to increase, and the elevation angle of the magnetic field decreased (Fig. 2). These observations suggest that the magnetotail was recovering from the reduction in the total pressure at ~1200 UT, indicating that the magnetic flux was transported from the dayside magnetosphere to the magnetotail to refill the magnetic pressure lost by an unloading process, even when the dayside merging rate was extremely low. The viscous cell is thought to play an important role in this process (Axford and Hines, 1961).

From the observations shown in Fig. 3, the movement of the TPA can be inferred to occur in conjunction with the growth of the merging cell. Since the dawnside (duskside) TPA tends to be assimilated with the dawnside (duskside) auroral oval in the northern polar cap when the IMF B_y is positive (negative), only the duskside (dawnside) TPA is usually observed when the IMF B_y is strongly positive (negative). Thus, the TPAs appear to move duskward (dawnward) when the IMF B_y component is positive (negative) (Frank *et al*., 1986).

How the sunward convection within TPAs should be mapped to the magnetotail has been a long debated question. Closed field lines threading an area close to the cusp region in the polar cap are generally mapped onto the magnetotail equatorial plane further from Earth. Since plasma flows sunward within TPAs, this implies that a narrow tailward plasma flow exists in the magnetotail (Kan and Burke, 1985). We have, however, found that an intense merging cell can coexist with a TPA. The coexistence of a tailward flow and a predominant earthward convection from the distant-tail neutral line is unlikely.

In our opinion, the difficulty in mapping TPAs on the magnetotail equatorial region cannot be solved as long as one assumes the existence of a tailward plasma channel. One possible alternative is that the earthward plasma flow branches in the magnetotail equatorial plane. In this model, part of the earthward plasma flow in the merging cell is assumed to branch off, leading to the flank of the magnetotail as a result of the interaction between the merging cell and the viscous cell. A conceptual view of this model is shown in Fig. 5. The magnetic field lines (dashed lines) and the plasma convection patterns (solid lines with arrows) in the duskward half of the magnetotail are depicted together with the ionospheric convection pattern shown in Fig. 4. Note that this figure is not scaled. Panels (a) and (b) show the merging cell and the viscous cell, respectively. Panel (c) shows the "branch," which is assumed to be mapped to the TPA along the magnetic field lines. The "branch" is referred to as the TPA channel hereafter. Although the radial distance at which the earthward flow branches off is not known, it is assumed to occur before the distant neutral line. Given that the spatial scale of the TPA is 200×3000 km^2 and that the B_z component in the equatorial region is 5 nT, the area of the TPA channel is estimated to be ~180 R_E^2, based on the conservation of magnetic flux. Therefore, the width of the TPA channel along the X axis is estimated to be ~10 R_E.

The mapping of the "lobe" cells into the magnetotail was carefully considered during the formation of our model. Since the IMF B_y was positive during the period concerned, the geomagnetic field lines reconnected at high latitudes near the cusp were dragged dawnward to form the merging cell. Therefore, such field lines are not likely to be responsible for the duskside open region (Fig. 3). Instead, the field lines from the duskside open region are likely to reconnect with the IMF at the polar magnetopause, tailward of the cusp (Burch *et al*., 1985). If the closed field lines near the flank of the magnetotail reconnect with the sheath field, some portion of the magnetic field lines in the viscous cell

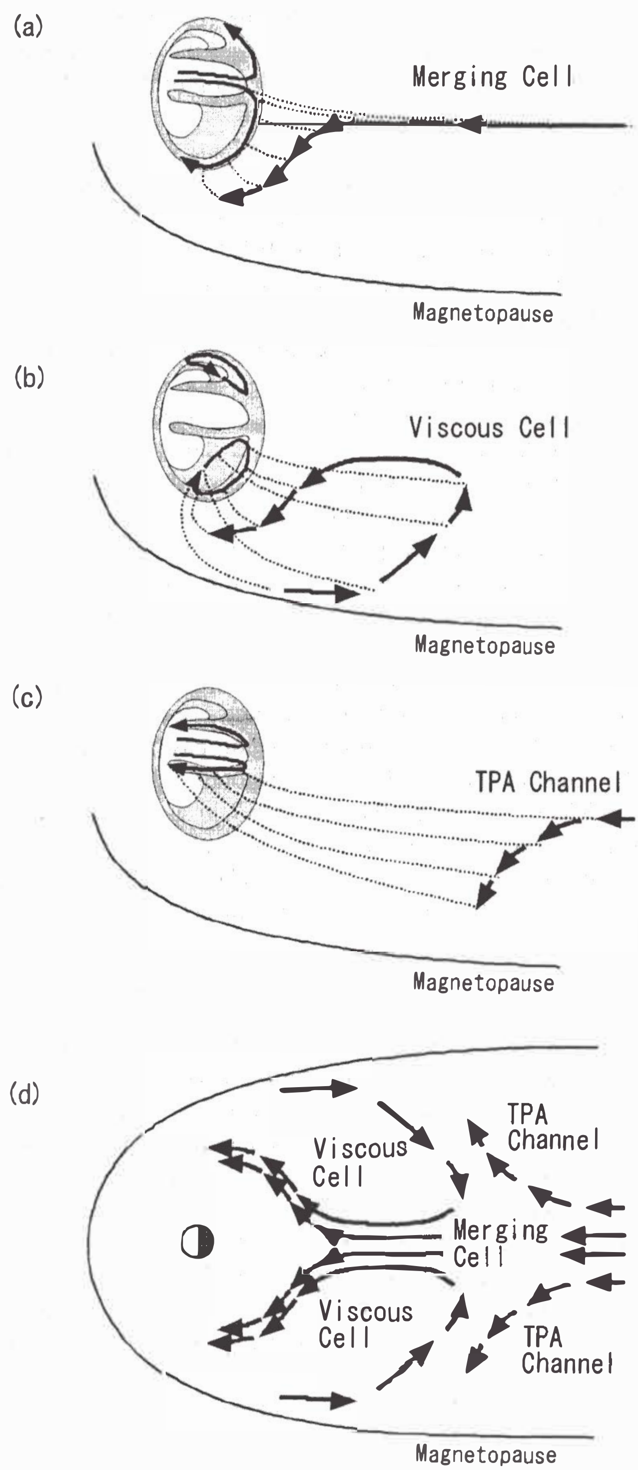

Fig. 5. Mapping of the ionospheric convection patterns to the plasma convection patterns in the magnetotail. The ionospheric "open/closed" pattern of magnetic field lines is overlaid on the magnetospheric equatorial plane in panels (a)–(c). The flow patterns are shown schematically by the arrows for (a) the merging cell, (b) the viscous cell, and (c) the TPA channel. The dashed lines indicate the magnetic field lines that connect the ionosphere and the magnetotail. The combined patterns in the magnetotail are shown schematically in the panel (d).

would change into those in the lobe cell through the boundary between the lobe and viscous cells. Since the open region of the lobe cell does not reach the nightside auroral oval (Henderson *et al.*, 1996), bifurcation of the lobe's cross section would probably occur only in the near-Earth magnetotail.

Newell and Meng (1992) and Chang *et al.* (1998) suggested that TPAs often appear in association with a southward turning and/or change in the polarity of the IMF. Our observations were consistent with this suggestion. Additionally, the nightside half of the TPA was brightened between 1603 UT and 1619 UT in response to an increase in the ε parameter. These observations indicate that the enhancement of the merging cell is a prerequisites for the generation of a TPA. Consistent with this view, our hypothesis predicts that the TPA channel is populated by energetic particles in association with an intensification of the merging cell.

The nozzle of the merging cell is formed between the dawn and dusk viscous cells in our model. Since it is assumed that the branching of the merging cell is caused by its interaction with the viscous cell, the diverging point is fixed upstream of the nozzle point. Therefore, even when the TPA moves duskward in association with the expansion in the open region of the merging cell, the diverging point is thought to be fixed at around the midnight meridian, consistent with the present observation. The diverging point may eventually move duskward, as the nozzle is expanded by the extremely enhanced merging cell.

When the $|B_y|$ component of the IMF is larger than the $|B_z|$ component, the dayside magnetic field reconnection is expected to occur at high latitudes. Merged field lines connected to the southern polar region pass through the equatorial region, draping along the flank of the near-Earth magnetotail. Thus, the closed field lines are likely to be inefficiently driven by the "viscosity" in association with the resulting expansion of the merging cell. This mechanism can explain why the nightside termination of the TPA began to move duskward at ~1706 UT. The dynamics between the viscous cell and the merging cell should be investigated in detail.

Acknowledgments

We deeply thank the staff of the following institutes: Institute of Space and Astronautical Science, Japan (http://www.darts.isas.ac.jp/spdb/indes.html), for the magnetic field and plasma data from Geotail; NASA/Goddard Space Flight Center, USA (http://rumba.gsfc.nasa.gov./cdaweb/istp-public/), for the solar wind data from Wind and the energy spectrograms from FAST; The Johns Hopkins University, Applied Physics Laboratory, USA (http://sd-www.jhuapl.edu/), for the energy spectrograms from DMSP; and World Data Center for Geomagnetism, Kyoto, Japan (http://swdcdb.kugi-kyoto-u.ac.jp/) for the magnetogram data obtained at Kakioka and Phu Thuy. We greatly appreciate the efforts of J.M. Ruohoniemi and F.J. Rich in preparing the data maps for Super-DARN and DMSP ion drift data, respectively. This work was performed by a joint research program at the Solar-Terrestrial Environment Laboratory, Nagoya University.

The editor thanks Drs. N. Sato and M. Pinnock for their help in evaluating this paper.

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(Received November 1, 2001; Revised manuscript accepted April 16, 2002)