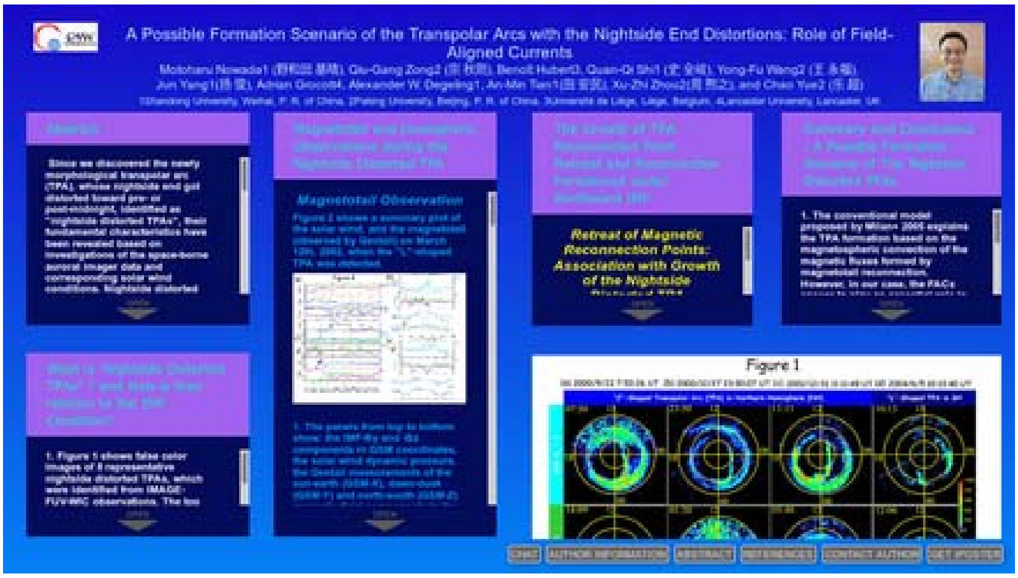
A Possible Formation Scenario of the Transpolar Arcs with the Nightside End Distortions: Role of Field-Aligned Currents



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ABSTRACT

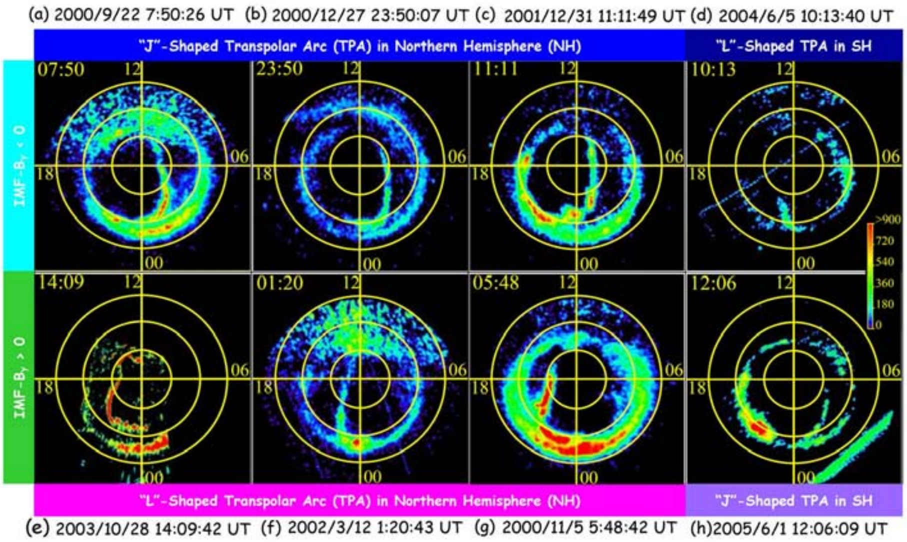
Since we discovered the newly morphological transpolar arc (TPA), whose nightside end got distorted toward pre- or post-midnight, identified as “nightside distorted TPAs”, their fundamental characteristics have been revealed based on investigations of the space-borne auroral imager data and corresponding solar wind conditions. Nightside distorted TPAs had two types; “J”- and “L”-shaped TPAs, and their locations of appearance (dawn or duskside of the polar cap) were governed by the polarity of the By component of the Interplanetary Magnetic Field (IMF). Furthermore, we found that the nightside distorted TPAs have antisymmetric morphologies in the Northern and Southern hemispheres, also depending on the IMF-By orientation.

In this presentation, we show that that the electric currents flowing aligned to the magnetic field lines which connect between the magnetotail and the ionosphere, that is, Field-aligned currents (FACs) play an essential role in the formations of the “J”- and “L”-shaped TPAs. They are induced by significant plasma flow velocity difference (plasma flow shear) between the fast plasma flows associated with nightside magnetic reconnection and slower background plasma flows in the magnetotail. The current vortex structures with the counterclockwise rotation are also clearly seen in the ionospheric current vectors derived from fluctuations of the geomagnetic field measured at the ground observatories beneath and in close proximity of the growth regions of the nightside distorted TPA. This result suggests that the FACs were flowing out of the ionosphere toward the magnetotail (upward FACs) near the TPA. Furthermore, based on the geomagnetic field variations and the SuperDARN HF radar data, we obtained evidence in which the locations of magnetotail magnetic reconnection, which persisted even during northward IMF-Bz intervals, that is, the TPA durations, retreated further down tail as the TPA grew to the dayside. Taking into account these observational results, we finally show a model to illustrate the nightside distorted TPA (particularly, “L”-shaped TPA) formation.

WHAT IS "NIGHTSIDE DISTORTED TPAS" ? AND HOW IS THEIR RELATION TO THE IMF CONDITION?

1. Figure 1 shows false color images of 8 representative nightside distorted TPAs, which were identified from IMAGE-FUV-WIC observations. The top (bottom) row of panels correspond to cases of IMF-By < 0 (IMF-By > 0), and the first three columns show Northern hemisphere (NH) observations, while the last column displays Southern hemisphere (SH) observations. In each panel, the top and bottom corresponds to noon (12 MLT) and midnight (24 MLT), and the right and left sides correspond to dawn (6 MLT) and dusk (18 MLT) meridians, respectively. The color scale is approxinately expressed in the observed auroral brightness.

Figure 1



2. The upper panels (a) to (c) display the dawnside TPAs with the nightside ends distorted toward midnight or pre-midnight observed in the NH. Hereafter, we identify these as "J"-shaped TPAs based on their resemblance to the letter "J". In all observed TPAs, the "J"-shaped TPAs in the NH occur during a negative (dawnward) IMF-By interval.

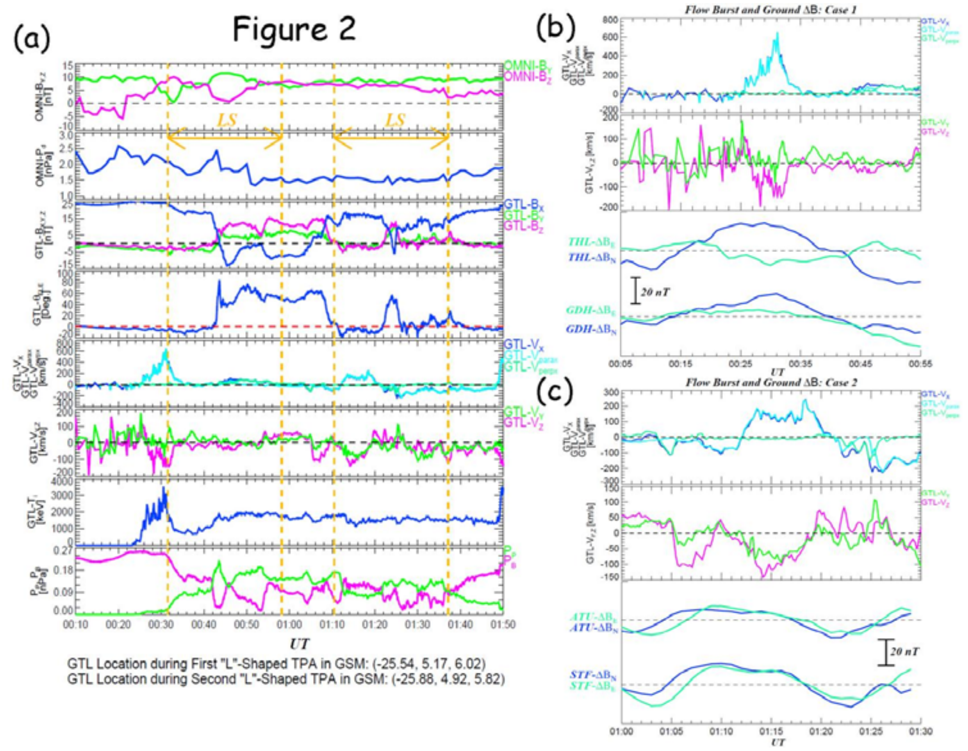
3. In bottom panels (e) to (g), the nightside distorted TPAs with the opposite chirality occurred on the duskside, in which the nightside ends get distorted toward midnight or post-midnight. We identify them as "L"-shaped TPAs based on their resemblance to "L".

4. Panels (d) and (h) show observations in the SH during negative and positive IMF-By intervals, respectively. Interestingly, these two panels appear to show the opposite chirality to their NH counterparts under the same IMF conditions, with an "L"-shaped TPA (panel d), and a "J"-shaped TPA (panel h).

MAGNETOTAIL AND IONOSPHERIC OBSERVATIONS DURING THE NIGHTSIDE DISTORTED TPA

Magnetotail Observation

Figure 2 shows a summary plot of the solar wind, and the magnetotail (observed by Geotail) on March 12th, 2002, when the "L"-shaped TPA was detected.



1. The panels from top to bottom show: the IMF-By and -Bz components in GSM coordinates, the solar wind dynamic pressure, the Geotail measurements of the sun-earth (GSM-X), dawn-dusk (GSM-Y) and north-south (GSM-Z) magnetic field components in the duskside magnetotail, the associated magnetic field elevation angle, and the ion flow velocity in GSM, parallel and perpendicular to the local magnetic field lines from 00:10 UTto 01:50 UT. During this interval, the "L"-shaped TPAs (LS) were twice observed as bracketed by two gold broken lines.

2. The IMF-By and -Bz components were oriented roughly duskward and northward during two TPA intervals. Associated solar wind dynamic pressure showed no significant changes.

3. The large abrupt decreases and increases in the Geotail-Bx component indicate multiple (four times of) crossings of the magnetotail current sheet. The enhancements of the Bz component and elevation angle, seen in both LS intervals, indicate the occurrence of the dipolarization. The Vx components showed earthward "bursty" enhancements, indicating the occurrence of magnetotail magnetic reconnection. Taking a look at the x-directional components of plasma flow speed parallel and perpendicular to the field lines (Vparax, Vperpx), This flow burst had much more dominant field-aligned component (Vparax) than the perpendicular flow velocity (Vperpx). The second flow bursts seen during the second LS interval also had strong field-aligned velocity.

4. These earthward flow burst profiles also suggest the tailward retreat of the reconnection locations; the Vx component in the first interval had already started to decrease at the onset of the "L"-shaped TPA, and the flow burst velocity during the second "L"-shaped TPA interval was lower than that in first TPA interval (if considering that there was little difference in the satellite positions between first and second TPA intervals).

5. The magnetic pressure ($Bt^2/2\mu_0$: Bt is the magnetic intensity) was higher than the plasma pressure (NikTi) during the two flow burst intervals, indicating that the regions where observed flow burst events might be plasma sheet boundary layer (PSBL). Baumjohann+ 1988 reported that faster plasma flows in PSBL intend to have dominant field-aligned components, advocating that two flow bursts seen for these 1.4 hours are considered to occur in PSBL.

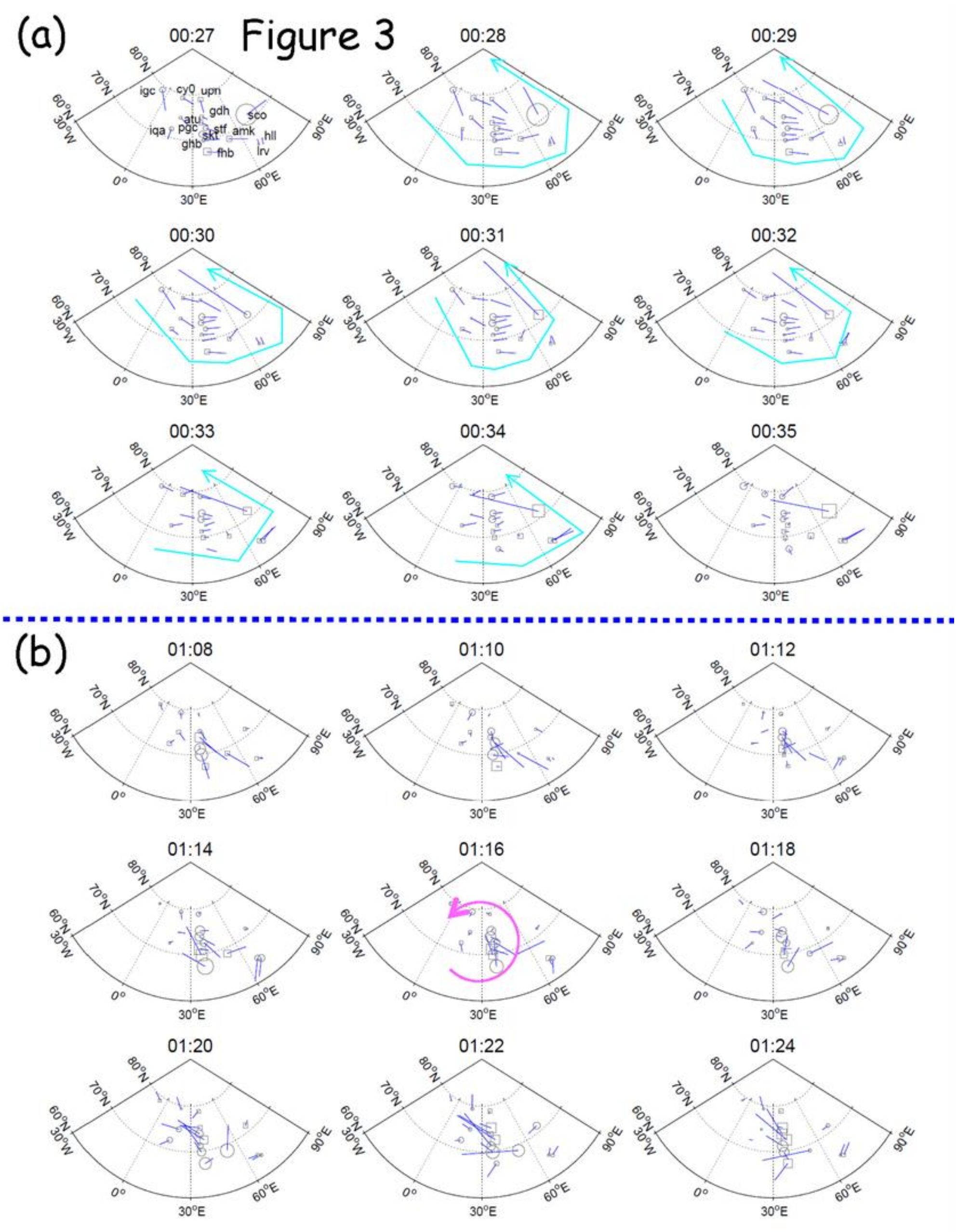
6. The panels (b) and (c) show zoomed-in plots of the three plasma flow velocity components in GSM coordinates and the x-directional components of plasma flow speed parallel and perpendicular to the local magnetic field (upper two panels) and the ground magnetic field

perturbations in the B_N (local magnetic north-south) and B_E (local magnetic east-west) components measured at two representative ground magnetic observatories close to the TPA (lower panel). In the first plasma flow burst (panel b), the peaks of the Vx and Vparax components, and those in the ΔB_N components are seen at the same time, suggesting that the fast flows associated with magnetotail reconnection might trigger electric currents, and cause the variations of geomagnetic field. During the second flow burst interval, the geomagnetic field peaks were not seen as shown in panel (c).

Ionospheric Observation

1. When the "flow velocity difference (flow shear)" between reconnection-associated earthward fast flows and slow magnetotail background flows is present, electric currents flowing aligned to the geomagnetic field lines (Field-Aligned Currents: FACs) can be driven. These FACs are closely related to auroral phenomena in high-latitude atmosphere. In order to investigate this current system, an electric current map is made based on the geomagnetic field variations measured at the ground observatories beneath and in close proximity to the regions of growth of the "L"-shaped TPAs.

2. Figure 3 shows the current maps projected onto geomagnetic coordinates before and during the "L"-shaped TPAs, including the intervals of earthward flow bursts. The electric current maps near the "L"-shaped TPAs are derived based on perturbations of the local magnetic north – south (B_N) and east – west (B_E) components of the geomagnetic field which were measured at the ground magnetic observatories beneath and in close proximity to the growth regions of the nightside distorted TPA.



3. On the maps during both the first (a) and second (b) flow burst intervals, counter-clockwise current vortices were found as highlighted with cyan arrows and magenta circle arrows. This anti-clockwise vortex-structured current suggest that FACs, launched from the ionosphere toward the magnetotail, might be caused by electron supply (precipitation) to the ionosphere due to fast plasma flows aligned to the magnetic field lines, which were triggered by magnetotail magnetic reconnection. This result is also clear evidence that the energized plasma (electrons) were conveyed by the magnetotail fast flows from the magnetotail to the ionosphere.

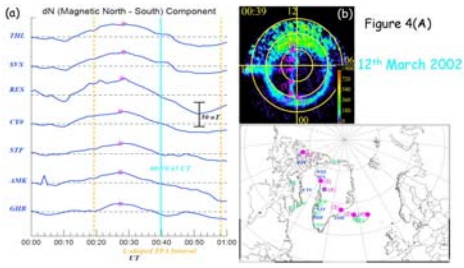
4. Furthermore, the vortex spatial scale is different between first and second interval. In panel (a), a "large-scale" vortex-like current structure is discerned by the electric current vectors measured at most observatories, while "small-scale" current vortices with a similar rotational sense are indicated during the second interval (panel b). Neither vortex current structure showed any poleward (high-latitude) migration as the "L"-shaped TPA grew to the dayside.

THE GROWTH OF TPA: RECONNECTION POINT RETREAT AND RECONNECTION PERSISTENCE UNDER NORTHWARD IMF

Retreat of Magnetic Reconnection Points: Association with Growth of the Nightside Distorted TPA

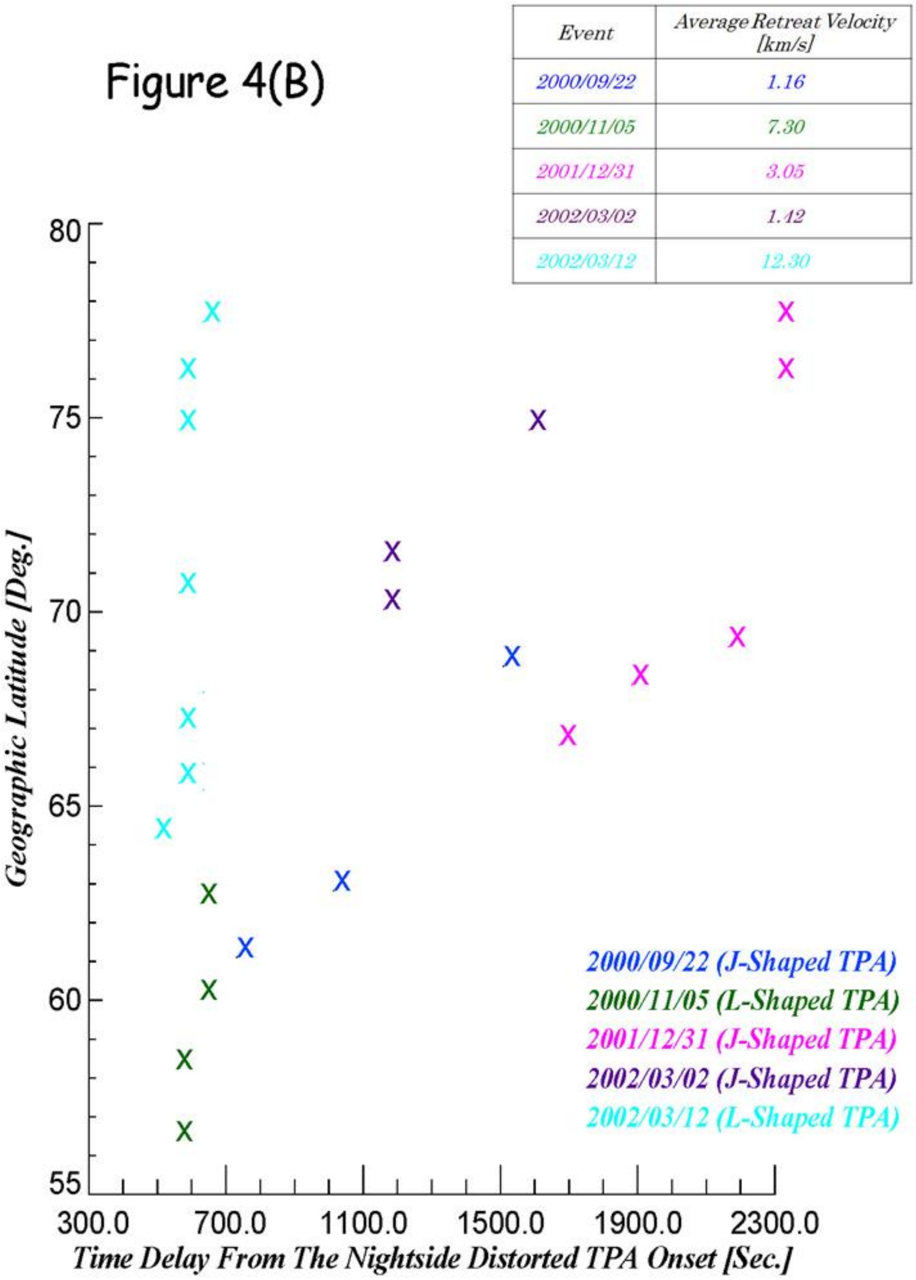
1. We consider the "growth" of the TPA. According to conventional model to explain the TPA formation based on nightside reconnection, which does not take into account the influence of FACs in the TPA formation, the reconnection points should retreat tailward as the TPA grows to the dayside. A summary plot of the Geotail observations shown in Figure 2 has already suggested the tailward retreat of the reconnection point. To further support the scenario, we examine the geomagnetic field variations associated with the nightside distorted TPAs using ground-based observations.

2. Figure 4(A) shows an example of the geomagnetic field observational results at several ground magnetic observatories corresponding to the locations beneath or in close proximity to the regions of growth of a nightside distorted TPA ("L"-shaped TPA observed on 12th March 2002). All magnetic field data for the ground observatories were taken from the ground magnetic obervatories.



Several magenta points labelled with numbers in the IMAGE FUV-WIC plots in panel (b) correspond to similarly labelled locations in geographical map (panel c). Panel (a) shows the plots of geomagnetic field fluctuations in the local magnetic north-south magnetic field component (ΔB_N) at these observatories highlighted by blue. The magnetic fluctuations are obtained by the subtraction of average magnetic field over the time interval of interest from the observed magnetic field values. The fluctuation component at each station is plotted upon their averages as indicated by horizontal grey broken lines, and its peak during the "L"-shaped TPA intervals bracketed by two gold broken lines, is marked by magenta open circle. The plots are sorted in decreasing order of latitude. The magnetic field fluctuation component at the time of panel (b) is indicated by a horizontal solid line in the panel. The color code of the IMAGE FUV-WIC data is assigned according to the strength of auroral brightness.

3. Figure 4(B) shows a scatter plot of the fluctuation peaks in the local magnetic north-south magnetic field component (ΔB_N) at several ground magnetic observatories from geographical low- to high-latitudes against the time delay between the peak times and the onset times of the 5 nightside distorted TPAs.

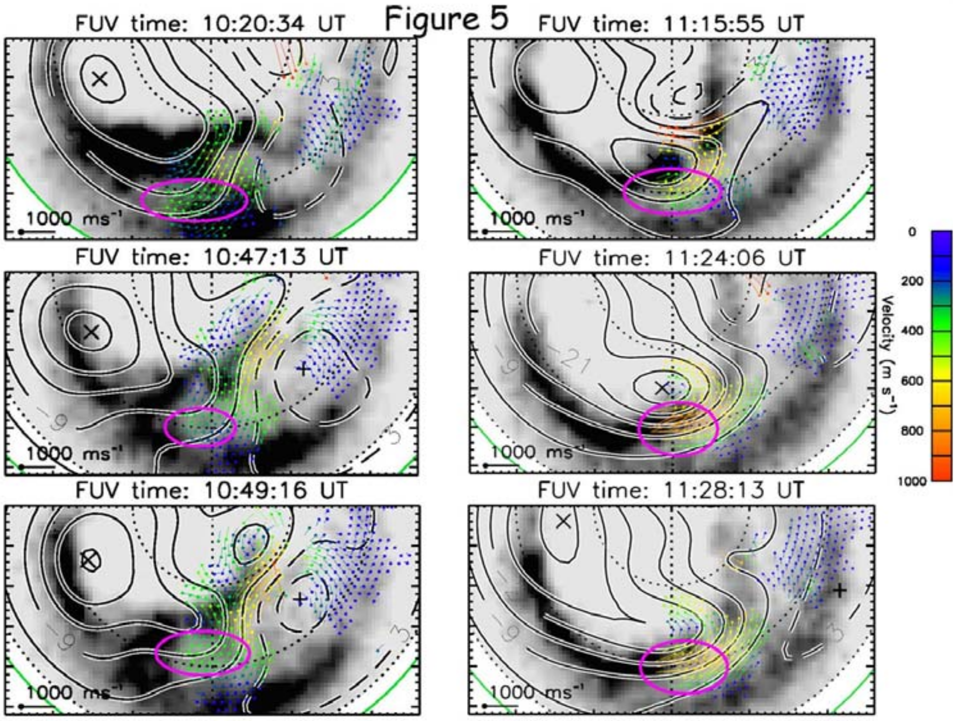


All peaks seen in the magnetic field fluctuation components were positive, implying enhancements of FACs flowing out of the ionosphere, that is, downflowing of electrons from the magnetotail. In the three TPAs (2000/09/22, 2001/12/31 and 2002/03/02), the magnetic peaks are seen at later times for observatories with higher latitude, suggesting that the reconnection points (the source regions of the energetic electrons) were retreating further down-magnetotail, associated with the growth of the TPA to the dayside. This result supports not only the tail reconnection occurrence but also the retreat of the reconnection points. The average velocity of the reconnection point retreat can roughly be estimated based on a slope of line of geographical latitude versus the time delay between the magnetic peaks and the TPA onsets and a value of 1 degree = 110.95 km. The estimated reconnection point retreat velocity is summarized in the table in the upper right of the figure. The three TPAs had the reconnection point retreat velocity within a range between about 1.2 km/s and 3.0 km/s, but the others (2000/11/05 and 2002/03/12) showed a much faster retreat speed (7.3 km/s and 12.3 km/s) because their magnetic field peaks appeared with much less time lags, irrespective of the latitudes of the observatory locations.

Persistence of Magnetotail Reconnection During the Northward IMF Interval

1. In order to obtain evidence for the persistence of magnetotail magnetic reconnection even under the northward IMF conditions (,that is, during the nightside distorted TPA intervals) the plasma flow patterns in the polar cap, measured by SuperDARN HF radars, were examined.

2. Figure 5 presents the 6 selected northern hemispheric plasma flow streamlines and drift velocity vectors during the interval of the nightside distorted TPA ("J"-shaped TPA) observed on 31st December 2001. We overlay these flow velocity profiles onto the corresponding IMAGE FUV-WIC auroral imager data. Black regions indicate higher auroral luminosity, and the IMAGE observational time is shown on the top in each panel. The left, bottom and right sides in each panel correspond to 18h, 24h, and 6h in magnetic local time, respectively. The dotted semicircles indicate the magnetic latitude (MLat) range between 60 degrees and 80 degrees.

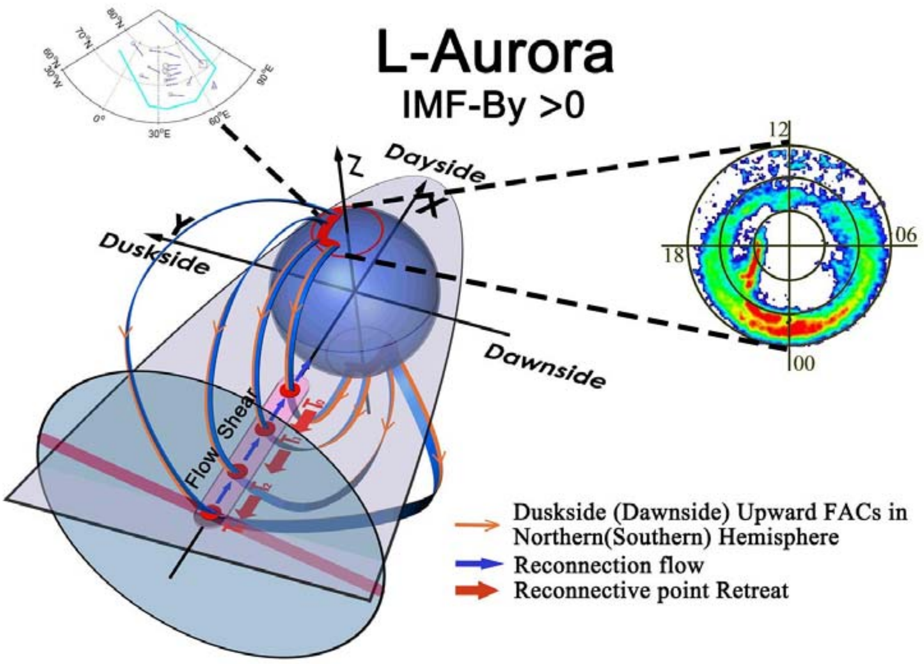


3. During the growth of the "J"-shaped TPA, westward plasma flows were locally (although non-continuously) observed poleward edge of the midnight-sector main auroral oval, highlighted by magenta ovals. These flows were originally oriented toward the equator, but rotated toward the west at the poleward edge of the main auroral oval. They are highly suggestive of magnetic reconnection in the magnetotail, identified as "Tail Reconnection during IMF Northward and Non-substorm Intervals (TRINNIs)". Therefore, at least, nightside reconnection was ongoing during the growth of the "J"-shaped TPA even under the northward IMF conditions, and should play a significant role in the nightside distorted TPA formation.

SUMMARY AND CONCLUSIONS
: A POSSIBLE FORMATION SCENARIO OF THE NIGHTSIDE DISTORTED TPAS

1. The conventional model proposed by Milan+ 2005 explains the TPA formation based on the magnetospheric convection of the magnetic fluxes formed by magnetotail reconnection. However, in our case, the FACs appear to play an essential role in the nightside distorted TPA formation. The ground-based observations revealed that the reconnection points retreated tailward with the poleward growth of the TPAs. Furthermore, the SuperDARN HF radar detected TRINNIs, which are remote-sensing evidence for persistent magnetotail reconnection even under the northward IMF conditions.

2. Taking into account these observations, we construct a model to illustrate the nightside distorted TPA ("L"-shaped TPA) formation. The illustration displays a schematic diagram of the possible formation process of an "L"-shaped TPA under positive IMF-By conditions. The main "bar-like" emissions of the nightside distorted TPAs are located on the dusk side under positive IMF-By conditions as seen in Figure 1. The location of the "L"- ("J")-shaped TPAs strongly depends on the IMF-By sign; the relation between the location of the main TPA part and the IMF-By polarity is the same as that for the "regular" TPA.



3. This model is depicted in terms of the configuration changes of magnetic field lines due to magnetospheric convection, FACs, reconnection-associated plasma flows, and the reconnection point retreat. The closed field lines formed by nightside reconnection are illustrated by thick blue solid curves, and the orange curves indicate the electric currents induced by the plasma flow shear between the background slow plasma flows and fast flows originating from magnetic reconnection (blue arrows).

4. FACs flowing out of the ionosphere toward the magnetotail should be the "source" of the nightside distorted TPAs, being consistent with large- and small-scale electric current vortices beneath and in close proximity to the growth regions of the nightside distorted TPAs. Magnetotail reconnection continues at the point denoted by red dots until the TPA completely forms, and associated closed field lines convect earthward. The reconnection location retreats further tailward from T0 to T3, which are highlighted by the thick red arrows and pink-shaded area, as TPA approaches the dayside. This is because higher latitude field lines within the TPA have their nightside (equatorial crossing) positions further down-tail.

5. The FACs associated with polar cap arcs, including the TPAs, indicate the presence of upward and downward current pairs. Furthermore, considering the magnetotail-ionosphere FACs generated by the reconnection fast flows, this whole

current system should be "closed". Therefore, in the dawn (dusk) sectors of nightside magnetosphere, oppositely to the sector where the nightside distorted TPAs are lying, in Northern (Southern) hemisphere, the FACs flowing into the ionosphere from the magnetotail (downward FACs) must be present as illustrated with thin yellow curves, and connected with the TPA-associated FACs in the ionosphere and the magnetotail as linked with the magnetotail and ionospheric currents, indicated with orange and yellow thick arrows.

6. In the nightside distorted TPA, the reconnection points retreat tailward, but the TPA-associated closed flux tubes are simultaneously twisted clockwise (anti-clockwise), depending on the dawnward (duskward) IMF-By component during concomitant oppositely-oriented nightside plasma sheet deformation, shown by inclined red bars. The closed flux tube twisting is caused by the IMF-By penetration, which produces "asymmetry" for the magnetic fields in the Northern and Southern hemisphere, exerting "torque rotation" due to the electromagnetic force.

7. This results in the "L"- and "J"-shaped TPAs, corresponding to the ionospheric footpoints of these field lines in the Northern and Southern hemispheres.

AUTHOR INFORMATION

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