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Multiple transpolar auroral arcs reveal insight about coupling processes in the Earth’s magnetotail

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A distinct class of aurora, called transpolar auroral arc (TPA) (in some cases called “theta” aurora), appears in the extremely high-latitude ionosphere of the Earth when interplanetary magnetic field (IMF) is northward. The formation and evolution of TPA offers clues about processes transferring energy and momentum from the solar wind to the magnetosphere and ionosphere during a northward IMF. However, their formation mechanisms remain poorly understood and controversial. We report a mechanism identified from multiple-instrument observations of unusually bright, multiple TPAs and simulations from a high-resolution three-dimensional (3D) global MagnetoHydroDynamics (MHD) model. The observations and simulations show an excellent agreement and reveal that these multiple TPAs are generated by precipitating energetic magnetospheric electrons within field-aligned current (FAC) sheets. These FAC sheets are generated by multiple-flow shear sheets in both the magnetospheric boundary produced by Kelvin–Helmholtz instability between supersonic solar wind flow and magnetosphere plasma, and the plasma sheet generated by the interactions between the enhanced earthward plasma flows from the distant tail (less than ~100Rₑ) and the enhanced tailward flows from the near tail (about ~20Rₑ). The study offers insight into the complex solar wind-magnetosphere-ionosphere coupling processes under a northward IMF condition, and it challenges existing paradigms of the dynamics of the Earth’s magnetosphere.

Transpolar arcs (TPAs) are the large-scale auroral forms that stretch almost entirely across the polar cap and connect the dayside and nightside auroral oval (1–5). TPAs can appear as a single or multiple arcs (6–8). Previous theories and observations indicated that TPAs are related to the magnetospheric cusp as their dayside ends join together in the cusp region (called “cusp-aligned” auroral arcs) (9, 10), and are generated by the solar wind–magnetosphere–ionosphere coupling processes as a whole system during northward interplanetary magnetic field (IMF) and quiet geomagnetic conditions (2–5). TPAs are sometimes seen simultaneously in both polar caps (11) and have been inferred to be on both open and closed magnetic field lines (12).

TPA formation processes have long been debated, in particular whether they are driven by dayside or nightside processes (5). The main candidates for dayside processes have been day-side reconnection at the low-latitude magnetopause or high-latitude lobe regions (13–17) and plasma instabilities (e.g., Kelvin–Helmholtz instability, interchange instability) near the magnetospheric low and high-latitude boundary layers (8, 18–20). The main candidates for nightside processes have been proposed as nightside reconnection in the magnetotail (4, 7) and twisting of the magnetotail due to IMF variations (3, 21, 22).

These processes could result in plasma sheet bifurcation, filamentary extent into the lobes, or hot plasma trapped in the tail lobes (1, 7, 23–25). None of the suggested processes can explain all of the observed characteristics, and especially multiple TPAs. It has also been difficult to investigate the phenomenon due to constraints on obtaining simultaneous observations at multiple points across the solar wind–magnetosphere–ionosphere system. Here, we present ground-breaking multiple-instrument observations of multiple TPAs structures seen simultaneously both in the ionosphere and the distant magnetotail. The observations are interpreted using a global three-dimensional (3D) magnetohydrodynamic (MHD) simulation, giving for a discussion of the formation of multiple TPAs from a global perspective.

On 7 September 2017, long-lasting, relatively stable northward IMF conditions (IMF B₀ > 0 for more than 8 h) occurred with comparable dawn–dusk components (IMF Bₚ) and roughly stable solar wind conditions, except for some IMF variations and}

**Significance**

Colorful and dynamic aurora has attracted human’s attention since the dawn of time. However, mystery remains in understanding a distinct class of aurora, transpolar auroral arc (TPA) (or “theta” aurora) which occurs in extremely high latitude of the Earth polar regions when interplanetary magnetic field (IMF) is northward. Previous theories are unable to explain why multiple TPAs often occur. Our comprehensive observations in the ionosphere and magnetotail as well as a three-dimensional magnetosphere modeling shed insight on how multiple TPAs form. Our study offers clues how solar wind energy and mass transfer into the magnetosphere and ionosphere under a northward IMF that occurs nearly half of the time.}


The authors declare no competing interest.

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Data deposition: The 3D MHD simulation data are available on the website of https://zenodo.org/record/3772765 with a separate DOI of 10.5281/zenodo.3772765. The time sequence of 557.7-nm aurora images from the all-sky imager at the Chinese Antarctic Zhongshan Station (ZHS) are available on the website of https://zenodo.org/record/3778095 with a separate DOI of 10.5281/zenodo.3778095.

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dynamic pressure increases around 12:30 UT (Fig. 1 A–C). The northward IMF reached around 8 nT and was roughly stable, with the Bz component around 4 nT, and a high solar wind speed of around 520 km/s (see gray shading in Fig. 1 indicating the interval of interest). These conditions are favorable for triggering of the Kelvin–Helmholtz instability between the solar wind and magnetosphere (26–29) and multiple cusp-aligned auroral arcs in the polar cap (9, 10). The auroral electrojet AL and AU indices, the smallest (AL) and largest (AU) values of geomagnetic variations in the horizontal component observed at 11 selected observatories along the auroral zone in the northern hemisphere, show nonsubstorm conditions after 15:30 UT (Fig. 1D), indicating a quiet auroral oval.

Auroral observations from the Southern Hemisphere are presented in Fig. 2 A–E. Poleward of a normal auroral oval at lower latitudes, Fig. 2A shows at least six bright TPAs in the otherwise empty polar cap (poleward of −78° MLAT, and highlighted by gray shading in Fig. 2 F–H) from Defense Meteorological Satellite Program (DMSP) F17 Special Sensor UV Spectrographic Imager (SSUSI) data. In addition, there are several radially aligned arcs both within the dawnside (−70 to −78° MLAT) and duskside (−70 to −77° MLAT) auroral oval. Several of the TPAs were brighter than the main auroral oval with brighter spots within them and persisted for more than 2 h including their evolution and decay (SI Appendix, Fig. S1 B–D).

Fig. 2 B–E shows the time evolution of the aurora during an overflight by the DMSP F17 spacecraft of one TPA, as recorded by a 557.7-nm all-sky imager at the Chinese Antarctic Zhongshan Station (ZHS) (30). The projected field-aligned current (FAC) along the satellite track suggests that each arc was associated with an upward FAC (Fig. 2 A and F). Minor offsets can be attributed to altitude differences between the two datasets. The in situ plasma observations of the electron energy flux (Fig. 2G) show that each auroral arc was associated with precipitation of electrons that have been accelerated to more than 1 keV. Most of the TPAs were not associated with observable ion precipitation, but may be associated with upward ion beams observed by Cluster satellites in other events (31, 32). The electron energy fluxes (Fig. 2G) also reveal several smaller arcs that were not visible in the DMSP/SSUSI images with a limited spatial resolution and/or sensitivity (Fig. 2A). The formation of such multiple/filamentary TPAs has remained an intriguing and unresolved puzzle for many years.

Using the measured interplanetary conditions as input, a high-resolution 3D global MHD code called Piecewise Parabolic Method with a Lagrangian Remap to MHD (PPMLR-MHD) (33, 34), was run to investigate the formation of multiple TPAs. An electrostatic ionosphere shell with height-integrated conductance is imbedded in the MHD code, allowing for the electrostatic coupling and calculation of FACs between the ionosphere, which is near the Earth, and the model’s magnetospheric inner boundary. Fig. 3A shows a two-dimensional extract from a movie (Movie S1) of simulated FACs and plasma velocity vectors in the Geocentric Solar Magnetosphere (GSM) X-Y plane [Z ∼ −1 RE for better capturing the phenomenon in the Southern Hemisphere (35)]. The magnetotail is to the left, and the subsolar magnetopause is to the right. Pairs of strong and filamentary FACs are shown in red and blue color, generated by flow shear sheets around the dayside magnetopause at both flanks in the low-latitude boundary layer (LLBL) due to the Kelvin-Helmholtz instability (KHI), and newly formed flow shear and FAC sheets are added while the previous shear sheets are gradually pushed inward and tailward resulting in multiple FACs sheets in the LLBL (Movie S1). Some of these FACs merge with the existing FACs; others remain distinct and fade. These upward FACs cause magnetic field-aligned acceleration of magnetospheric electrons [probably through the Knight’s current-voltage process (36, 37)] that precipitate into the polar ionosphere and generate the poleward-moving aurora arcs in the
Fig. 2. Aurora and in situ plasma and FAC observations in the Southern Hemisphere. (A) Aurora in the Lyman–Birge–Hopfield short-band (LBHS) band (wavelength of 140–150 nm) observed by the SSUSI instrument on board the DMSP F17 satellite from JHU/APL and the sign of the FACs shown in red and blue color along the satellite track. The FAC is calculated from the special sensor microwave (SSM) magnetic field measurement on board the satellite, (B–E) sequence of 557.7-nm aurora images from the all-sky imager at the ZHS, (F) time series of the calculated FACs and the aurora intensity extracted from A along the track of DMSP F17, and (G) and (H) electron and ion energy flux spectrograms from JHU/APL special sensor for precipitating particles (SSJ5) instrument on board the DMSP F17. The magenta ellipse in A shows the field of view (FOV) of the ZHS all-sky imager. B–H are shown in the reversed order to better align with the DMSP F17 trajectory in A; i.e., time runs from the right to the left (dusk to the left, dawn to the right).
auroral oval (seen in Fig. 2A–E). Meanwhile, a narrow and roughly stable upward FAC appears around \( Y = 0 \) \( \text{RE} \) and extends down the magnetotail from \( X = -10 \) to \(-100 \) \( \text{RE} \) at the beginning, which starts to locally break up inside the center plasma sheet at about \(-20 \) \( \text{RE} \) in association with enhanced tailward flows from about 15:10 UT. Then at about 15:45 UT, strong bursts of earthward flow come in from the distant tail (less than \(-100 \) \( \text{RE} \), Movie S1). When these earthward and tailward flows with FACs encounter each other around \(-35 \) \( \text{RE} \), they split and form multiple flow shear and FAC sheets that extend along the dawn and dusk flanks of the magnetotail and merge with those developed by the flank KHI (Movie S1). These result in a large number of filamentary FACs and associated flow shears that populate the multiple auroral arcs in the polar cap and auroral oval.

When the FACs are mapped along the magnetic field to the ionosphere in the Southern Hemisphere, a striking pattern emerges (Fig. 2B and Movie S1). These FACs show clear cusp-aligned, “arclike” structures in both the polar cap and the auroral oval that are similar in shape and size to the observed arcs shown in Fig. 2A. A few selected points on the arclike FAC structures have been mapped back to the X-Y plane (seen in SI Appendix, Fig. S3). This shows that the filamentary FACs in the central magnetotail map to the central polar cap and are directly associated with the structures having the appearance of multiple TPs. On the other hand, the filamentary FACs in the magnetospheric boundary layer map to the auroral oval and are associated with discrete arcs in the auroral oval. The white blank area in the afternoon sector polar cap of Fig. 2B is indicative of magnetic field lines that did not cross the X-Y equatorial plane, due to a significant IMF \( B_y \) component resulting in a distorted magnetotail and/or out of the simulation region.

To verify the simulation results we present simultaneous observations from spacecraft B and C of the THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission (38) near the equatorial plane in the dawnside magnetotail. These spacecraft were in an orbit around the moon at \([-59.0, -17.8, 4.0]\) and \([-58.6, -15.1, 3.8]\) \( \text{RE} \), GSM, respectively. Red stars in Fig. 3A mark the locations of each spacecraft, which both observed multiple flow shears in the X-Y plane that remarkably well resemble those from the KHI within the model (Fig. 3C and D). In this analysis, the data have been detrended by subtracting the mean velocity. The results confirm
that there is indeed strong flow shears in the magnetospheric boundary layer, triggering KHI between the solar wind and magnetosphere. Both the simulation results and the THEMIS observations show very similar behavior (Fig. 3 C and D, and SI Appendix, Fig. S4), which adds confidence that the PPMLR-MHD model is indeed capturing the key physical processes for these northward IMF conditions.

The observations and simulation confirm the existence of strong multiple flow shears in the entire magnetosphere from the magnetopause, the lobe, and the magnetotail under a northward IMF condition. These flow shears directly lead to multiple FAC sheets that join together in the cusp region in both hemispheres and field-aligned acceleration of electrons which create multiple cusp-aligned auroral arcs both in the polar cap and auroral oval. This is a general mechanism for the formation of auroral arcs due to field-aligned acceleration of electrons through the Knight due to field-aligned acceleration of electrons through the