**Multi-instrument observations of multiple auroral arcs in the duskside polar cap region**

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**Abstract:**

Polar cap auroral arcs (PCAs) are one of the outstanding phenomena in the polar cap region during periods of northward interplanetary magnetic field (IMF). In order to gain more comprehensive understanding of the field-aligned plasma transport in the vicinity of PCAs, we have investigated an event of PCAs on November 10, 2005, during which multiple PCAs were detected by a ground-based all-sky camera at Resolute Bay, Canada. During this interval, several PCAs were detached from the duskside oval and moved poleward. The large-scale structure of these arcs was visualized by space-based imagers of TIMED/GUVI and DMSP/SSUSI. In addition to these optical observations, we employ the Cluster satellites to reveal the high-altitude particle signature corresponding to the small-scale PCAs. The ionospheric footprints of the 4 Cluster satellites encountered the PCAs sequentially and observed well correlated enhancements of electron fluxes at weak energies (< 1 keV). The Cluster satellites also detected signatures of upflowing beams of ions and electrons in the vicinity of the PCAs. This implies that these ions and electrons were accelerated upward by a quasi-stationary electric field existing in the vicinity of the PCAs and constitute a current system in the magnetosphere-ionosphere coupling system. Ionospheric convection measurement from one of the SuperDARN radars shows an indication that the PCAs are embedded in the lobe cell during northward IMF conditions.

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**1. Introduction**

Polar cap auroral arcs (PCAs) are one of the outstanding phenomena at the highest part of the polar ionosphere during prolonged periods of northward interplanetary magnetic field (IMF) [Berkey et al., 1976]. Some fractions of PCAs extend from the nightside to the dayside across the central polar cap and form a pattern that resembles the Greek letter *θ*. Such a type of large-scale polar cap arc is called transpolar arcs or theta aurora [see the review by Kullen, 2012 and references therein]. Other arcs are relatively shorter in length and tend to occur either on the duskside or dawnside of the polar cap [Weber and Buchau, 1981]. Such smaller-scale arcs are generally aligned with the noon-midnight meridian and are known to drift in the dawn-dusk direction depending on the sign of the IMF By [Valladares et al., 1994]. Recently, Hosokawa et al. [2011] have showed that about 70% of the small-scale arcs detected with an all-sky airglow imager at Resolute Bay, Canada move in the direction of IMF By. Hosokawa et al. [2011] suggested that the motion of such By-dependent small-scale PCAs can be explained by a model for the motion of large-scale transpolar arc proposed by Milan et al. [2005]. Milan et al. [2005] interpreted the motion of transpolar arc in terms of open flux transport between two polar cap compartments separated by the arc. When the polar cap arc appears during an interval of northward IMF and polar cap (and magnetotail lobe) is divided into two compartments by the arc, the lobe reconnection occurring poleward of the cusp can transport the open flux in one compartment into the other. Such a flux transport can cause the former to contract and the latter to expand. This expansion/contraction of the polar cap compartments can reasonably explain the arc motion in the direction of IMF By. In reality, however, it has never been confirmed if the flow caused by the lobe-reconnection actually controls the motion of small-scale PCAs.

In the past literature, small-scale PCAs have been studied extensively by combining low Earth orbiting satellite, ground-based radars and all-sky cameras because studies of PCAs are of particular importance because they represent dynamical characteristics of their source plasma in the magnetosphere, for example, in the interaction region between the solar wind and magnetosphere or in the boundary between the plasma sheet and tail lobe [see the review by Zhu et al., 1997 and references therein]. In order to conduct such a research, it is highly needed to reveal the field-aligned plasma transport and resulting field-aligned current system above PCAs. Particle signature of PCAs has been studied for a long time by using low Earth orbiting spacecraft [Zhu et al., 1997 and references therein]. Many of the past studies showed an existence of field-aligned potential drop above PCAs. For example, by using data from low altitude spacecraft data, Burke et al. [1982] showed that the electrons causing PCAs have been accelerated through a field-aligned potential drop of 1 kV. A more comprehensive study of fainter and smaller-scale PCAs was carried out by Weber et al. [1989] by using rocket measurements. They demonstrated that a small-scale arc at F region altitude was produced by fluxes of low-energy electrons (< 1 keV), and the field-aligned potentials in the arc inferred from the electron spectra had a maximum value of ~300V. Later, Weiss et al. [1993] showed that three narrow regions of very low-energy (< 100 eV) precipitating electrons were found to be associated with the arcs. These precipitation channels were shown to be associated with small-scale upward and downward current pairs. Although a number of studies have been conducted at low altitude, there has been almost no studies which combines auroral image together with high and low altitude particle observations. For this reason, even to date, very little has been known about the field-aligned transport of electrons and ions above PCAs.

In contrast to the studies of discrete arc in the polar cap region, field-aligned acceleration by quasi-static electric field has been extensively investigated at the auroral latitudes [Ergun et al., 1998 and references therein]. Such an electric field can accelerate magnetospheric electrons downward and ionospheric ions upward, and establishes a current system coupling the ionosphere with the magnetosphere (M-I coupling system). In particular, accelerated electrons precipitating into the ionosphere produce discrete auroral arcs through impact excitation process [Kletzing et al., 1983]. The equipotential contours of the electric field structure generally forms a negatively charged U-shaped or S-shaped profile at altitudes of 5000-8000 km [Ref]. This potential drop, and equivalent converging electric field structure, can create so-called inverted-V structure in the Energy-time (E-t) spectrogram of precipitation electrons at low altitude and outflowing ions at high altitudes [Ref]. Marklund et al. [1994] showed, by using Freja satellite whose apogee is ~1700 km, an existence of diverging electric field structure adjacent to the auroral acceleration region. This region of positively charged potential structure is a counterpart of the auroral acceleration region above discrete arcs. At high-altitude of the diverging electric field region along the field line, spacecraft often observe up-flowing electron beams whose energy well matches an integrated potential difference [Ergun et al., 1998]. Such a region of positively charged potential is known to be located at relatively lower altitude ~1500-3000 km. Electron beams of ionospheric origin in this region carry downward field-aligned currents (FACs) and constitute auroral current circuit together with the upward FACs in discrete aurora and horizontal current in the ionosphere.

In the polar cap region, outflowing ion beams have been observed by the Cluster spacecraft at altitude ranging from 4 to 8 RE during periods of northward IMF [Maggiolo et al., 2006]. An existence of such outflowing ion beams (polar cap ion beams: PCIB) is an indication of the field-aligned acceleration by quasi-static potential structure. Maggiolo et al. [2011] carried out a statistical analysis of 185 PCIB signatures observed by Cluster and revealed that their fundamental characteristics are very similar to those of PCAs, which implies that PCIB is a high-altitude ion signature of PCAs. Teste et al. [2007] observed, by using Cluster, up-going electron beams in the polar cap which surround the outflowing ion beams. These outflowing electron beams were generally detected below 100 eV and typically between 40 and 70 eV, slightly above the photoelectron level. Their energy gain can be explained by the positively charged potential structure below the spacecraft, which is very similar to the one reported in the auroral region [e.g., Marklund et al., 1994]. These studies using high-altitude particle measurements imply that the up-flowing ion and electron beams form a succession of upward and downward current sheets of similar intensity, establishing a local closure of the current system in the vicinity of PCAs.

As introduced above, recent in-situ particle measurements by Cluster at the high-altitude polar cap have greatly contributed to the detailed understanding of the field-aligned plasma transport in the polar cap region. In particular, the observations suggested that both the up-flowing ion and electron beams are closely related to the current system in the vicinity of PCAs. To date, however, there have been no studies which directly compared the optical signature of PCAs and particle measurements at high-altitude. In order to solve this problem, this study aims at combining in-situ plasma measurements by Cluster at the top of the acceleration region and DMSP at low-altitude together with optical observations of PCAs from an all-sky imager (ASI) at Resolute Bay, Canada. The large-scale structure of PCAs was visualized by space-based imagers of TIMED/GUVI and DMSP/SSUSI. By combining data from multiple instruments, we discuss the fundamental characteristics of field-aligned plasma transport in close association with optical signatures of PCAs. In addition, we employ the SuperDARN flow measurements to check if the model for the motion of PCAs proposed by Milan et al. [2005] is applicable not only to large-scale transpolar arcs but also to small-scale PCAs that are more commonly observed in the polar cap region.

**2. Instruments**

**2.1 OMTI all-sky imager at Resolute Bay**

An all-sky airglow imager has been operational at Resolute Bay, Canada (74.73 N, 265.07E; AACGM latitude 82.9) since January 2005 [Hosokawa et al., 2006] as part of the Optical Mesosphere Thermosphere Imagers (OMTIs) [Shiokawa et al., 1999; 2008]. The imager has a number of optical filters for the 557.7 nm, 630.0 nm, 777.4 nm, Na-line and OH-band airglow emissions. The imager has been extensively used for observing PCAs [Koustov et al., 2008; Jayachandran et al., 2009; Hosokawa et al., 2011]. In the present analysis, all-sky airglow images at a wavelength of 630.0 nm (OI, emission altitude ranges from 200 to 300 km), which are obtained every 2 min with an exposure time of 30 s, are employed for visualizing the two-dimensional structure of PCAs. The background continuum emission from the sky is sampled every 20 min at a wavelength of 572.5 nm, and it is used to compute the absolute intensity of the airglow lines [Shiokawa et al., 2000; 2008]. The all-sky imager was operative continuously for periods during the winter months (mid September to late March) when the Moon is well below the horizon.

**2.2 TIMED/GUVI and DMSP/SUSSI instruments**

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**2.3 Cluster spacecraft**

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**2.4 DMSP in-situ measurements**

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**2.5 SuperDARN**

The plasma convection in the vicinity of the PCAs were inferred from the coherent HF radars of Super Dual Auroral Radar Network (SuperDARN [Chisham et al., 2007]) in the Northern Hemisphere. The radars of SuperDARN are capable of detecting backscatter from plasma irregularities at F region heights that are generated by plasma instabilities. Because these irregularities tend to drift at the background plasma velocity, the line-of-sight component of ionospheric convection is measurable by examining the obtained Doppler spectra. During the interval described in this paper, the radars were operating in the fast normal-scan mode. In the current version of this mode, the radar scans through 16 beams every minute, with an integration timeof 3 s for each beam, and these are binned into 75 range gates (separation between the gates is 45 km).

**3. Observations**

**3.1 Optical observations**

During a 4 h interval on November 10, 2005, a series of PCAs was observed by the ASI at Resolute Bay in the duskside polar cap region. Figure 1a displays the 630.0 nm ASI data in a format of the keogram along the south to north cross-section. Near the southward edge of the keogram, a continuous band of bright structure is seen, which could be a possible signature of the poleward edge of the auroral oval (i.e., polar cap boundary: PCB) in the dusk sector. Three outstanding traces of PCAs appeared from the possible signature of PCB, which are denoted as arcs A, B and C, respectively. These PCAs first detached from the PCB and then moved poleward across the zenith of Resolute Bay. Since the arcs were located on the duskside, their poleward motion corresponded to a dawnward excursion of the arc. The arcs A and C were relatively brighter, whose optical intensity was well larger than 500 R. In contrast, the arc B was less prominent, the optical intensity being only 300 R, and disappeared soon after it reached the zenith of Resolute Bay. There can be identified a few fainter arcs in the vicinity of the prominent three, which may imply that regions between the prominent PCAs are not always empty. As mentioned above, the main three arcs, and several adjacent arcs, drifted poleward (i.e., dawnward in this case). A few previous studies [e.g., Valladares et al., 1994; Hosokawa et al., 2011] demonstrated that such a motion of PCAs in the dawn-dusk direction is controlled by the sign of the IMF By. That is, the observed dawnward excursion of PCAs may be caused by the forcing of the upstream IMF.

Figures 1b and c respectively show the IMF By and Bz observed by the ACE spacecraft situated upstream of the Earth (Xgsm ~220 RE). As displayed in the bottom two panels of Figures 1, a solar wind velocity of ~400 km s-1 and a proton density of ~4 cc-1 were measured by ACE during the present interval, which implies a delay of 72 min between the observed IMF feature at the location of ACE and its incidence on the dayside magnetopause. An additional 2 min has been considered to account for the propagation of Alfven waves from the subsolar magnetopause to the dayside polar cap. These calculations were performed following a procedure documented by Khan and Cowley [1999]. The IMF time-series in Figures 1b and c have been shifted accordingly. The IMF Bz (Figure 1c) was directed mostly northward throughout the 4 h interval, which is known to be a typical condition for an appearance of PCAs [e.g., Ismail et al., XXXX]. The IMF By (Figure 1b) was predominantly negative before ~0330 UT. Valladares et al. [1994] and Hosokawa et al. [2011] demonstrated that typical PCAs move dawnward (duskward) when the IMF By is negative (positive). Therefore, the observed dawnward excursion of the PCAs is generally consistent with the westward orientation of the IMF By shown in Figure 1b. At around 0350 UT, however, the arc C stopped drifting poleward and then moved backward toward dusk. This sudden change in the moving direction of the arc could be associated with a switch in the sign of the IMF By at around 0330 UT. Hosokawa et al. [2011] indicated that a certain delay time of ~22 min is needed for the motion of PCAs to respond to changes in the sign of the IMF By. The delay of ~20 min during the present interval is in good agreement with the value suggested by Hosokawa et al. [2011]. This fact further confirms that the dawn-dusk motion of PCAs is strongly dominated by the sign of the IMF By.

In the central part of the present interval, four Cluster spacecraft were situated in the high-altitude polar cap region and their magnetic footprints were located within the field-of-view (FOV) of the ASI. All the spacecraft moved duskward and the PCAs moved dawnward; thus, the footprints of Cluster sequentially crossed the outstanding three arcs 10 times in total. In Figure 1a, the vertical dashed lines mark the timings of the 10 crossings of Cluster across the arcs A, B, and C. Figure 2 gives 8 snapshots of the 630.0 nm ASI images captured when the footprints of Cluster crossed the PCAs. Note that the alphabets in the top of Figure 1a respectively correspond to the panels in Figure 2. Colored circles indicate the footprints of Cluster 1 to 4 as estimated by using Tsyganenko 1996 model [Tsyganenko, XXXX]. In these panels, the original all-sky ASI images have been converted into altitude adjusted corrected geomagnetic (AACGM) coordinates [Baker and Wing, 1989] assuming an emission height of 250 km and then mapped in coordinates of magnetic local time (MLT) and magnetic latitude (MLAT). The magnetic midnight is to the bottom and the dotted circles represent MLAT of 70° and 80°, respectively. In all the panels, PCAs, having a few tens of kilometer width, are identified near the central part of the FOV. The spatial structure of the arcs was roughly sun-aligned, but, more precisely speaking, the arcs elongated toward the cusp. In addition to the thin arcs in the middle of the FOV, brighter and thicker features were always seen at MLAT below 80°. In Figure 2a, for example, such a bright structure in the south seemed to be a signature of the PCB. However, in other images, for example Figures 2b, c and d, PCAs were just detaching from the PCB; thus, it is not straight forward to locate the PCB in the ground-based ASI images. An animation showing the temporal evolution of the PCAs and their relationship with the footprints of Cluster accompanies the electronic version of this paper (Animation 1). The animation better shows the sequential crossings of four Cluster spacecraft across the arcs A, B, and C.

As described above, the ASI data from Resolute Bay well tracked the temporal evolution of the PCAs, especially their dawnward excursion, in a two dimensional fashion. However, the FOV is not large enough for visualizing the entire structure of the PCAs. In order to see the large-scale feature of the PCAs, complemental optical observations by TIMED/GUVI and DMSP/SUSSI have been investigated. Figure 3a shows the DMSP/SUSSI data superimposed on the 630.0 nm ASI data at 0208 UT. The footprints of four Cluster spacecraft are also overplotted for reference. The SUSSI data show a very weak PCA structure in the central polar cap region. Such a signature is more clearly seen in Figure 3b, which is a zoom-up image of Figure 2a. Interestingly, the arc A traveling in the central polar cap was commonly detected by the ASI from the ground and SUSSI from space. The combination of these two instruments demonstrates that the arc A extended well beyond the FOV of the ASI and almost reached the circle of 80° MLAT on the dayside. The DMSP/SUSSI data can also be used for identifying the possible location of the PCB, which is roughly outlined by the dashed circle. Important thing to remind is that all the bright structures near the equatorward part of the FOV of the ASI did not correspond to the dusk side auroral oval (i.e., region of closed field line). In particular, the SUSSI data shown in Figure 3b demonstrate that there were several patchy FUV signals between the arc A and the inferred location of the PCB. This again suggests that the region between the PCA and PCB is not empty. Figures 3c and d show the TIMED/GUVI data superimposed on the ASI data at around 0234 UT and 0410 UT, respectively. At times of these images, the arc B and C were located in the middle of the FOV of the ASI. In these two panels, the location of the PCB is again traced by the dashed circle. The estimated location of the PCB was well outside the FOV of the ASI. This again indicates that some of the bright structures in the equatorward part of the ASI data may not be a signature of the auroral oval, which will discussed in detail in the later part of this section.

**3.2 High-altitude observations**

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One of the primary purposes of this study is to understand the particle signature of PCAs in the very high-latitude magnetosphere that maps to the polar cap. For this purpose, we employ the Cluster PEACE and CIS data obtained during the overpass of four Cluster spacecraft above the three PCAs, the arc A, B, and C. Figure 4 summarizes the electron data obtained from the PEACE instruments onboard the four Cluster spacecraft from 0030 to 0430 UT. For each spacecraft, energy-time spectrograms of electrons in the field parallel direction (i.e., precipitation electrons) are displayed. To avoid contaminations of photoelectrons, electrons having energy flux above 55 eV are plotted. Cluster 1 crossed the arcs A, B, and C at ~0202, 0248 and 0308 UT, respectively. These timings are marked by the colored vertical arrows. At ~0202 UT, Cluster 1 was located above the arc A (Figure 2b) and detected an enhancement of the energy flux of precipitating electrons whose energy was below 300 eV. At ~0248 UT, the spacecraft passed through the arc B (Figure 2f), but the signature in the precipitating electrons was very weak. At ~0308 UT, the spacecraft was located above the arc C (Figure 2g) and again observed an increase in the energy flux of precipitating electrons whose energy was mostly less than 1 keV.

In the PEACE data from Cluster 2, similar structures can be identified. Namely, when the spacecraft crossed the arcs A and C, remarkable enhancements in the energy flux of precipitating electrons whose energy was below 1 keV were detected. Such signatures in the precipitating electrons were much weaker for the arc B. This difference is simply due to the fact that the arc B was much fainter than the arcs A and C. Thus, the optical intensity of the arcs is actually proportional to the energy flux of precipitating electrons. The PEACE data from Cluster 3 were not available before ~0243 UT; thus, the spacecraft could not observe the precipitating electrons associated with the arc A. However, a clear enhancement in the energy flux was detected for the arc C. Cluster 4 crossed the arc C only, but it observed corresponding arc signature in the energy flux. The other important point to note is that the regions between the main three PCAs were not always empty, but often filled with low-energy electron precipitations. For example, Cluster 2 observed an almost continuous band of electron precipitation especially between the arcs A and B. During this interval, the spacecraft was located in the dark area sandwiched by the arcs A and B where no detectable optical structure was seen (e.g., Figures 2b and c). In contrast to this region of weak electron precipitation, the far dawnside of the arc A did not contain any signatures of electron precipitation. For instance, Cluster 1 was overflying the far dawnside part of the arc A before 0130 UT and precipitating electrons were almost empty in this region.

In order to further look into the high-altitude particle signature of PCAs, we focus here on three 20 min intervals indicated in Figure 4 (Interval I for Cluster 1, Interval II and III for Cluster 2). Figures 5a, b and c respectively show the energy-time spectrograms of precipitating, trapped and up-going electrons (> 55 eV) from Cluster 1 during Interval I. Figure 5d displays the pitch-angle distribution of these electrons in the same interval. During this interval, Cluster crossed the arc A at ~0202 UT (Figure 2b). Precipitating electrons causing the arc A were evident during ~5 min interval around the crossing. The width of this region of precipitating electrons is estimated to be XXX km at the altitude of Cluster, which corresponds to YYY km in the ionosphere. This value is roughly consistent with the width of the arc A in the ASI data. Interesting point to note is weak signatures of up-going electrons near the edge of the arc A precipitation, which can be seen in Figures 5c and d. These signatures are probably indications of upwelling electrons in the polar cap first reported by Teste et al. [2007]. However, the signatures of the up-going electrons were quite weak during this crossing; thus, we look into other crossings of Cluster 2 across the arcs B and C.

Figures 5e-h show the same set of data for Cluster 2 during Interval II. During this interval, Cluster 2 crossed the arc B at ~0227 UT. At the time of the crossing, the PEACE instrument detected a blob of precipitating electrons whose energy was below 500 eV. An interesting point is that there existed a series of enhancements in the energy flux of up-going electrons, which is indicated by the arrows in Figure 5g. The energy of these electrons was quite high up to 500 eV, almost comparable to that of precipitating electrons. Figure 5h indicates that the pitch angle of these electrons had a peak at ~180°; thus, these are up-going electron beams. Such upwelling electrons in the polar cap were first reported by Teste et al. [2007] who demonstrated that these outflowing beams were generally detected below 100 eV and typically between 40 and 70 eV, just above the photoelectron level. They explained the generation of the upwelling electron beams by the presence of a field-aligned potential drop below the spacecraft, as in the auroral zone, and further suggested that these upwelling electrons are the main carriers of downward field-aligned current in the polar cap. Figures 5i-l show the same set of data for Cluster 2 during Interval III, in which Cluster crossed the arc C at ~0241 UT (Figure 2e). The PEACE instrument onboard Cluster 2 observed an enhancement of precipitating electrons whose energy was below 1 keV. More interestingly, Figure 5k shows that this region of precipitating electrons was sandwiched by enhancements of upwelling low energy electrons (< 300 eV), which is indicated by the arrows in Figure 5k. The pitch-angle distribution of electrons in Figure 5l again indicates that these low energy electrons had a pitch angle of ~180°. These signatures are very similar to those observed by Cluster 2 during the Interval II.

Figure 6 shows the ion data from the CIS instruments onboard the Cluster 1, 3, and 4 during the interval of the PCA events. Cluster 1 crossed the PCAs three times at ~0202 UT (Figure 2b), ~0248 UT (Figure 2f) and ~0308 UT (Figure 2g). The Cluster 1 ion data show corresponding enhancements in the energy flux in the energy-time spectrogram of all ions (Figure 6b). The energy of these ions ranged roughly from 100 eV to 10 keV. The pitch-angle distribution of these ions shown in Figure 6a indicates that there was a beam component in the direction anti-parallel to the magnetic field (i.e., up-going direction in the northern hemisphere) superimposed on the isotropic hot population. Such a signature of outflowing ion beams in the polar cap has already been reported by Maggiolo and co-workers [Maggiolo et al., 2006; 2011; 2012]. They suggested that these ion beams are locally accelerated by quasi-static electric field structures with a field-aligned potential drop extending up to 5 RE. Maggiolo et al. [2012] suggested that the outflowing ion beams in the polar cap are closely associated with small-scale PCAs by comparing the data from Cluster with that from TIMED/GUVI. Maggiolo et al. [2011] pointed out that the existence of the background isotropic ion population suggests that the origin of the small-scale PCAs is in the plasma sheet. In the Cluster 3 ion data (Figures 5c and d), similar signatures are seen at the times of the PCA crossings. That is, there were outflowing ion beams superimposed on isotropic hot population. In the data from Cluster 4 (bottom two panels of Figure 5), which only measured protons, there existed a combination of isotropic ion population and outflowing ion beams when the spacecraft crossed the arc C.

In order to further investigate the high-altitude ion signature associated with the PCAs, we focus here on the Cluster 3 data during a 2 h interval from 0152 to 0352 UT. Figures 7a and b show the ion data from CIS in a format of pitch-angle distribution and energy-time spectrogram, respectively. Figure 7b again indicates that Cluster 3 observed ions whose energy ranged from 100 eV to 10 keV when it crossed the arcs A, B, and C. Figure 7a demonstrates that the pitch angle of these ions had a beam component at ~180° above the arcs. This again implies that ions were escaping from the ionosphere towards the magnetosphere above the PCAs, which is consistent with the findings of Maggiolo et al. [2012]. Figure 7c shows the energy-time spectrogram of up-going ions, which implies that the average energy of the outflowing ion beams ranged from 100 eV to 1 keV, mostly slightly less than 1 keV. Figure 7f shows that the electric field associated with the PCAs did not show a typical bipolar signature but rather a mono polar variation. If the acceleration is caused by a quasi static electric field, it suggests that the electric potential have an S-shape instead of a U-shape. Assuming such an S-shape equipotential structure, we estimate the field-aligned potential drop from the electric potential variation along Cluster orbit by removing a sliding average (Figure 7d). The derived potential drop is in relatively good agreement with the energy of the outflowing ion beams.  
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**3.3 Low-altitude observations**

In addition to the Cluster observations in the high-altitude polar cap, we have used low-altitude particle measurements by the DMSP spacecraft during the present PCA event. Figure 8a shows the track of the DMSP F16 spacecraft superimposed on the ASI image at 0210 UT. DMSP F16 was cutting through the afternoon sector of the polar cap from the duskside toward the dayside cusp. During this interval of DMSP overflight, the ASI at Resolute Bay was observing the arc A in the duskside central polar cap; thus, the footprints of DMSP F16 were not well inside the FOV of the ASI. However, the simultaneously obtained DMSP/SUSSI data in Figure 8b indicate that the arc A extended towards the cusp and almost reached the circle of MLAT 80° which was very close to the footprints of DMSP F16. This enabled DMSP F16 to observe the particle signature of PCAs at low-altitude. Slightly before the time of the image (0210 UT), Cluster 1 crossed a different part of the arc A in the central polar cap area (Figure 2b). Figures 8c and d respectively show the electron and ion energy spectrograms from DMSP F16 for a 10 min interval from 0204 to 0214 UT. During the first ~1.5 min and last 3 min intervals, electrons having at least 1 keV energy were seen, which should be a signature of the main auroral oval [e.g., Milan et al., 2003]. By using this simple criteria, we estimate the MLAT of the PCB as ~76° on the duskside and ~77.5° on the dayside. These values are roughly consistent with the location of the PCB inferred from the DMSP/SUSSI data in Figure 8b. Within the polar cap region, a number of structured precipitations of electrons whose energy is well below 1 keV were detected, some of which must be signatures of the PCAs observed by the optical instruments. In particular, a characteristic structured series of precipitations was seen between 0210 and 0211 UT, during which DMSP F16 was passing through the dayside part of the arc A. We will look into the data during this interval later in this section. The other thing worth introducing is that two outstanding inverted-V type precipitations were observed from 0206 to 0207 UT in a region 1-2 degrees poleward of the PCB; thus, they must be signatures of bright optical feature seen near the equatorward edge of the ASI FOV. This suggests that these bright structures in the ASI data were not a direct signature of the auroral oval, but a polar cap arc already detached from the main oval.

In order to see the particle signature of PCAs at low-altitude in detail, we plot the DMSP F16 data for a 3 min interval from 0209 to 0212 UT in the bottom three panels of Figure 8. During this 3 min interval, DMSP F16 overpassed the dayside part of the arc A and observed precipitation of ions and electrons associated with the PCA. In Figures 8e and f, electron and ion energy spectrograms are shown. In the electron spectrogram, 5 regions of electron precipitation can be identified, which are denoted as 1-5 in the top of the panel. Although we cannot directly associate these electron precipitations with the optical signature of the arc A, these structures should have corresponded to the fine-scale arc structure within or in the vicinity of the arc A. In the ion data, there existed an almost continuous band of precipitation from 0210 to 0211 UT. Interesting to note is that the energy flux of ions is found to be less intense within the 5 regions of electron precipitation. This suggests that there should have been an electrostatic potential structure above the arc, which accelerated electrons and decelerated ions, and eventually created these characteristic feature. The average energy of electrons in the 5 precipitation regions was ~300 eV. Cluster 1 observed the high-altitude signature of the different part of the arc A. The average energy of the precipitation electrons was as large as 200 eV. Thus, it is suggested that the field-aligned potential drop above the arc A was not larger than 100 eV. We will discuss whether this value is enough to accelerate the outflowing ion beams in the Discussion section. In Figure 7g, DMSP F16 magnetic field data in the cross track direction are displayed. Since the spacecraft flew from the duskside towards noon, the cross track component of the magnetic field perturbation represents FACs in the vicinity of the arc structure. In the panel of the magnetic field observation, the direction of FACs is indicated by the vertical arrows. Upward FACs are seen in the 5 regions of electron precipitation, while the downward FACs are distributed adjacent to them (i.e., in regions between the arcs). Such successive sheets of FACs are well consistent with the particle signature at low-altitude.

**3.4 Ionospheric convection measurements**

In addition to the low altitude observations of DMSP, we also employ the SuperDARN plasma drift data to see the background convection in the vicinity of the PCAs, which will be important information for discussing the mechanism causing the duskward motion of the PCAs during the present interval. Figure 9 shows selected snapshots of the line-of-sight Doppler velocity data obtained from the Kodiak SuperDARN radar between 0132 and 0148 UT. The Kodiak SuperDARN radar overlooked the FOV of the ASI at Resolute Bay. During this time interval, the ASI observed the arc A in the middle of the FOV. The two dimensional maps of the line-of-sight velocity data show that the convection was sunward on the duskside of the arc A and anti-sunward on the dawnside. In Figure 8b, for example, reddish pixels are seen in the equatorward side of the arc, which corresponds to the velocity away from the radar, i.e., roughly anti-sunward. In the poleward side of the arc, there are bluish pixels indicating velocity towards the radar, i.e., roughly sunward. Similar structures are also seen in other panels. The magnitude of the line-of-sight velocity in the region of anti-sunward flow was as large as 500 m s-1. If we interpret this anti-sunward flow on the duskside of the arc as a part of the lobe-cell, the open magnetic flux in the other side (i.e., dawnside) of the arc is transported into the region between the arc A and polar cap boundary on the duskside. This results in an enhancement of open flux on the duskside of the arc A and eventually the arc A moves dawnward. We will discuss the validity of the model in more detail in the Discussion section.

**4. Discussion**

Rob, Dominique, Romain: I had not time to complete this part. I’ve just listed up my ideas about what should be discussed. Please let me know what you think about the following points of discussion.

**4.1 Field-aligned plasma transport in the vicinity of PCAs**

Mention the observed weak electron precipitations above the arcs, a few hundreds of eV  
- Timing is almost perfect, but sometimes delayed by a few min, maybe due to the accuracy of mapping  
- Flux and energy were most intense for the arc C, and weakest for the arc B, consistent with the luminosity

Does the acceleration region really exist above the PCAs?  
- Mention PCIB in the Cluster CIS data, they are always there, inverted-V signature can be seen?  
- Mention DMSP data, is there any inverted-V signatures in the electron E-t diagram? Blobs are too small?  
- Mention the nested structure of ion and electron precipitations in the DMSP data, negative potential stops   
 the ions to precipitate? Adjacent positive potential prevents electrons from precipitating?   
- Mention the Cluster electric potential data, potential is not U-shape but S-shape  
- The answer might be like “there was a weak S-shaped acceleration region above the sub-visible PCAs”

Estimate the potential drop for both the acceleration region and return current region  
- Value: 100 eV or 200 eV or 1 kV? Smaller than usual? [Ref] If so, is it consistent with 557.7/630.0 ratio?  
- Discuss the height profile of the acceleration region, in particular its upper boundary, 5 or 7 or 9 RE?  
- Comparison with the auroral zone cases, what is the difference? Potential value? Scale size? Height?

Discuss differences between low and high altitude using Cluster and DMSP conjunction  
- For acceleration region: difference in energy flux, difference in average energy  
- Spatial structure: fine-scale structures are seen at low altitude, only a large structure at high altitude?  
 If so, what is the reason for the difference

Why the up-going electron beams were not always observed?  
- Depending on the spacecraft potential? Sometimes masked and sometimes observed?  
- What is the condition for them to be observed?  
 Observed only above brighter arcs? or large-scale arcs?

**4.2 Open/closed issue?**

We should leave this part undiscussed for the Romain’s next paper. Please let me know what you think.  
Mention isotropic ion population behind PCIB, always there in the current case: indication of plasma sheet?  
- It may be interesting to estimate plasma beta by using the moment data from Cluster, Romain?

Mention double loss cone structure if it exists: indication of closed field line?  
- May need to show the distribution function, Dominique?  
- Situation may be different arc by arc: open/closed issue is very difficult to answer…

Mention precipitation ions in the DMSP data: maybe a signature of closed field line? Why? [Ref]

In the region between the optical arcs, there are continuous electron precipitations  
- Expansion of the oval? Hose-Collar structure?  
- Thickening of LLBL toward the pole? [Ref: Yongliang’s paper? Onsager’s paper?]

Where is the source of PCAs, open or closed?  
- Mix: LLBL [Echim et al., GRL, 2009], Velocity shear-FAC-PCA, mixture of open/closed, KHI?  
- Open: HLBL: an idea of Dominique, a boundary between hot PS and cold lobe [De Keyser, 2010]

**4.3 Large-scale motion of PCA and its association with the background convection**

SuperDARN flow cannot resolve the converging electric field near the arc due to poor spatial resolution  
- The flow should be large-scale background flow

Sunward flow in the duskside side of the arc A: flux is transported from the dawnside  
- Employ Steve’s model [Milan et al., 2005] for the dawnward motion of the small-scale PCAs  
- Stress that Steve’s model is valid for smaller-scale PCAs

Many reports of sunward flow at TPA [Cumnock et al., 2001; Liou et al., 2005; Eriksson et al., 2005]

**5. Summary**

Studying polar cap aurora is very fun!

**Acknowledgements:**

Thank you very much, ISSI.

**References**

References are not perfect at all, I will revise this part before submission.

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**Figure Caption**

Figure 1:   
(a) 630.0 nm keogram along south to north cross section during a 4 h interval from 0030 to 0430 UT on November 10, 2005. (b-e) Time-series of the IMF By, Bz, solar wind Vx and proton density obtained from the ACE spacecraft shifted by 72 min to account for the solar wind propagation delay from the spacecraft to the dayside polar cap

Figure 2:  
Snapshots of the 630.0 nm ASI images captured when the footprints of Cluster crossed the PCAs. The images are shown in MLAT/MLT coordinates, and the absolute airglow intensity is scaled in units of Rayleigh. Magnetic midnight is to the bottom, and the dashed circles represents contours of MLAT of 70° and 80°, respectively. The colored circles respectively indicate the footprint of the four Cluster spacecraft calculated by using Tsyganenko 96 model.

Figure 3:  
(a) DMSP/SUSSI data superimposed on the 630.0 nm ASI data at 0208 UT. The footprints of the four Cluster spacecraft are also shown for reference. The polar cap boundary inferred from the SUSSI data is drawn by the dashed line. (b) zoom up image of Figure 3a. (c) TIMED/GUVI data superimposed on the ASI data at 0234 UT. (d) TIMED/GUVI data superimposed on the 630.0 nm ASI data at 0410 UT.

Figure 4:  
Summary of the electron observation by the PEACE instrument onboard the four Cluster spacecraft during a 4 h interval from 0030 to 0430 UT. For each spacecraft, energy-time spectrograms of precipitating electrons (> 55 eV) are shown. The vertical arrows mark the timings of the Cluster crossing of the PCAs.

Figure 5:  
Summary of the PEACE data for three intervals (Interval I, II and III) indicated in Figure 4. (a-c) E-t spectrograms of precipitating, trapped and up-going electrons (> 55 eV) for Interval I, (d) pitch-angle distribution of electrons (> 55 eV) for Interval I, (e-h) same data for Interval II, (i-l) same data for Interval III.

Figure 6:  
Summary of the ion observations by the CIS instrument onboard Cluster 1 (a,b), Cluster 3 (c,d) and Cluster 4 (e,f) from 0010 to 0430 UT. For Cluster 1 and 3, pitch angle distribution and energy-time spectrogram of all ions are shown. For Cluster 4, pitch angle distribution and energy-time spectrogram of protons are shown.

Figure 7:  
Romain: Please describe the caption for Figure 7, especially for the bottom 3 panels.

Figure 8:  
(a) Overpass of DMSP F16 superimposed on the 630.0 nm ASI image at 0210 UT, (b) same as Figure 7b except for the DMSP/SUSSI data overlaid. (c, d) Energy-time spectrogram from DMSP F16 during 10 min interval from 0204 to 0214 UT. (e, f) Energy-time spectrogram from DMSP F16 during 3 min from 0209 to 0212 UT. (g) Cross-track component of the magnetic field data from DMSP F16. The direction of FACs is indicated by the vertical arrow.

Figure 9:  
Line-of-sight velocity data from the SuperDARN Kodiak data superimposed on the 630.0 nm ASI image from Resolute Bay.