A Study of the November 15, 1993 Transpolar Arc

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An arc observed at Eureka (88.9°N, 318°E CGM) on November 15, 1993, was also observed at Resolute Bay (84.5°N, 316°E CGM) and Cambridge Bay (77.6°N, 306°E CGM) and seen to extend from the central polar cap to the nightside oval. The auroral activity continued for 10 hours with its maximum intensity up to 20 kR (557.7 nm). The transpolar arc was mapped into the magnetotail by using Tsyganenko’s magnetic field model (T89). It is found that the source region was located at central plasma sheet boundary layer and extended to the tail lobe. It is also found that there is a sunward electrojet along the transpolar arc, based on analysis of magnetic signatures. The arc occurred during a period of strongly northward IMF Bz and time varying By, from negative to positive, which controlled the motion of the transpolar arc in the dawn-dusk direction.

1. Introduction

Theta auroras were first extensively studied by Frank et al. (1986) using DE-1 and DE-2 satellite images, electric field and particle data; it has become clear that the phenomena coincide with the discrete polar cap aurora (Lassen, 1969; Chiu, 1989). The study showed sunward convection associated with transpolar arcs. The magnetosheath was identified as one of the source regions because of observed hot ions (H+, He++). A bifurcated magnetospheric configuration was employed to explain how transpolar arcs occurred on closed field lines. Conclusions reached by the study of DMSP F6 auroral images and particle data (Meng, 1981; Makita et al., 1988, 1991) and Viking UV images (Craven et al., 1991; Austin et al., 1993) were that transpolar arcs occurred at the poleward boundary of the closed field line region. More observations of theta aurora associated with magnetospheric plasma (Huang et al., 1989) suggested the source region of the theta aurora was located in the magnetospheric lobe region. Elphinstone et al. (1991) used mapping along magnetic field lines to explore the source regions of transpolar arcs.

There also have been extensive studies of polar auroras using ground based techniques (most recently reviewed by Valladares et al. (1994)). The results from these studies have added materially to the excellent global data obtained by satellite observations. Ground based cameras offer higher resolution in general and can provide continuous coverage of auroral events extending through their lifetime, which in some cases is many hours.

An observatory very close to the north magnetic pole has been in operation at Eureka (80.0°N, 274.1°E) since the winter of 1990–91 (Zhang et al., 1993) and continuous observations have been made there through each winter with an all-sky camera and a meridian scanning photometer. Two other observatories at Cambridge Bay and Resolute Bay together with the Eureka observatory form a chain which covers the area from the center polar cap to the poleward edge of the auroral oval. The chain is well located for studies of transpolar arcs.
2. Instrumentation

During the 1993–94 winter the following instruments were operated at the 3 polar stations. An All-Sky Camera (ASC) and a 6-channel Meridian Scanning Photometer (MSP) were operated at Eureka by the University of Saskatchewan. The ASC took auroral images each 4 seconds in a sequence with 557.7 nm, 630.0 nm filters and an open frame. The MSP scans were repeated every 38 seconds with 1 degree spatial resolution. The emissions at 630.0, 557.7, 589.3 and 486.1 nm were monitored with a threshold sensitivity of 5–10 R. Two other ASCs were operated at Resolute Bay and Cambridge Bay by the
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University of Nagoya with images recorded each second. A 3-component flux-gate magnetometer with a 1 Hz sample rate was operated at Eureka by the University of Tokyo.

3. The Transpolar Arc on November 15, 1993

3.1 ASC and MSP observations

An especially bright and long-lived polar arc was observed on November 15, 1993. It first appeared around 0530 UT at about 85° magnetic latitude in the dawn sector of the central polar cap, and it lasted about 10 hours. Figure 1 shows 12 selected images from the Eureka ASC during the period of the event, from 0742 UT to 1218 UT. In these images geographic north is at the top and the sun direction is to the right. The arc was weak, diffuse and stable (about 500 R of 557.7 nm emission) from 0730 UT to about 0900 UT, remaining in the dawn sector. Its intensity then increased to 2-3 kR by 0921 UT and it moved duskward. This was followed by a dawnward motion of the arc between 0930 UT and 1030 UT. Later, it again drifted duskward to the zenith and reached a maximum intensity of 20 kR at 1148 UT. It continued its duskward motion, crossing the north magnetic pole, and then remained in the dusk sector about 85° magnetic latitude until it disappeared in twilight at about 1600 UT. The arc co-rotated with the Earth during its 10 hour lifetime, retaining sun-alignment.

The arc was also recorded by the ASCs at Resolute Bay (74.7°, 265.1°E) and Cambridge Bay (69.1°N, 255.0°E). These imagers had overlapping fields of view with Eureka and allowed latitude coverage extending from the central polar cap to the poleward edge of auroral oval. Figure 2 shows the polar arc as recorded by all three imagers at 0921 UT projected in geographic coordinates assuming an auroral height of 150 km. Here the sunward direction is toward the upper right corner and the arc extends over both Resolute Bay and Cambridge Bay to join the poleward edge of the auroral oval about 0230 MLT. Its extent, seen in the 3 fields of view, was well over 2000 km and the arc was very likely a transpolar arc continuing on to join the dayside oval. With the arc co-rotating with the sun-earth line it left the Cambridge Bay field of view at 1020 UT.

Fig. 2. Images observed at 0921 UT, November 15, 1993 by Eureka, Resolute Bay and Cambridge Bay All-Sky Cameras were overlapped with each other and projected in geographic coordinates.
Fig. 3. Plots of Meridian Scanning Photometer data (630.0 nm and 557.7 nm channels) during the transpolar arc period.
Table 1. $K_p$ index on November 15, 1993.

| UT  | 0130 | 0430 | 0730 | 1030 | 1330 | 1630 | 1930 | 2230 |
|-----|------|------|------|------|------|------|------|------|
| $K_p$ | 3.0 | 3.3 | 1.3 | 1.7 | 1.3 | 1.7 | 3.0 | 4.3 |

Fig. 4. $H$, $D$ and $Z$ components of the magnetic field at Eureka between 1000 and 1400 UT, November 15, 1993.
Figure 3 shows condensed sequential meridian scans from the MSP (2 channels at 630.0 nm and 557.7 nm) for the period 0730 UT to 1400 UT. The MSP co-rotated with the sun and scanned in a direction always perpendicular to the sun-aligned direction. Therefore, the motion of the transpolar arc shown in Fig. 3 was in a dawn-dusk direction. The arc can be traced from the dawn sector through zenith around 1200 UT and finally moving to the dusk sector as illustrated by the dashed line in Fig. 3.

3.2 IMF condition and \( K_p \) level

The IMP-8 solar wind data on November 15, 1993 showed that the IMF \( B_z \) was negative until 0500 UT then went strongly positive (20 nT) for the whole period from 0500 UT until 1800 UT. This encompassed the whole period of the observed transpolar arc. The \( K_p \) levels for the whole day of November 15, 1993, are listed in Table 1. These indicate that the \( K_p \) level was relatively high (\( \geq 3.0 \)) when the IMF \( B_z \) was southward but dropped to 1.3 and 1.7 when the \( B_z \) turned northward.

While the \( B_z \) component remained steadily northward, the IMF \( B_y \) component changed its orientation (from negative to positive and vice versa) two times between 0730 UT and 1030 UT. It finally reached a steady positive state.

3.3 Currents and convections associated with the transpolar arc

Field aligned currents, which are mainly due to the precipitating electrons, and horizontal currents in the polar ionosphere, which are mainly due to convection, may show as magnetic field variations. Such kind of signature was observed by a 3-component magnetometer operated at Eureka. Figure 4 shows the \( H, D, \) and \( Z \) components of the magnetic field recorded at Eureka from 1000 to 1400 UT on November 15, 1993 (frequencies larger than 2 mHz were filtered from the data). There are significant variations on both \( Z \)-component and \( H \)-component traces around 1148 UT when the arc reached its maximum intensity and moved across the zenith at Eureka. There was a 26 nT surge on the \( Z \)-component from negative to positive and a 23 nT enhancement on \( H \)-component. If one assumes these changes were due to a horizontal electrojet current along the arc in the sunward direction at an altitude of 150 km, then the current is calculated to be \( 2 \times 10^4 \) A. There was no clear magnetic disturbance due to the field aligned currents.

The electrojet is very likely caused by polar convections. Observations of polar cap convection by satellite during northward IMF show existence of isolated cells with spatial scales of 100 km in dawn-dusk direction and a few 1000 km in noon-midnight direction (Carlson et al., 1988). Another study showed that distorted 2-cell or multi-cell convections are usually the convection pattern in the polar cap during northward IMF (Moses et al., 1991). Our study suggests that the convection in the polar cap during the transpolar arc might be simply a 2-cell structure.

4. Discussion

4.1 Arc and its motion

The November 15 transpolar arc discussed above had the longest duration of any of the many polar arcs observed at Eureka during the winters 1990–94. The transpolar arc occurred when IMF \( B_z \) was northward. It is evident that the IMF \( B_y \) generally controlled the motion of the transpolar arc since it moved from the dawn to dusk sector as \( B_y \) changed gradually from strongly negative at 0800 UT to strongly positive by 1200 UT. These changes were positively correlated with the motions of the transpolar arc in dawn-dusk direction if a time delay (about 30 minutes) was taken into count.

The possible mechanism for the \( B_z \) control of the motion is that the \( B_y \) component affected the magnetic configuration and current system in the magnetic tail. Asymmetries in the magnetotail related to IMF \( B_y \) are clearly seen in the plasma sheet, based on observations of the IMF (IMP-8) and plasma (ISEE 3) (Kaymaz et al., 1994). They also found that the tail current sheet rotated in a counter clockwise direction for positive \( B_y \) and clockwise for negative \( B_y \). This rotation increased with IMF \( B_y \). This agrees well with the present observation that the larger the IMF \( B_y \), the larger the velocity of the transpolar arc’s motion in dawn-dusk direction.
4.2 Mapping of the transpolar arc

In order to explore the source region of the transpolar arc, the arc was mapped into the magnetotail by using Tsyganenko’s magnetic field model (T89) (Tsyganenko, 1989). Figure 5 shows the transpolar arc mapped in the Y-Z plane (GSM coordinates) at X = -50 and -70 Earth Radii (Re). Figure 5(a) shows that the aurora at the poleward edge of the oval was mapped into the central plasma sheet (CPS) and the plasma sheet boundary layer (PSBL) (Z ≤ 4Re at X = -50Re). The transpolar arc then traced back to the region of Z ≥ 4Re or the PSBL and the tail lobe region. This suggests that the particles from the PSBL were transported to the tail lobe region. This is consistent with a satellite observation that showed the presence of plasma sheet plasma intruding into the tail lobes (Huang et al., 1987). The source region of the oval aurora and that of the transpolar arc are very close to each other, but they are not connected as can be noted in the gap in Fig. 5(a). Figure 5(b) is similar to Fig. 5(a), but for X = -70Re. It suggests that the nightside end of the transpolar arc had its source located in the CPS near Z = 0Re at X = -70Re, which implies that the nightside part of the transpolar arc and therefore the whole transpolar arc was on closed field lines. However, the transpolar arc in the dayside mapped into upper tail lobe region (Z < -34Re at X = -70Re). Taguchi et al. (1994) showed a similar result based on the study of source regions of plasma convection in the polar cap. The model naturally doesn’t give a real-time magnetic field configuration but only a mean magnetic field configuration (Stern and Tsyganenko, 1992). The results shown here based on the T89 model give a general and average picture of the source region of the transpolar arc.

4.3 Possible mechanism

Chiu and Gorney (1983) found that there was a clear intrusion of plasma sheet (~keV) and magnetosheath (~100 eV) plasma into a background low energy polar plasma during periods of polar arcs based on study of S3-3 plasma and electric field data over the polar cap. The energy of the precipitating electrons producing the transpolar arc was above 1 keV as can be deduced from the intensity ratio of 630.0 nm and 557.7 nm emissions (Steele and McEwen, 1990) and suggest that its source region is plasma sheet.

The long time (more than 10 hours) negative IMF B_z before the the transpolar arc occurred around
0730 UT allowed the solar wind particles to penetrate the magnetosphere in the deep tail. The northward turning of IMF $B_z$ caused those solar wind particles to be trapped in the magnetotail lobe and plasma sheet. When IMF $B_z$ is big enough, the magnetotail is well compressed and can trigger some plasma instabilities so the stored solar wind plasma can be accelerated while it moves back to the polar region. New solar wind particles can reach the magnetosheath only with a strong northward $B_z$ component. This may explain the results obtained by both satellite observation and magnetic mapping that the source region of the transpolar arc could be in the plasma sheet, the lobe region and the magnetosheath. As the transpolar arc was not connected to the nightside poleward edge of auroral oval, the source region of the transpolar arc was separated from that of auroral oval and located in the deeper tail. The low level of $K_p$ index during the period of the transpolar arc implied that the central plasma sheet region which connected to the auroral oval was not active. The instability region moved into the deeper tail region due to northward $B_z$.

5. Summary

Major results are listed here based on the study of the 10-hour transpolar arc.

(a) The transpolar arc occurred on closed field lines.
(b) The source region of the transpolar arc was located in both the plasma sheet and the tail lobe regions.
(c) A Sunward electrojet along the transpolar arc suggested a possible simple 2-cell convection pattern over the polar cap for very strong northward IMF $B_z$.
(d) The motion of the transpolar arc in the dawn-dusk direction was consistent with control by the IMF $B_y$.

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