Unusually elongated, bright airglow plume in the polar cap F region: Is it a tongue of ionization?

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[1] We report an event of unusually elongated, bright airglow plume, which is considered as an optical manifestation of tongue of ionization (TOI) in the central polar cap. This optical structure was detected with an all-sky airglow imager at Resolute Bay (74.73°N, 265.07°E) during a large magnetic storm on December 15, 2006. The absolute optical intensity of the plume was ≈1 kR, which is much brighter than that of non-stormtime polar cap patches. Two-dimensional imaging capability of the all-sky imager demonstrates that some meso-scale structures (≈250–600 km) were embedded within the plume. Simultaneous ion density and drift measurements with the DMSP spacecraft strongly suggest that the plume was extending from the dayside as a narrow stream of dense plasma and thus is an optical manifestation of polar cap TOI. The DMSP data also implies that the possible source of the plume is a narrow stream of storm enhanced density (SED) transported from lower latitudes. The DMSP auroral particle observation demonstrates that the polar cap extremely expanded equatorward during this interval. This extreme expansion allowed the anti-sunward convection to capture plasmas within the SED and deliver them deep into the polar cap as a luminous airglow plume. This observation claims that the plasma transport from the dayside lower latitudes plays an important role in controlling the plasma environment in the polar cap ionosphere during magnetic storms. **Citation:** Hosokawa, K., T. Tsugawa, K. Shiokawa, Y. Otsuka, T. Ogawa, and M. R. Hairston (2009), Unusually elongated, bright airglow plume in the polar cap F region: Is it a tongue of ionization?, *Geophys. Res. Lett.*, *36*, L07103, doi:10.1029/2009GL037512.

1. Introduction

[2] When the interplanetary magnetic field (IMF) is southward, rapid anti-sunward convection driven by the magnetopause reconnection entrains the dense plasma of midlatitude origin into the polar cap and then tongue of ionization (TOI), region of plasma density enhancement at the F region heights, is formed near the dayside cusp [*Moen et al.*, 2008]. TOI has been considered to be a major source of polar patches, which is a chunk of plasma of increased density whose spatial extent is around a few hundreds of kilometers. Recently, first global observations of TOI was presented by *Foster et al.* [2005], who demonstrated that TOI extended from the dayside midlatitude toward the nightside along the streamline of anti-sunward convection. They also showed that the origin of TOI is storm enhanced density (SED) [*Foster*, 1993], which is a longitudinally narrow stream of dense plasma driven by an enhanced convection at the subauroral latitudes known as subauroral polarization streams (SAPS) [*Foster and Vo*, 2002]. More recently, *Yin et al.* [2008] reproduced the large-scale structure of the stormtime TOI by using the algorithm proposed by *Spencer and Mitchell* [2007] and compared its behavior with the airglow observations at the polar cap.

[3] The plasma irregularities are often formed within patches and TOI. These small-scale density perturbations impose a significant scintillation on the communication link from satellites along its path crossing the polar ionosphere. In order to predict the possible effects on the communication system precisely, it is necessary to visualize the temporal evolution of patches and TOI with improved spatial resolution. In particular, it is desirable to examine the behavior of meso-scale electron density (≈100–500 km) features associated with TOI. A major obstacle to conduct such research has been the lack of ionospheric measurements at higher latitudes. In the past studies of TOI, the original GPS-TEC data had to be integrated for at least a few tens of minutes to construct a dense TEC map sufficient for visualizing large-scale structures of TOI, because the spatial distribution of the GPS receivers in the polar cap area is still very sparse.

[4] In this paper, we first report an event of unusually elongated, bright airglow plume observed by an all-sky imager at the polar cap latitude, which is considered as an optical manifestation of polar cap TOI. The data, obtained as OI 630 nm airglow images, give two-dimensional structure of TOI at 2 min time resolution, which allows us to examine how TOI changes its characteristics in shorter temporal scale. In addition, two-dimensional imaging capability enables us to find some meso-scale structures embedded within the TOI. Such structures have never been identified in the past studies, although individual patches have been imaged with an all-sky airglow observations [*Weber et al.*, 1986; *Hosokawa et al.*, 2006, 2009].

2. Observations

[5] An intense magnetic storm occurred on 14–16 December, 2006. The provisional Dst index, as shown in Figure 1, started decreasing around 2100 UT on 14 December 2006 and reached its minimum (−146 nT) at around 0700 UT on 15 December 2006. Our interval of interest, 0230–0430 UT on 15 December 2006 (highlighted in grey

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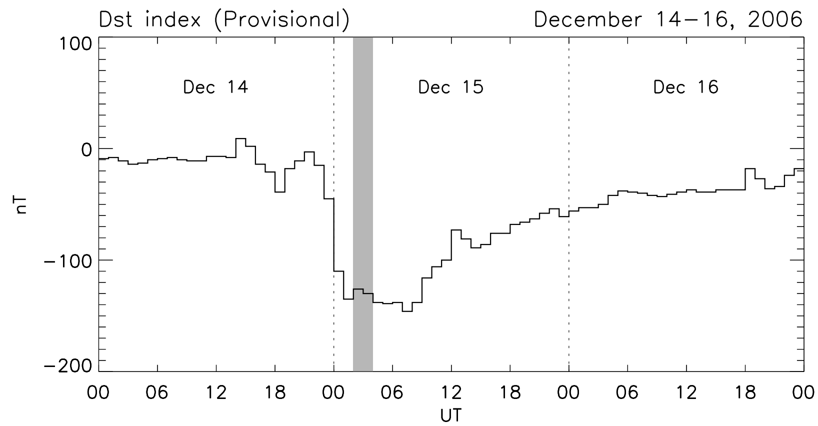

Figure 1. Dst index during the magnetic storm on 14–16 December, 2006. The interval in which elongated, bright airglow plume was observed is highlighted in grey.

in Figure 1), corresponds to the early stage of the main phase of this storm, during which the airglow plume was observed by an all-sky airglow imager at Resolute Bay (RSB; 74.73°N, 265.07°E). The imager has been in operation since January 2005 [*Hosokawa et al.*, 2006] as part of the Optical Mesosphere Thermosphere Imagers (OMTIs) [*Shiokawa et al.*, 2009]. The optical plume was visualized using 630 nm airglow images taken every 2 min with an exposure time of 30 s.

[6] Figure 2 shows time sequences of 630.0 nm airglow images picked at 10 min intervals between 0230 UT and 0420 UT. The airglow plume is observed as a region of enhanced luminosity elongated almost along the noon-midnight line. Note that prominent feature in the equatorward part of the field-of-view (FOV) corresponds to the poleward edge of auroral oval. The plume firstly appeared on the western edge of the FOV at 0230 UT. After this image, the plume moved eastward and then reached the central part of the FOV at 0230 UT. Subsequently, the channel of the plume was located around the zenith for about 1 h although the plume changed its spatial structure very dynamically. After 0420 UT, the plume moved almost off the FOV by 0450 UT because the FOV shifted toward midnight according to the rotation of the Earth. See Animation S1 for the temporal evolution of the plume at a rate of one frame every 2 min.[1] The bright airglow plume may look as a train of patches streaming along a narrow passage across the polar cap, especially during the first half of the interval. However, the airglow structure was not broken into individual parts and was found to be a continuous stream during the second half of the interval (for example, at 0330 UT). Of course, the airglow plume contains meso-scale structures drifting along the stream of the plume. This would correspond to patches. However, the past optical observations in the polar cap area suggested that patches are normally seen as a circular or cigar-shaped individual structure elongated somewhat in dawn-dusk direction. In contrast, the plume shown here is narrow in the dawn-dusk direction and elongated along noon-midnight direction, which infers that there exists a significant difference between this optical plume and usual non-stormtime patches.

[7] *Foster et al.* [2005] found that the electron density within the polar cap TOI was greatly elevated, which suggested that the source of the TOI is the SED transported from the dayside lower latitudes. The current observation demonstrates that the optical intensity within the plume was enhanced up to 1 kR, which is 3–4 times brighter than that of patches. This indicates that the plume observed at RSB is also lower latitude origin and suggests that the plume is an optical manifestation of polar cap TOI. The other important feature is that the spatial structure of the plume is far from uniform. Figure 2 shows that some meso-scale structures existed within the plume although main body of the plume is elongated continuously within the FOV. These smaller-scale patterns are drifting in anti-sunward direction along the structure of the plume. We estimated the typical horizontal extent of the meso-scale features clearly seen in the images in Figure 2 (see Figures 2c, 2d, 2f, and 2l), which shows that the horizontal scale size of the structure ranges from 250 to 600 km. These values are very similar to the spatial scale size of polar cap patches.

[8] All-sky airglow imager data enabled us to well visualize the temporal evolution of the plume. However, it is difficult to see if the plume was really continuous stream of plasma extending from the dayside, because the FOV of the imager is limited. To confirm it, we employ the ion density data obtained by the DMSP F13 satellite passing through the dayside part of the polar ionosphere. Figure 3a shows the 630 nm airglow image at 0410 UT, where the track of DMSP F13 is superimposed. Figure 3d shows the ion density data observed along the track of the spacecraft. The ion density increased from 10^{10} to 11^{11} m^{-3} at 860 km altitude at 0408:10s UT (denoted as "B") and decreased at around 0411:30s UT (denoted as "C"). This interval of elevated ion density is marked by a horizontal line "B–C" on the top of Figure 3d and in Figure 3a. *Foster et al.* [2005] demonstrated by using incoherent scatter radar observations that TOI can be observed even at altitudes higher than 800 km. This means that TOI is not thin in altitude but extends from the lower F region to the topside ionosphere. Then we conclude that the region of enhanced ion density ("B–C") corresponds to the dayside part of the plume observed at RSB.

[9] Comparison of the airglow plume seen over RSB and the region of enhanced ion density detected with DMSP strongly suggests that the plume extended deep into the central polar cap from the dayside and thus is actually an optical manifestation of polar cap TOI. The DMSP observa-

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL037512.

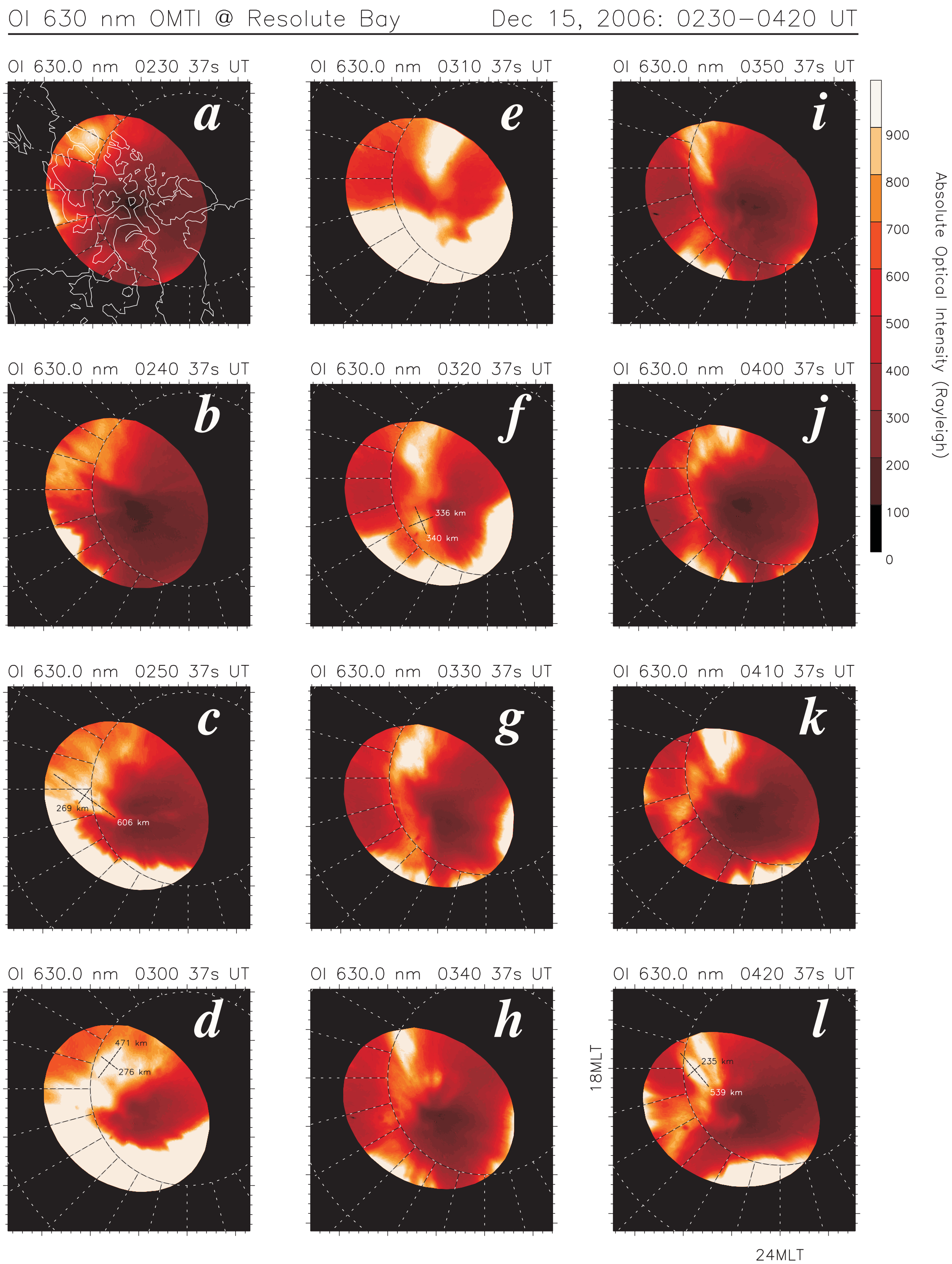

Figure 2. Sequence of 630.0 nm airglow images at 10 min intervals from 0230-0420 UT.

tion also implies that the source of the plume is located at least some degree equatorward of the ion density enhanced region (“B–C”). In general, the dense midlatitude plasma within TOI is captured by the anti-sunward convection in the polar cap area. Thus, it is important to check extension of the polar cap during this interval. Figure 3b shows energy spectrograms of electrons observed by the DMSP F13 spacecraft. Marked enhancements of energy flux of precipitating auroral electrons are identified during intervals before 0404 UT (denoted as “A”) and after 0416 UT (denoted as “D”), which correspond to the electron auroral oval in the dusk and dawn sectors, respectively. In the region sandwiched by “A” and “D”, there exists a region of no auroral particle precipitation, which corresponds to the polar cap. Equatorward boundary of the polar cap along the DMSP track is located at approximately 63° magnetic latitude, that is 10–15° lower than its nominal position. This indicates that the polar cap area, which is composed of anti-sunward plasma

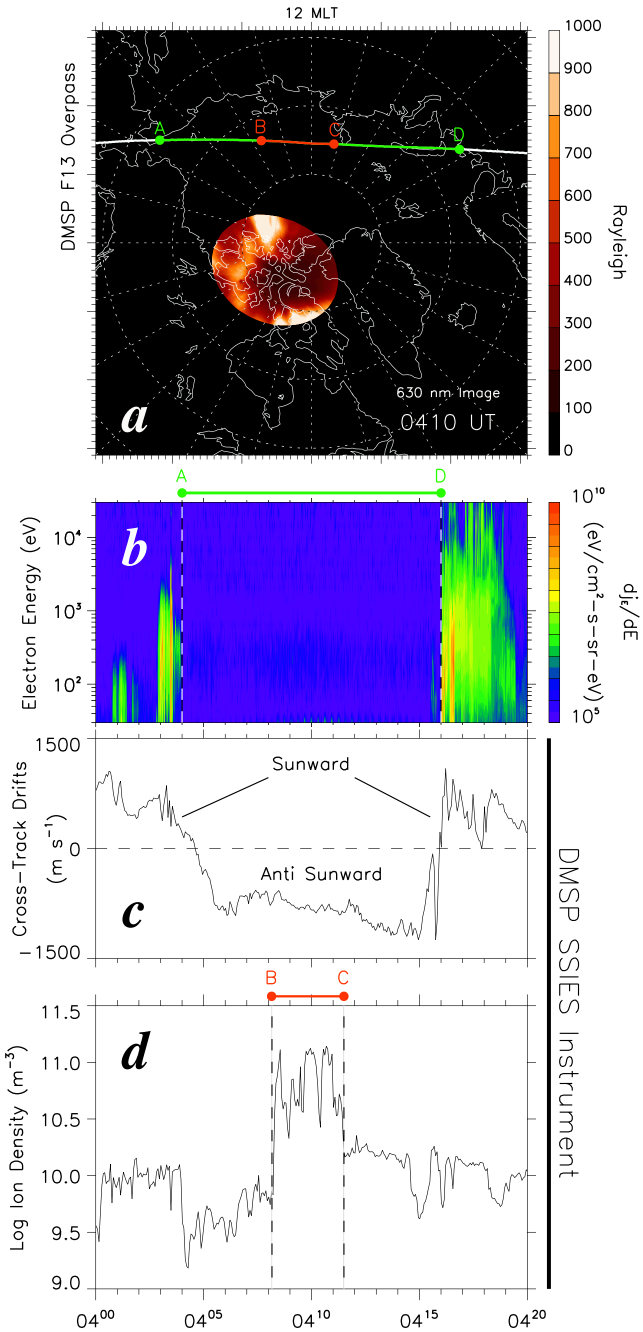

Figure 3. (a) The 630 nm airglow image at 0410 UT. Superimposed line is the track of the overpassing DMSP F13 satellite. (b) Electron measurement from the overpassing DMSP satellite. (c) Ion density measurement from the DMSP satellite.

convection, extended equatorward extremely during the interval of interest. Note that there is no electron precipitation within the region of enhanced ion density. This confirms that the airglow plume is not associated with the precipitating electrons of magnetospheric origin. This evidences that the optical plume is not a polar cap aurora but an optical manifestation of TOI.

[10] The longitudinal width of the region of enhanced ion density is found to be very narrow (≈1400 km along the track of DMSP). In addition to this, Figure 3d shows that the duskward and dawnward edges of the enhanced ion density region are quite sharp. These characteristics suggest that the background anti-sunward convection is increased only within the narrow area of the plume. In other words, the plume may be delivered by a narrow channel of extremely rapid anti-sunward convection extending from the dayside cusp to deep inside the polar cap. In order to confirm this point, we have checked the ion driftmeter measurement by the DMSP spacecraft. Figure 3c shows the cross-track ion drift measurement along the DMSP track. Within the polar cap ("A–D"), the cross-track ion drift has negative values, corresponding to the anti-sunward convection. There is no particular enhancement of the speed of the anti-sunward convection when DMSP passed through the dayside part of the plume. We will discuss this point in detail in the next section.

3. Discussion and Conclusion

[11] The transport of solar EUV ionized plasma in a narrow channel on the dayside is a regular feature and is not a particular storm time phenomenon [*Moen et al.*, 2008]. However, occurrence of TOIs penetrating deep into the central polar cap is generally rare. They are basically stormtime phenomena although SED, which is the possible source of the polar cap TOIs, could be identified at values of Kp as low as 2 [*Foster*, 1993]. The polar cap ionosphere during non-stormtime period is filled with polar cap patches in case the IMF is directed southward. The current observations demonstrated that the optical intensity of the stormtime TOI plume is much brighter than that of polar cap patches. The question addressed here is "what causes the difference in the optical intensities of the TOI and polar cap patches?". We suggest here that extreme expansion of the polar cap during magnetic storm could be a key to answer this question. As shown in Figure 3b, the polar cap area expanded to at least 63° magnetic latitude during this interval. This may allow the anti-sunward convection near the cusp to directly capture the noontime dense plasmas and deliver them deep into the polar cap. If we follow this simple picture, the width of the plume should correspond to that of the anti-sunward flow. However, the DMSP observations demonstrate that the extent of the anti-sunward convection is much wider than that of the plume, which indicates that the dayside source of the plume was already confined in longitude before the anti-sunward flow entrained the source plasmas further into the polar cap. *Foster et al.* [2005] claimed that SAPS field, especially flow in its equatorward part, plays an important role to transport the duskside midlatitude plasma to the noon time cusp as a narrow SED. Our observations suggests that SED occurred also during this interval and dense thermal plasma in the equatorward portion of the afternoon convection cell was transported to the noon time cusp as a narrow SED plume. Once the SAPS field delivers the midlatitude plasmas to the cusp inflow region as a narrow plume, the anti-sunward high-latitude flow is responsible for carrying these plasmas further deep into the central polar cap. This transportation process made the optical intensity of the TOI plume seen over RSB much brighter than that of polar cap patches. Recent paper by *Lei et al.* [2008] have simulated the ionospheric disturbances during the magnetic storm on December 14–15, 2006. They showed that the positive storm occurred in the initial phase of

this storm, which was supported by an enhancement of TEC in the duskside midlatitude zone. Greater optical intensity in our observation is also consistent with the result of their simulation.

[12] Global TEC map presented by *Foster et al.* [2005] gave an excellent view of the two-dimensional large-scale structure of TOI during major magnetic storm. However, spatial and temporal resolution of their GPS-TEC map was not enough to clarify smaller-scale structure embedded within the TOI. We have visualized two-dimensional structure of the smaller-scale feature within the TOI plume with improved spatial and temporal resolution of the all-sky imager. We found that some meso-scale patchy structures were distributed within the main body of the TOI plume. An existence of such kind of meso-scale patchy structures implies that some structuring process is working even within the plume although the TOI plume is not broken into individual parts (i.e., polar cap patches) completely. In the past observations, any smaller-scale structures have not been identified in SED because the GPS-TEC observations do not have the resolution to observe such features. Thus, we do not know if SED plasmas were already structured before they are transported into the polar cap through the cusp inflow region. However, one of the possible explanation for the generation of the structures is that some process puts a pattern on the TOI on the way from the dayside cusp to the central polar cap.

[13] There are several proposed processes through which daytime dense plasmas are detached from continuous TOI as discrete patches, such as the IMF controlled reorientation of the cusp inflow region [*Moen et al.*, 2008], bursty plasma transport from the subauroral latitudes [*Moen et al.*, 2006], in-situ plasma reduction under an intense electric field [*Ogawa et al.*, 2001], and an expansion of the polar cap convection driven by pulsed reconnection [*Carlson et al.*, 2004]. Important thing to remind is that all of the suggested mechanisms employ temporal variation of plasma convection near the cusp to detach patches from TOI. These temporal variations of the speed and direction of the plasma convection in the dayside cusp and inside the polar cap can contribute to the structuring of TOI. In reality, the airglow plume is sometimes elongated along zigzag path (e.g., Figures 2f and 2g). Such kind of zigzag path of the polar cap convection streamline is possibly associated with the temporal variation of the IMF B_y and B_z and/or time-varying reconnection rate. This implies that the temporal variation and/or spatial inhomogeneity of the background plasma convection due to the changes in the IMF could create the meso-scale structure within the TOI plume.

[14] In summary, we present first optical observation of bright airglow structure during a large magnetic storm. The optical structure was elongated in noon-midnight direction as a narrow plume without being broken into individual patches. The observations show that the polar cap plasma environment during a large geomagnetic storm is quite different from the moderately disturbed conditions. In the next series of investigations, we intend to combine the measurements from GPS-TEC, SuperDARN and CHAMP satellite with the current data set, and discuss why the TOI plume was observed as a discrete feature without being broken into polar cap patches. Temporal variation of the IMF orientation and extent of polar cap area will be examined in more detail. Such kind of study contributes to clarify what kind of physical process can break tongue of ionization into smaller parts and generate polar cap patches.

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