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AKEBONO OBSERVATIONS OF POLAR CAP ARCS —INCLUDING REVIEW—

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Abstract: The auroral arcs seen at very high latitudes have traditionally been called "high latitude arcs" or "polar cap arcs" and have received much attention during last two decades. In this paper we overview the observational signatures of "polar cap arcs" with paying a particular interest in studying more dynamical meso-scale features relating to the polar cap arc phenomena. We next demonstrate recent progress in the issues which have remained unanswered based on the Akebono (EXOS-D) measurements along with simultaneous ground-based observations. We lastly emphasize the importance of polar cap arc phenomena in understanding the basic magnetospheric processes during northward IMF conditions with some implementation plans.

1. Introduction

It has been known that the polar cap *F*-region is unexpectedly active for $Bz>0$ of the interplanetary magnetic field (IMF); there occur auroral arcs. It was MAWSON (1925) who demonstrated detailed signature of these arcs and inferred the arcs show sun-aligned feature. BUCHAU *et al.* (1983) documented that polar cap arcs are predominant during quiet periods and disappear during magnetically active periods. As given in the following section, many case studies and statistical studies have been carried out on the polar cap arcs. With the diversity of the observational results, a variety of names have been given to the auroral arcs seen at very high latitudes; for instance, polar cap arcs, high latitude arcs, sun-aligned arcs, transpolar arcs and theta aurora. ZHU *et al.* (1993) used the term "polar cap arcs" to refer to the general types of auroral arcs seen at very high latitudes. However there seems to be a difference between the theta aurora and polar cap arcs, since the theta aurora is very bright and shows the transpolar feature, whereas the polar cap arcs demonstrate multiple feature with an extension from 100 km to 1000 km, having a rather short life time (OZNOVICH and MCEWEN, 1994). We will use the term "polar cap arcs" to refer to the general type aurora seen in the polar cap region during magnetically quiet periods. Some arguments on the relationship between the polar cap arcs and transpolar arc (theta aurora) will be given later.

In this paper, we will first overview some of the observations carried out in the polar cap region during the magnetically quiet condition. We will next discuss on the unanswered issues on the basis of Akebono measurements along with simultaneous ground based observations.

2. Overview of Meso-scale Observations

2.1. Optical signatures

DAVIS (1960) revealed an existence of the aurora at a very high latitude ($>80°$) which have been mostly sun-aligned, being extended from 100 km up to the size of whole polar cap. A more detailed study on the orientation of arcs inside the auroral oval was made by LASSEN (1973), giving the alignment nearly parallel to the sun-earth direction, based on all-sky cameras operated in Greenland. Dependence of the aurora inside the polar cap on the geomagnetic activity has been studied by LASSEN (1972) in which the polar cap arcs appeared during magnetically quiet periods. Direct comparison with solar wind parameters demonstrated that the occurrence of polar cap arcs was influenced by the sign of Bz (BERKEY and KAMIDE, 1976); namely, the polar cap arc was prevalent when the interplanetary magnetic field was directed northward ($Bz>0$). LASSEN and DANIELSEN (1978) demonstrated that sun-aligned arcs were northward IMF feature and also revealed there has been slight control of IMF By component with respect to the dawn-dusk shift of the arc's location.

Observations by means of equipments aboard an airplane (ROMICK and BROWN, 1971) and in satellites (ANGER *et al.*, 1974; AKASOFU, 1976) were made, showing the very elongated nature of the polar cap arcs. Auroral scanning photometer on board the ISIS-2 satellite demonstrated the characteristics of the polar cap arcs (ISMAIL *et al.*, 1977), that is, polar cap arcs were observed on only a few percent of polar cap paths and appeared most frequently in the magnetically quiet periods.

Based on the image data from DMSP satellite, GUSSENHOVEN (1982) tried to divide polar cap auroras into a few groups; *i.e.* morning side arcs, evening side arcs, and nightside sun-aligned arcs. The occurrence of morning side/evening side aurora was slightly controlled by the IMF By (morning side aurora in $By<0$, evening side aurora in $By>0$ in the northern polar cap). ISMAIL and MENG (1982) classified the polar cap aurora into three types; (1) distinctly sun-aligned polar cap aurora, (2) evening/morning arcs expanded from the ovals, and (3) hook shaped arcs connecting to the ovals. The predominant occurrence for three types was seen in (1) $Bz>0$ and low Kp, (2) $Bz>0$ and recovery phase of a substorm and (3) no specified condition but $Bz>0$. It was also found that the arcs were excited by low-energy (less than 1 keV) electrons based on the ratio of 5577Å to 3914Å emission intensities. This result was confirmed later directly by the particle observations.

Some of the arcs are very bright and extend the entire polar cap region from the dayside to the nightside auroral oval, forming a pattern that resembles the Greek letter "theta" (FRANK *et al.*, 1982). In the past decade, most of observations were focused on this special configuration of the polar cap arc, called theta aurora (FRANK *et al.*, 1986). Detailed description on the electrodynamics as well as particle signatures will be given in the following section. The theta aurora is observed only a few percent of time (FRANK *et al.*, 1986).

Recently CARLSON (1990) found that the polar cap was illuminated very often, close to half of the time (~50%), using a highly sensitive imaging system. The illumination is by the 6300Å emission with its intensity near or exceeding tens of Rayleigh, when the conditions were quiet and the IMF was presumably northward.

2.2. Particle observations

The electrons which reach the low altitude polar cap region have been categorized as "polar rain" and "polar shower" by WINNINGHAM and HEIKKILA (1974). Polar rain is a relatively uniform flux of electrons and is enhanced during southward IMF condition, while polar shower is spatially localized with more intense electron flux (WINNINGHAM and HEIKKILA, 1974) and is enhanced during northward IMF conditions (HARDY, 1984). ISMAIL *et al.* (1977) investigated the electron flux when the satellite passed through the polar cap arc region, giving the accelerated feature of the electrons. WEBER and BUCHAU (1981) compared the polar cap auroras taken at Thule in Greenland with the DMSP particle data and demonstrated a good coincidence between them, confirming that the polar cap arcs were generated by the localized electron precipitations. Based on the simultaneous optical and particle data obtained from ISIS-2 satellite, MURPHREE *et al.* (1983) demonstrated that the average energy of electrons, causing the polar cap aurora, was in a range from 300 eV to 600 eV.

After the finding of the "theta aurora", most of observations were focused on this special configuration of the polar cap aurora. PETERSON and SHELLEY (1984) examined the ion composition in the theta aurora region and found the existence of two components; *i.e.*, one from the ionosphere, and the other from the distant plasmasheet. This observation suggests that cross-polar auroral feature is seen on closed lines which extend to the distant plasmasheet or plasma sheet boundary layer. HOFFMAN *et al.* (1985) investigated a polar cap arc event using AE-C particle and DMSP image data. They demonstrated that the source region was at 5–8 R_E on the field line, threading the plasma sheet or plasma sheet boundary layer. FRANK *et al.* (1986) showed that plasma properties above the transpolar arc are similar to those of plasma sheet boundary layer. ELIASSON *et al.* (1987) studied Viking particle data and found that the electron angular distribution indicating a feature of closed field lines. OBARA *et al.* (1988) examined EXOS-C data together with Viking data and found the conjugacy of the theta aurora, suggesting that arcs are on the closed field line. MAKITA *et al.* (1991) examined the particle data associated with transpolar aurora phenomena on the basis of DMSP observations. They found that the transpolar arcs are located at the poleward edge of the soft particle precipitation region extending from either the dawn or dusk part of the auroral oval precipitation and they are not embedded in the polar rain region. This evidence suggests that the transpolar arcs are located along the poleward boundary of the closed field line region.

In order to investigate the particle precipitations into the polar cap region with respect to the IMF condition, HARDY (1984) performed a systematic survey of the polar shower electrons in the very high latitude region ($>85°$) using the data observed from DMSP satellite together with the IMF data from IMP-8 spacecraft. A key result of his study is that an electron flux exceeded the level of polar rain in almost 50% of the observations. The maximum energy flux and number flux above 85° appear to be spreading in a range from 10^7 keV/cm^{2}s sr to 10^{10} keV/cm^{2}s sr, depending on the magnitude of IMF *Bz* component. The cases when the electron energy flux is rather high, amounting to 10^9–10^{10} keV/cm^{2}s sr, enable the imagers on board the satellite to detect the auroral arc feature. In the cases when the electron energy flux is rather low, it is difficult to detect the arcs in the polar cap region (MURPHREE *et al.*, 1983). OBARA *et al.* (1994) confirmed Hardy's results by using the Akebono (EXOS-D) satellite observations. Both observations are rather consistent with the optical observations by CARLSON (1990), who found that the polar cap was illuminated very often, close to half of the time (~50%), when the IMF was presumably northward.

GUSSENHOVEN and MULLEN (1989) examined the case when the relativistic electrons were observed in the polar cap region together with electrons causing polar cap arc. They demonstrated that relativistic electron precipitation does not change significantly as the sign of *Bz* changes, whereas the population which causes polar cap arcs filled the entire polar cap region during northward IMF condition. The result presented by them supports the polar cap arc formation on open field lines and suggests that the tail lobe plasma is the source of auroral particles at high latitude. Based on DMSP and HILAT observations during northward IMF condition, RICH *et al.* (1990) demonstrated that there is no evidence that the source of the polar cap arc is an intrusion of CPS plasma into very high latitude and suggested that polar cap arc was observed in regions of open field lines.

2.3. *Electrodynamics*

On the basis of S3-2 observations, BURKE *et al.* (1982) found a one-to-one correspondence between the transverse component of the electric field and the residual magnetic field above the polar cap arc, which suggests that upward field aligned current was associated with the polar cap arcs. HOFFMAN *et al.* (1985) inferred that polar cap arcs are associated with upward field-aligned currents, which are carried by energetic electrons moving downward and producing enhanced auroral emissions. BURKE *et al.* (1982), WEBER *et al.* (1989) and HEELIS (1988) showed that the arcs are associated with shears in the convection flow; arcs are located on a negative divergence of the electric field across the arcs. CARLSON *et al.* (1988) combined all-sky image data with the satellite data to study the ordered convection features associated with the polar cap arc. They showed the relation between div$E$ and the electron flux. The upward field-aligned current associated with the arc was calculated from the electric field measured by the radar observations (WEBER *et al.*, 1989). The calculation showed good agreement with the value estimated from the electron flux.

VALLADARES and CARLSON (1991) have reported cases where the estimated field-aligned current is directed upward on the duskside of the arc and downward on the dawnside. The direction of the plasma flow within the arc was anti-sunward in the cases studied by MENDE *et al.* (1988) and VALLADARES and CARLSON (1991). On the other hand, the cases studied by WEBER *et al.* (1989) showed sunward flow within the arc. CARLSON *et al.* (1988) reported the flow observed in the arcs both sunward and anti-sunward. A full understanding of the current closure in the ionosphere has not been achieved for several years.

3. Recent Progress of Polar Cap Arc Study by Means of Akebono Satellites along with Ground Based Instruments at Qaanaaq

There have been unanswered issues;

1) Where is the possible source region of the polar cap arcs?
2) Is the arc electrodynamics coherent over its length and readily mapped up to the high-altitude region from the ionosphere?
3) How do polar cap arcs appear or disappear in response to IMF polarity change?
4) What is the contribution from the ionosphere?

In order to clarify these listed issues, we achieved a collaboration work between Akebono satellite and Phillips Laboratory All Sky Camera (ASC) at Qaanaaq in Greenland (OBARA *et al.*, 1996c). In this chapter we focus on recent progresses in the study of polar cap arc by means of Akebono and ground based equipments.

3.1. *Theta aurora (transpolar arc)*

Before moving to the detailed descriptions on 1) to 4), we will consider the difference between so-called theta aurora (transpolar arc) and multiple polar cap arcs. As has been demonstrated by several authors, the occurrence probability of theta aurora is quite low (less than a few percent). On the contrary, multiple polar cap arcs are seen very frequently, close to half of time (~50%). There is an opinion, saying that the theta aurora seems to indicate a special configuration of the magnetosphere under northward IMF condition (FRANK *et al.*, 1986; MAKITA *et al.*, 1991). MAKITA *et al.* (1991) proposed three possible configurations which lead to the theta aurora. The basic concept in MAKITA *et al.* (1991) is the deformation of the plasma sheet; bifurcation or tilting. If this is the case, the particle producing the theta aurora originates from the plasmasheet or plasmasheet boundary layer. OBARA *et al.* (1988) demonstrated the conjugacy of the transpolar arcs by means of EXOS-C(Ohzora) and Viking satellites, which has been in favor of bifurcation of plasmasheet as proposed by FRANK *et al.* (1986). They also investigated the signature of the precipitating electrons and suggested that they are from plasmasheet or plasmasheet boundary layer. On the basis of images and particle data from Viking satellite, AUSTIN *et al.* (1993) demonstrated that the equatorward region of the transpolar arc was filled with diffuse emissions and this region was threaded by closed field lines. The evidence reported by AUSTIN *et al.* (1993) is in favor of the idea that the transpolar arc appears to be the poleward boundary of an expanded morning/evening aurora distribution which was basically proposed by MENG

(1981).

3.2. *Source of polar cap arcs*

As mentioned by WEBER and BUCHAU (1981), the polar cap arcs are auroral emissions in *F*-layer. The energy is expected to be low (a few hundred eV) causing 6300Å emissions. On the large amount of observational data from Akebono, OBARA *et al.* (1996a) investigated the average energy of precipitating electrons in the polar cap during northward IMF conditions. Figure 1 demonstrated the distribution of average energy of electrons precipitating into the nightside (A) and dayside (B) polar cap regions. The average energies in both nightside and dayside regions were in a range from 100 eV to 400 eV, which is largely consistent with HARDY (1984). On inspection, most of the electrons had low average energy; *i.e.* less than 200 eV, which is closer to that of the magnetosheath/mantle electrons. Hence, OBARA *et al.* (1996a) inferred that the magnetosheath or mantle appear to be likely the source region of the precipitating electrons into the polar cap region. The electrons which were investigated by OBARA *et al.* (1996a) correspond to Type B polar shower events proposed by SHINOHARA and KOKUBUN (1996). They suggest that type B polar showers originates in the solar wind, and the field lines in the polar cap are open even when the IMF directed northward. Recent observations such as OBARA *et al.* (1996a) and SHINOHARA and KOKUBUN (1996) seem to support the scenario for an open field line source of polar cap arcs.

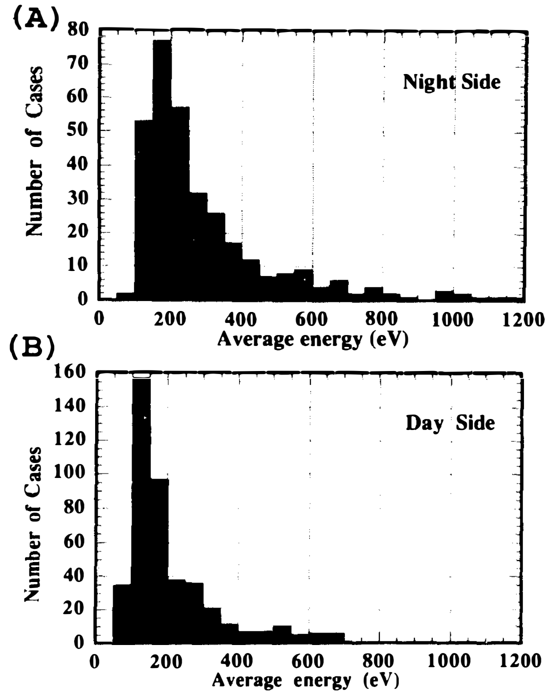

Fig. 1. Average energy of precipitating electrons in the nightside (A) and dayside (B) polar cap regions (after OBARA et al., 1996a).

3.3. *Meso-scale electrodynamics*

A question that remains unclear is how the field-aligned currents of the sun-aligned polar cap arc close in the ionosphere. ROBINSON *et al.* (1987) and VALLADARES and CARLSON (1991) have reported cases where the estimated field-aligned current is directed upward on the duskside of the arc and downward on the dawnside. The direction of the plasma flow within the arc was anti-sunward in the cases studied by ROBINSON *et al.* (1987) and VALLADARES and CARLSON (1991). On the other hand, the cases studied by WEBER *et al.* (1989) showed sunward flow within the arc. OBARA *et al.* (1993) investigated the electrodynamical signature in and around the polar cap arc on the basis of Akebono observations. They clarified that the spike-like variation of the electric field is a common signature and the polar cap arc is seen on the side where div$E$ is negative. On the side where div$E$ is positive, downward field aligned current was found. OBARA *et al.* (1993) also demonstrated that the direction of the spikelike flow is not unique; both sunward flow and anti-sunward flow are observed. The location of the upward field-aligned current and the downward field aligned current with respect to the noon-midnight direction depends on the flow direction in the spike.

Based on the larger amount of the observational data, OBARA *et al.* (1996a) demonstrated that most of electron precipitations occur in the div$E<0$. The variation of the electric field was predominantly seen in the dawn-to-dusk component rather than in the noon-midnight component. This means that the precipitation region is basically sun-aligned. OBARA *et al.* (1996c) further demonstrated the coincidence of the orientation of the arc elongation and the variations of electric field. Top two panels of Fig. 2 show the sunward (X) and duskward (Y) components of the electric field in GSM frame. The satellite traversed the polar cap region from the premidnight to the morning, passing by the north magnetic pole. Since the satellite moved from the duskside to the dawnside, the positive slope of the Y component gives a negative contribution to div$E$. For the X component, the positive slope contributes to div$E<0$, since the satellite moved from the dayside to the nightside. The bottom panel of Fig. 2 demonstrates the energy flux of

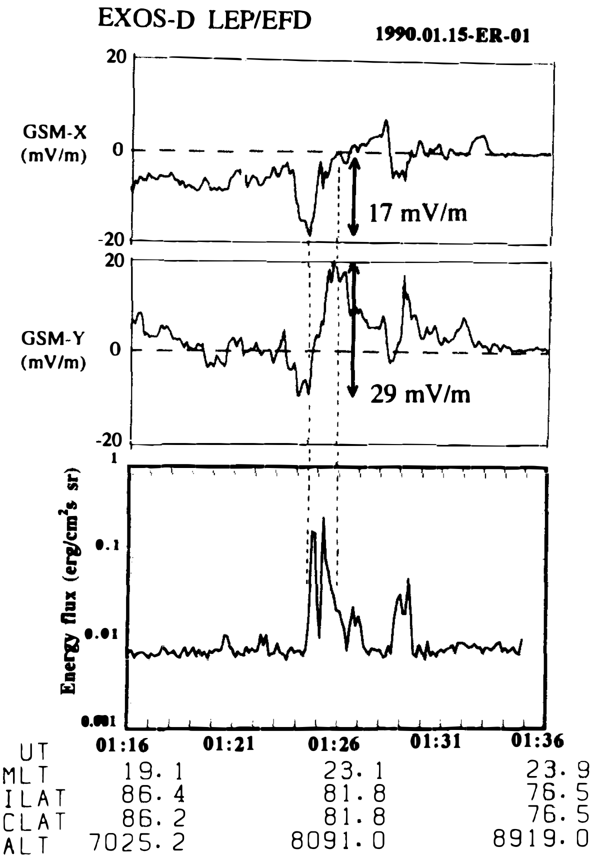

Fig. 2. Summary of the observations from Akebono in the polar cap. Observation was made on January 15, 1990 (after OBARA et al., 1996c).

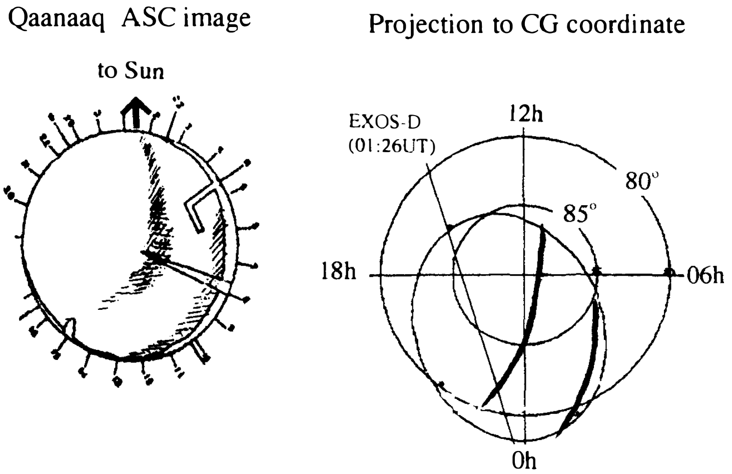

Fig. 3. A sketch of ASC image taken from Qaanaaq at 0125 UT on January 15, 1990 (left) and its projection to the polar map (right).

precipitating electrons. As has been explained in OBARA *et al.* (1996c), the ratio of two variations of the electric field gives the inclination angle Θ with respect to the noon-midnight direction; *i.e.*

$$\tan \Theta = \Delta Ex / \Delta Ey. \tag{1}$$

Substituting $\Delta Ex = -17$ mV/m and $\Delta Ey = -29$ mV/m, we obtain the angle; $\Theta = 30^\circ$ (a plus sign indicates clockwise rotation). At the same time Qaanaaq station observed the sun-aligned polar cap arc. Figure 3 (left) shows an image taken from an all sky camera at 0125 UT on January 15, 1990. We projected this sun-aligned arc to the polar map (see right). At the portion where the satellite encountered this polar cap arc, the inclination was about 30° which was consistent with the value estimated from the electric field variations. We have also confirmed the existence of downward current in the period from 0123:30 to 0124:40 UT.

3.4. *Response to IMF polarity change*

It has been expected that there might be a time delay in the appearance or disappearance of polar cap arcs with respect to the IMF polarity change. OBARA *et al.* (1996c) investigated the delay time on the basis of Qaanaaq ASC observations together with IMF data. Figure 4 demonstrates the appearance of the polar cap arc with respect to the IMF time-variation. The polar cap arc persisted for more than 4 hours on that night. At 0156 UT, the polar cap arc disappeared in association with the southward turning of the IMF at 0055 UT. There was a time delay of 1 hour in this case. At 0133 UT, the IMF turned northward and a polar cap arc appeared at 0235 UT again with a delay of about 1 hour. After the IMF turned southward at 0203 UT, the polar cap arc disappeared at 0308 UT. OBARA *et al.* (1996c) reported another example. They confirmed that the delay time is in a range from 25 min. to 1 hour. Such delay is consistent with the results of RODRIGUEZ *et al.* (1995), who studied a winter of Qaanaaq ASC images and IMF data. The effect of *Bz* reversal, which creates or distracts polar cap arcs, involves the introduction of

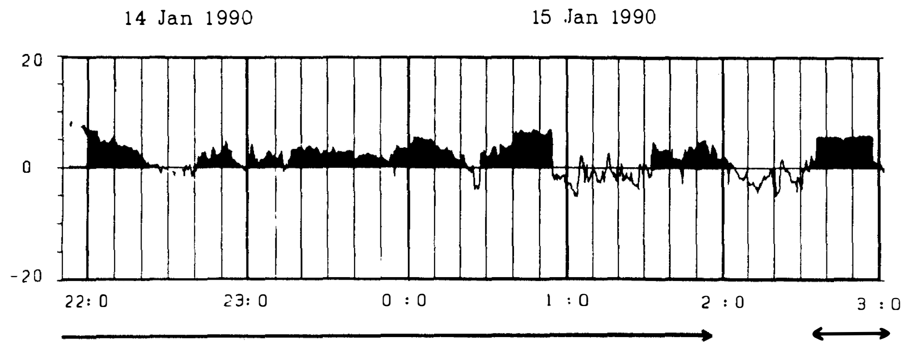

Fig. 4. Time variation of IMF Bz in the night of January 14–15, 1990. Intervals with Bz >0 are marked in black. Bottom allows demonstrate the periods when polar cap arcs were seen from Qaanaaq (after OBARA *et al., 1996c).*

new magnetic flux. Time lags may be determined (in part) by the convection velocity across the polar cap.

The disappearance of arcs is closely related to the decay of a velocity shear, and the polar cap arc decays from dayside (RODRIGUEZ, private communication). But a strange shape of deformation should occur in fading of polar cap arc (OBARA *et al.,* 1996d). This suggests that the polar cap convection changes greatly with IMF polarity change in a short time.

3.5. *Fine structure of the polar cap arc*

A sun-aligned polar cap arc has been considered to be a passive ionospheric manifestation of the dynamics occurring in the magnetosphere; the dynamical features of polar cap arcs are coherently determined by the dynamics in the magnetosphere. This is partly true, but ZHU *et al.* (1993) demonstrated that the ionosphere sometimes plays an important role. The enhancement of the conductivity with spatially small scale will excite Alfven waves, which lead to fine structures in the polar cap arc. ZHU *et al.* (1996) demonstrated a double arc structure in the Qaanaaq ASC images. A new arc appeared beside the primary arc with spacing distance of 90 km, suggesting the existence of downward current between them.

OBARA *et al.* (1996b) investigated the fine structure of the polar cap arc on the basis of Akebono observations. Figure 5 demonstrates a summary of Akebono observations across the polar cap arc. The observation was made in the nightside polar cap. In this case the satellite crossed polar cap arc from dusk to dawn. Top panel in Fig. 5 demonstrates an integrated electron energy flux, showing the split with spacing distance of 75 km. Second panel shows a magnitude of the field-aligned current density, where a positive value corresponds to the upward current. The bottom panel shows the *Ey* (dawn-to-dusk) component of the electric field. Since the satellite traversed the polar cap region from dusk to dawn in this case, a positive slope of the electric field trace corresponds to div$E<0$. The upward current region is strictly in the region with enhanced electron energy flux and div$E<0$. One of the findings by Akebono observations is the existence of downward current region embedded between the upward current regions, which has been predicted by the model calculation by ZHU *et al.* (1993).

4. Summary and Some Future Plans

We reviewed observations of the polar cap arcs during two decades and demonstrated recent progresses carried out by the Akebono satellite together with ground based instrument at Qaanaaq. The polar cap region is filled with lots of sun-aligned arcs during northward IMF conditions. This evidence has been confirmed both from satellite (HARDY, 1984; OBARA *et al.*, 1994) and ground based observation (CARLSON, 1990). Most of electrons which produce auroral luminosity in the polar region are magnetosheath/mantle origins, and the velocity shear is associated with the polar cap arc (OBARA *et al.*, 1996a). Upward current associated with the polar cap arc closes in the ionosphere forming downward current region beside the arc. The flow direction inside the arc is not unique; both sunward convection and anti-sunward convections are observed. The location of the upward current and the downward current with respect to the noon-midnight direction, therefore, depends on the flow direction in the spike.

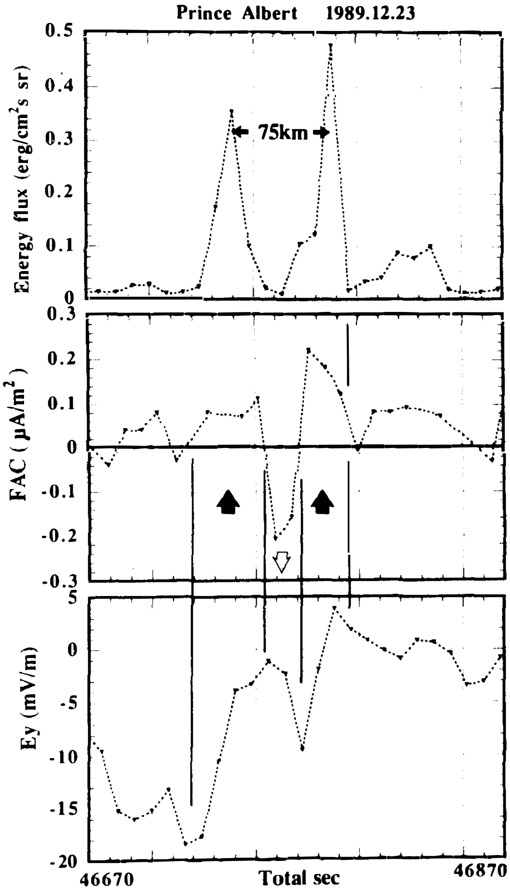

Fig. 5. Summary plots of the electrodynamical signature associated with multiple polar cap precipitation (double arcs). In this case, Akebono satellite traversed the polar cap from duskside to dawnside (after OBARA et al., 1996b).

Though the ionospheric features of the polar cap arc have been clarified, there is still unanswered issue; *i.e.* what is a realistic configuration of the magnetosphere which leads to the polar cap arcs. LYONS (1980) suggested that there occur discontinuities in the magnetospheric convection electric field during northward IMF condition and the region with div$E < 0$ generates electron precipitations into the polar cap region. Lyons' model assumes that the magnetic field line in the polar cap should be open, and the magnetosheath/mantle electrons may reach a low altitude polar cap region. We are speculating that there might occur meso-scale structures generated by a disturbance at the magnetopause boundary, when IMF is northward; a region with a negative divergence of electric field may exist along the magnetosheath flow discontinuities. In order to have a clue on this hyphosesis, much more observations at around the high latitude boundary of the magnetopause should extensively be carried out by the spacecraft such as Interball or Polar.

There is a discussion that the theta auroras may be different from the polar cap arcs. MAKITA *et al.* (1991) proposed possible configuration of the magnetosphere; bifurcation and the tilting of the plasmasheet. Continuous monitoring of the growth and decay of the theta aurora (transpolar arc) should also be needed. There have been lots of all sky cameras in the polar cap region which are maintained by Phillips Lab. and some Universities in US and Canada. There has been an effort to gather individual images to make a global distribution of the oval as well as auroras in the polar cap. HLPS (high latitude plasma structure) group is in charge of this project for the northern polar cap and AGO (Automated Geophysical Observatory) project is going on in Antarctica. Both data will enable us to understand how the high latitude aurora grows and decays in response to IMF changes.

One of the most interesting issues which we would like to understand is a relationship between high latitude arcs and the feature of global convection seen in the polar cap region. The Polar Cap Observatory (PCO) is on the track, yielding the polar cap data by means of incoherent scatter radar (ISR). In Europe and in conjunction with Japan, EISCAT is extending its facilities into the cusp and poleward edge of the oval. With PCO-ISR being proposed, the possibility for studying the entire polar cap will be realized (SOJKA and WEBER, 1996). Supar DARN project is providing convection data by means of the detection of the movement of plasma irregularities in the polar cap. Getting these data together, we will be able to understand the relationship between high latitude arcs and the global convection and further examine the underlying physics, producing the high latitude polar cap arcs.

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