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Multiple polar cap arcs: Akebono (Exos D) observations

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Abstract. Akebono (Exos D) observations demonstrate that polar cap arcs sometimes have a fine structure, that is, multiple (double or triple) arcs with spacing of a few tens of kilometers. The multiple polar cap arcs are dominantly observed in the nightside polar cap region, suggesting that low background conductance favors the appearance of the structured arcs. A relationship between the spacing and the average energy of the precipitating electrons is investigated. Results show that a higher energy leads to a wider spacing. Akebono observations also show the existence of a downward current region embedded between upward current regions (arcs). Comparison of the observations with results from a coupled magnetosphere-ionosphere Sun-aligned arc model is made, which shows good qualitative agreement between the modeling and observational results on the spacing-energy dependence and the effect of background ionospheric conductance.

Introduction

The electrons reaching low altitudes in the polar cap region were categorized as "polar rain" and "polar shower" by *Winningham and Heikkila* [1974]. Polar rain is a relatively uniform flux of electrons that is enhanced during southward interplanetary magnetic field (IMF) conditions [*Mizera and Fennell*, 1978]. A polar shower is a spatially limited (localized) and more intense electron flux [*Winningham and Heikkila*, 1974] that is enhanced during northward IMF conditions [*Hardy*, 1984]. Polar showers with very high downward fluxes have been identified as polar cap arcs. In the past decade many observations focused on the measurements of the electrodynamical signatures of the polar cap arcs [*Burke et al.*, 1982; *Carlson et al.*, 1988; *Weber et al.*, 1989; *Valladares and Carlson*, 1991; *Obara et al.*, 1993]. These studies have shown that a large velocity shear was associated with the very intense electron precipitation. From the Akebono satellite observations, *Obara et al.* [1996] found that (1) most of the intense electron precipitation was seen in a div$E < 0$ region, and (2) the dawn-to-dusk component of the electric field is the major contributor to the negative div$E$. These results suggest that localized electron precipitation in the polar cap region should be Sun-aligned and that the satellite traversed a Sun-aligned arc structure [*Obara et al.*, 1996]. The polar cap arc sometimes has an internal structure, that is, multiple (double or triple) arcs with spacing of a few tens of kilometers [*Zhu et al.*, 1994]. Recently, multiple polar cap arcs have attracted much interest because of the connection between multiple features and the magnetosphere-ionosphere (M-I) coupling processes. Such a feature, that is, bifurcation of the polar cap arc, was theoretically predicted by a time-dependent M-I coupling model of polar cap arc [*Zhu et al.*, 1993; *Sojka et al.*, 1994]. The model calculation produced some interesting results, including a short timescale for the arc formation, cross-arc plasma transport, local closure of the arc currents, and a tendency for a single arc to split into multiple structures [*Zhu et al.*, 1993].

Akebono (Exos D) is a polar-orbiting satellite that performs high-resolution measurements of both particle precipitation and electric fields. This provides us a unique observational tool for the study of the electrodynamics of multiple polar cap arcs. It also complements the ongoing ground-based observational and theoretical studies of the multiple arcs. The

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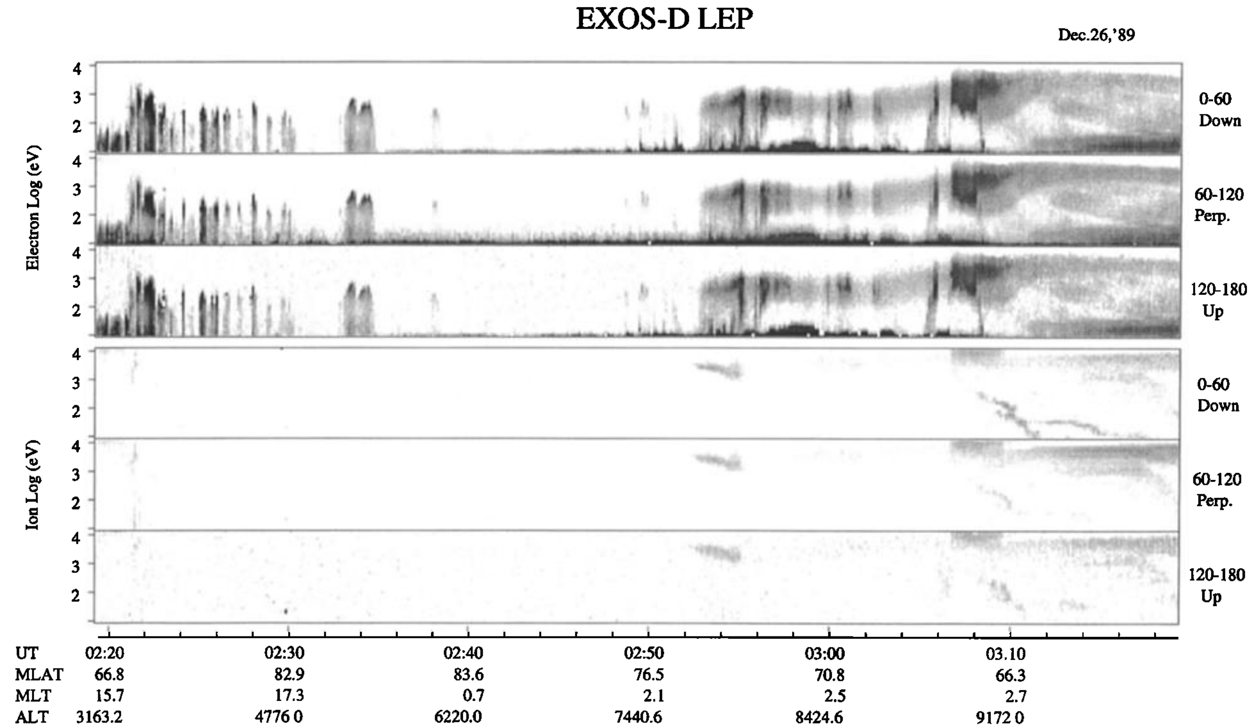

Figure 1. Akebono energy-time diagrams for electrons (top three panels) and for ions (bottom three panels) sorted by the pitch angles. Energy range is from 10 to 16 keV for both species, and the energy is logarithmically scaled in the vertical axis. Orbital parameters are given in the bottom of the figure. MLAT, MLT, and ALT correspond to magnetic latitude, magnetic local time, and altitude, respectively. Bifurcated electron precipitation fluxes are observed at around 0234 UT. Observation was made on December 26, 1989.

purpose of this paper is to present Akebono observations of multiple polar cap arcs and to compare them qualitatively with the theoretical predictions of *Zhu et al.*'s [1993] M-I coupling model of polar cap arcs. As demonstrated by *Zhu et al.* [1993], the ionosphere plays an important role in the formation of polar cap arcs, the appearance of multiple arcs, and the spacing of multiple arcs. There are still many theoretical issues associated with the polar cap arc phenomena remaining to be answered, and theoretical modeling will be very essential for further understanding of the physics of polar cap arcs. In this paper we focus on the electrodynamical features of multiple polar cap arcs with various spacing and compare the in situ observations from Akebono (Exos D) with model predictions in a qualitative fashion.

Akebono Observation of the Multiple Structure of Polar Cap Arcs

The Exos D satellite was launched from Japan on February 22, 1989, into an orbit with initial apogee of 10,500 km, perigee of 270 km, and initial inclination of 75.1°. The Exos D satellite was renamed "Akebono," meaning daybreak, after launch. On this satellite, eight scientific instruments were installed. We will use particle data [*Mukai et al.*, 1990], electric field data [*Hayakawa et al.*, 1990], and magnetic field data [*Fukunishi et al.*, 1990] to investigate the fine electrodynamical structure of polar cap arcs.

Figure 1 shows an example of a bifurcated electron precipitation in the polar cap region. The top panel displays the electron spectra for pitch angle ranges of 0°–60° (precipitation), 60°–120° (perpendicular), and 120°–180° (upward), and it is followed by the ion spectra for the same ranges of pitch angles. The energy is logarithmically scaled in the vertical axis, covering an energy range from 10 eV to 16 keV for both species. At around 0234 UT we can see spatially bifurcated electron precipitation. The split is very clear in the peaks with respect to the energy. On the contrary, we can hardly see the separation in the low-energy (~100 eV) portion, which is essential for the definition of the bifurcation, since the single arc likely splits into two structures. The spacing in this case is about 70 km with respect to the dawn-to-dusk direction. This spacing has been determined by mapping the precipitation down to 120 km. The optical signature at 630.0-nm emission should be seen near 250 km altitude. The reason why we chose an altitude of 120 km is for comparison with the theoretical work of *Zhu et al.* [1993]. In the model calculation [*Zhu et al.*, 1993] the ionosphere was treated as a two-dimensional slab with an integrated conductivity. The maximum of the altitude-dependent Pedersen conductivity is most likely located near 120 km, since the *E* layer conductivity is greater than the modestly increased *F* layer conductivity, and the field-aligned currents are strongly connected to the Pedersen conductivity increase at that altitude. *Zhu et al.* [1994] showed the images of polar cap arcs with spacing taken from the Qaanaaq station in Greenland. They named polar cap arcs with narrow spacing as "multiple arcs." Though we do not have simultaneous images, it is likely that Akebono traversed multiple polar cap arcs. We hereafter refer to the bifurcated electron precipitations observed by Akebono as "multiple polar cap arcs."

By using about 100 passes during the period from November 1989 to April 1990 we surveyed the multiple structure of the polar cap precipitation. In total we found 19 cases. In general, we could see several polar cap arcs in one pass. The occurrence probability of the multiple structure was about a few percent. Figure 2 demonstrates the distribution of spacing of the multiple polar cap arcs, ranging from 30 to 100 km with a center value of 70 km. Exact locations where the multiple polar cap precipitations were observed are plotted on the polar map (see Figure 3a). It is interesting to see that all the polar cap precipitations

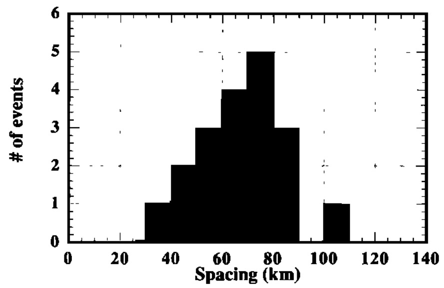

Figure 2. Distribution of arc spacing observed by Akebono satellite. Spacing is in a range from 30 to 100 km with a center value of 70 km.

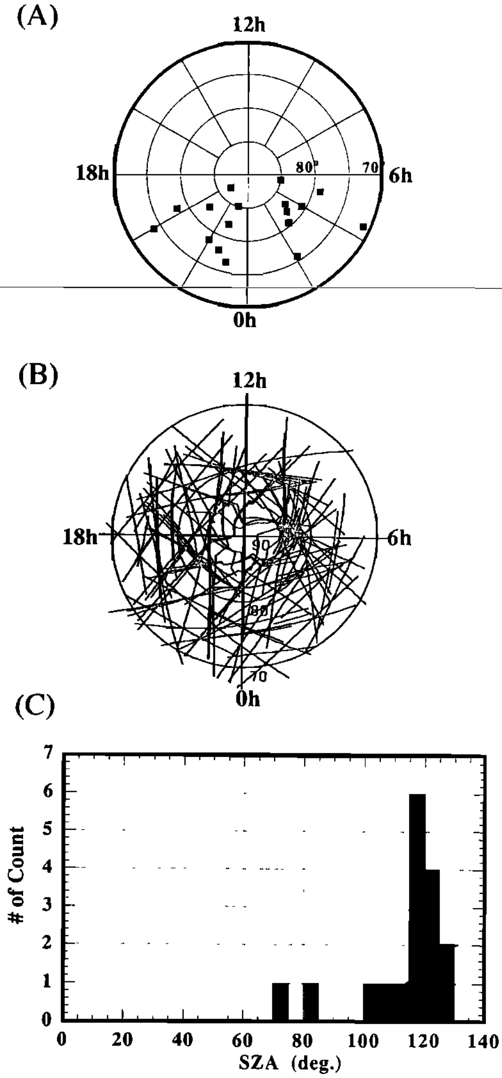

Figure 3. (a) Distribution of multiple polar cap precipitation locations showing that most of the multiple polar cap precipitation events were observed in the nightside region. (b) Coverage area of Akebono measurement in the polar cap. (c) Distribution of solar zenith angle (SZA) at the locations where the multiple polar cap precipitation events were observed.

with the multiple structures were located in the nightside portion. Figure 3b gives the coverage area of the satellite measurements, showing that there was complete coverage over the entire polar cap region, both dayside and nightside, but that multiple polar cap arcs were only observed on the nightside. We also plotted the solar zenith angle for the multiple polar cap precipitations in Figure 3c. These results suggest that low background conductance is a necessary condition for the existence of structured arcs.

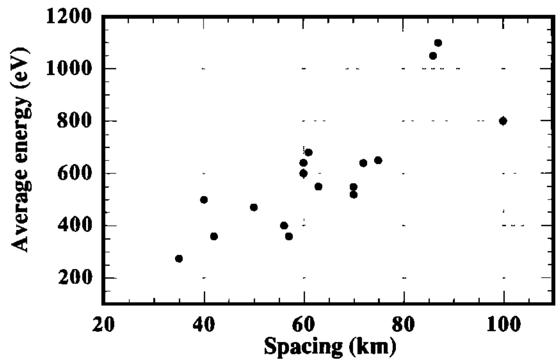

Figure 4. Dependence of the spacing on the average energy of the electron precipitation.

The relationship between the spacing of the multiple polar cap arcs and the average energy of the precipitating electrons was examined. In general, the average energy for multiple arcs was large compared with the usual value associated with polar cap electron precipitation [*Obara et al.*, 1996]. This is why we had a very small number of cases when Akebono observed multiple polar cap arcs. We have plotted the relationship between the spacing and the average energy in Figure 4, where the spacing increases with increasing average energy. The tendency that the higher energy leads to wide spacing is one of the findings of the Akebono observations.

Existence of Downward Current Region Between Double Arcs

It is expected from the model calculation by *Zhu et al.* [1993] that a region of downward field-aligned current is embedded between double arcs. In order to investigate the electrodynamic signature associated with multiple polar cap arcs we have examined the current structure together with the electric field and the precipitating electrons.

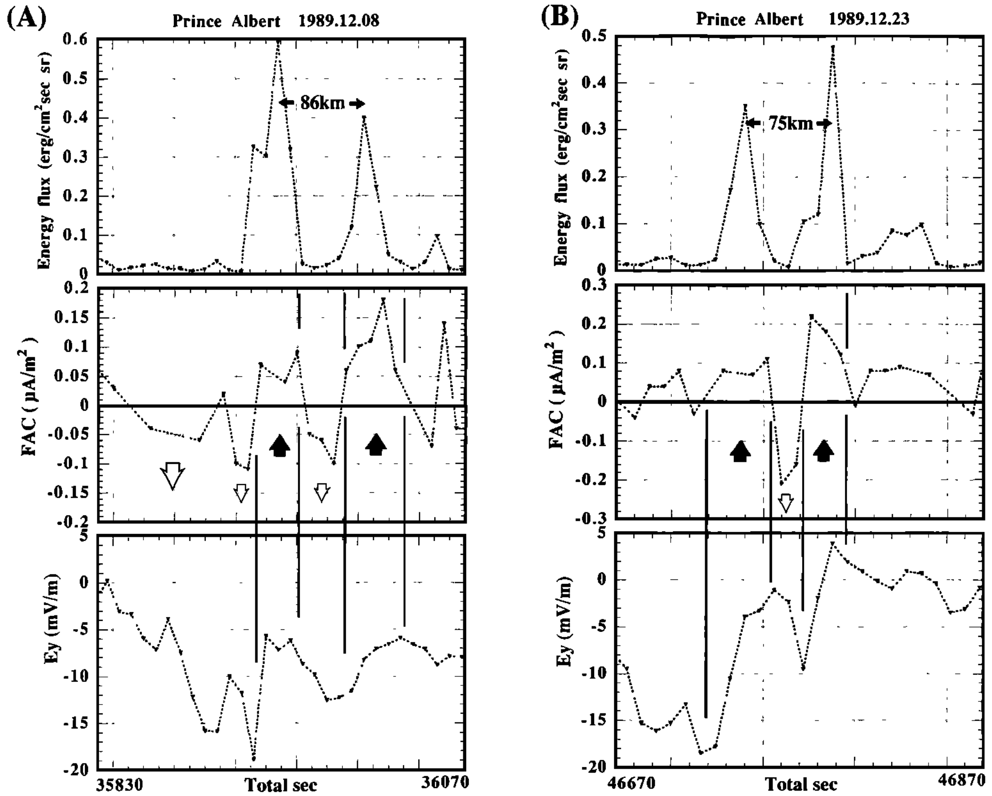

Figure 5. Summary plots of the electrodynamical signature associated with the multiple polar cap precipitation events. Observations made on (a) December 8, 1989, (b) December 23, 1989, (c) November 4, 1989, and (d) January 15, 1990.

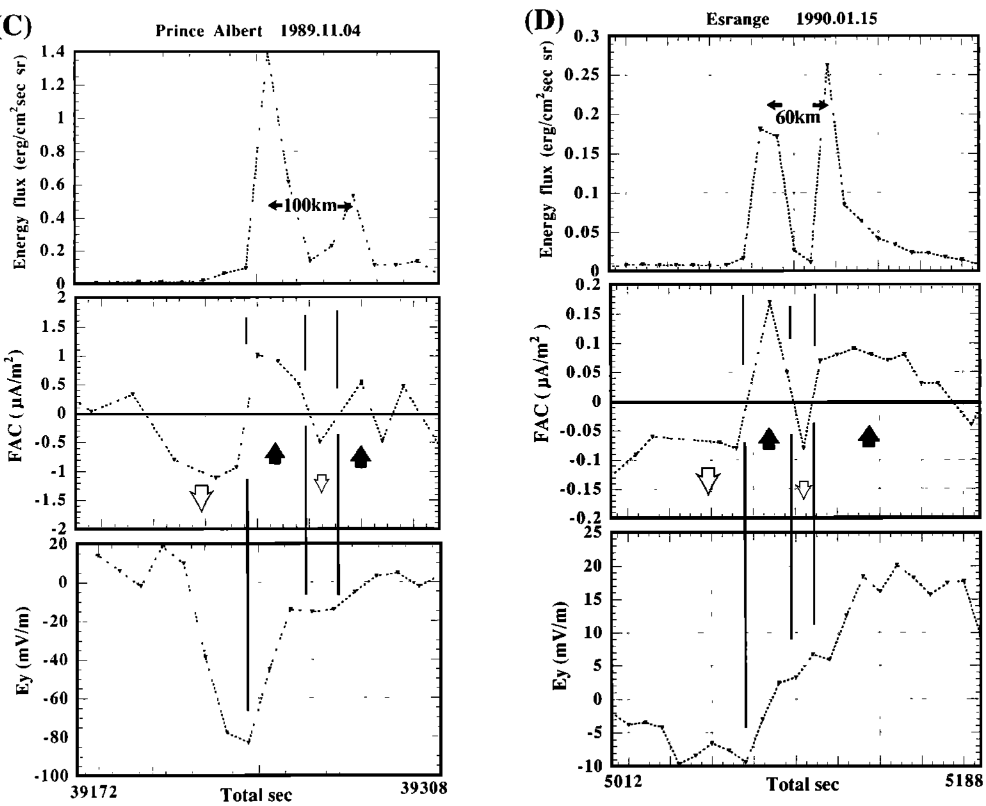

Figure 5. (continued)

Four minutes of data obtained on December 8, 1989, are plotted in Figure 5a. The top panel presents the total energy flux of the precipitating electrons, showing the remarkable two peaks with a spacing of 86 km in dawn-to-dusk direction. The second panel shows the magnitude of the field-aligned current density, where a positive value corresponds to the upward current and a negative value represents the downward current. The bottom panel shows the E_y (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 strictly corresponds to the region with enhanced electron energy flux and the div$E < 0$.

One of the findings by the Akebono satellite is the existence of the downward current region embedded between the upward current regions (arcs). Throughout these four cases we can identify the downward field-aligned current regions. The slope of the electric field was positive for the cases shown in Figures 5a and 5b, but the slope was flat for the other two cases. The problem with satellite measurement is that the up-down current pairs may be in such close proximity that measurements of div$E$ are smeared. This may address the possible explanation for the flat slope in the E field shown in Figures 5c and 5d.

Estimation of the Conductance From the Akebono Observations

We surveyed the entire polar cap region using data from half a year and found that the distribution of the multiple polar cap precipitation was likely to be limited to the nightside polar cap region. This suggests that low background conductance, which may be led by the slowdown of plasma convection due to the northward IMF condition, is a necessary condition for the existence of the multiple polar cap arcs. We estimated the height-integrated Pedersen conductance in the polar cap arc region. For the cases shown in Figures 5a to 5d the average upward current

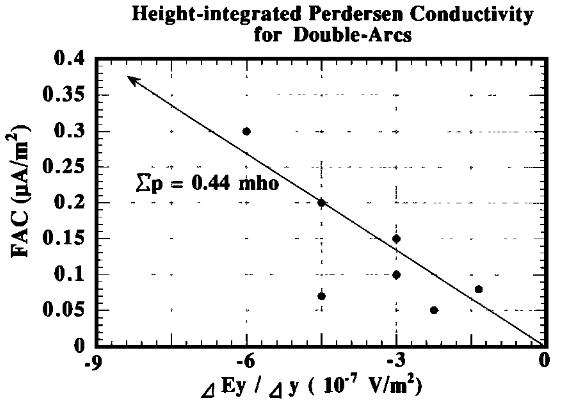

Figure 6. Relationship between the field-aligned current (FAC) intensity and the gradient of the electric field. Though the points are scattered, there is a significant relationship between them showing the rather constant conductance of about 0.5 mho.

density was plotted against the gradient of the electric field, as shown in Figure 6. We can estimate the height-integrated Pedersen conductance from the ratio of the current density to the gradient of the electric field. Although the points were scattered, we have a very significant height-integrated conductance with an amplitude of about 0.5 mho.

Winningham and Heikkila [1974] mentioned that the electron density over the polar cap is low, especially in the winter polar cap, during periods close to solar minimum. *Knudsen et al.* [1977] estimated the ionization product by the solar UV, showing that the lowest electron number density is about 10^4 cm^{-3} at the peak height (~250 km). In situ observations of the plasma density were measured by the AE-C satellite [*Brinton et al.*, 1978]. When the AE-C satellite was in the nightside polar cap region, the low-density regions of the ionospheric plasma, called the "plasma hole," were identified frequently. According to our previous observation by the Exos C (Ohzora) satellite, the plasma density in the nightside polar cap region is quite low (less than 10^3 cm^{-3} in the F layer) when the magnetic condition is quiet, forming the plasma hole state [*Obara and Oya*, 1989]. It is generally recognized that polar cap arcs appear during northward IMF conditions, and this suggests that the background conductance should be very low. We speculate that the background conductance is less than 0.5 mho.

Comparison With Model Predictions

Background Conductance and Multiple Polar Cap Arcs

Zhu et al. [1993] developed a time-dependent model of polar cap arcs in which the electrodynamics of the polar cap arcs is treated self-consistently in the frame of the coupled magnetosphere-ionosphere (M-I) system and the active role of the ionosphere is specially stressed. Figure 7 shows the asymptotic field-aligned current distribution from the M-I coupling model. The ionosphere is treated as a two-dimensional slab with an integrated conductivity. The x axis is defined along noon-midnight meridian and points to the dayside, and the y axis is defined along dawn-dusk meridian and points to the duskside. The ionospheric background conductance, which is mostly due to solar radiation, is uniform in the dawn-dusk direction and decreases from 2.5 mho on the dayside to 0.5 mho on the nightside. The initial magnetospheric input for the simulation is a shear flow, which is assumed to be carried by a downward propagating Alfven wave. The electric potential associated with the shear flow is assumed to be a Gaussian distribution with a minimum of -2 kV at the center. The large-scale ionospheric background convection is a uniform antisunward convection with a magnitude of 20 mV m^{-1} [*Zhu et al.*, 1993]. The dashed curves in Figure 7 denote the upward field-aligned current, while the solid curves denote the downward field-aligned current. It can be seen that in the dayside regions, where the ionospheric background conductance is higher, only a single polar cap arc exists. This can be explained by the fact that high ionospheric conductance allows the magnetospheric current to be freely closed in the ionosphere, which acts to smooth localized discrete structures. In the nightside regions, where the ionospheric conductance is low, there exist multiple polar cap arcs. This is because the low ionospheric background conductance in the nightside region blocks the free closure of the magnetospheric current in the ionosphere and forces the current to return back to the magnetosphere locally thereby distorting the initial magnetospheric current pattern and leading to the structured current sheets or structured arcs. As shown in the preceding section, Akebono observations revealed that most of the structured polar cap arcs (or multiple polar cap arcs) occurred in the nightside regions of the polar cap. This statistical result is consistent with the above theoretical prediction from the M-I coupling model.

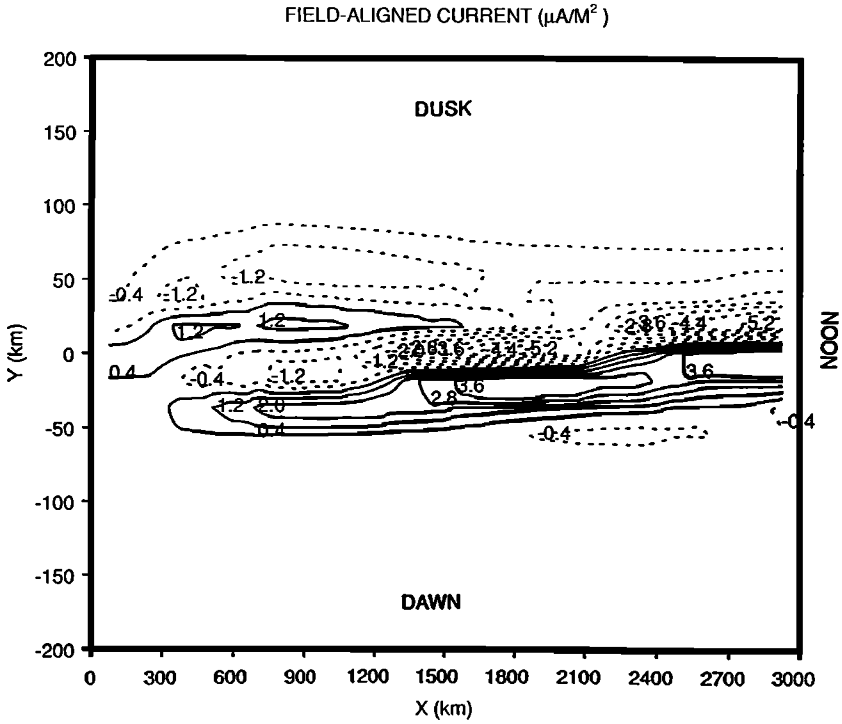

Figure 7. Asymptotic field-aligned current distribution showing the occurrence of multiple polar cap arcs due to the effect of the background conductance.

Relationship Between Spacing Distance and Average Energy

Figure 8 shows the quantitative relationship between the Hall-to-Pedersen conductance ratio and the spacing of the multiple polar cap arcs obtained from the model. The spacing is defined by the spatial separation of the peak brightness (or maximum field-aligned current intensity) of two arcs and falls in a range from 50 to 100 km. In *Zhu et al.*'s [1993] model the ionosphere is treated as a two-dimensional slab with an integrated conductivity. In general, the *E* region makes major contribution to the height-integrated conductance, which was the reason why we mapped the spacing of the arcs to 120 km ionospheric level in Figure 2.

It is commonly known that the Hall-to-Pedersen conductance ratio is an indicator of the hardness of the electron precipitation. A higher conductance ratio reflects a precipitation with higher average energy. Therefore the relationship between the spacing of multiple polar cap arcs and the average energy of the associated precipitation observed by Akebono is consistent with the theoretical prediction from M-I coupling model of polar cap arcs.

It should be noted that the above consistency between the theoretical simulation and Akebono observation is still qualitative in nature at this time. A future study along this line could be a direct quantitative comparison between Akebono observations and theoretical modelings. To do this, several case studies should be performed, and the M-I model needs to make further calculations of average energy instead of conductance ratio for each of the cases.

Summary

On the basis of the Akebono observations we have studied the multiple structure of polar cap precipitation. The following are our results: (1) The electrodynamic signature associated with the multiple polar cap arcs shows that a downward current region is embedded between the upward current regions (arcs). (2) The multiple polar cap arc regions are usually found in the nightside polar cap region. (3)

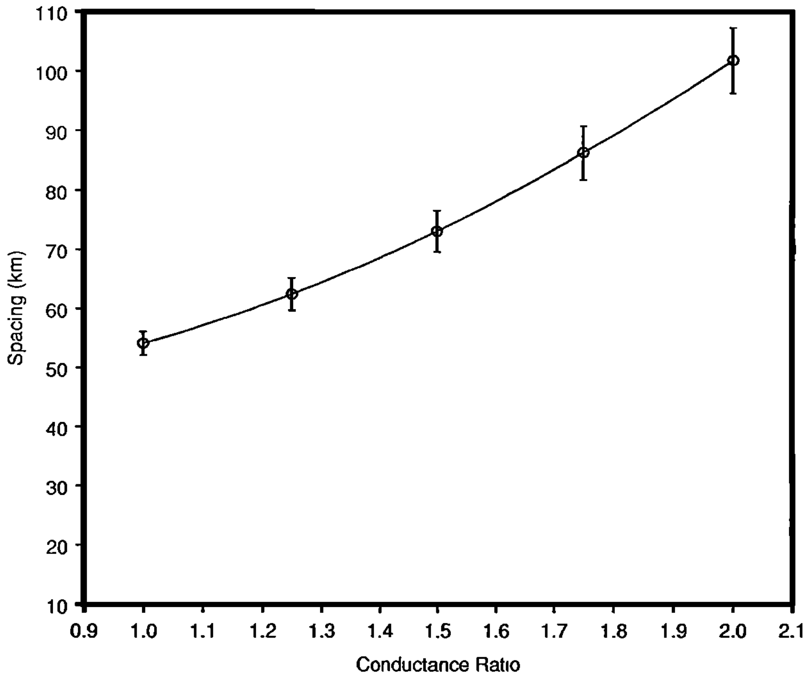

Figure 8. Modeled relationship between the spacing of the multiple polar cap arcs and the conductance ratio.

The spacing distance of the multiple arcs is in a range from 30 to 100 km with respect to dawn-to-dusk direction with a dependence on the hardness of the electron precipitation.

We have performed the comparison with the M-I coupling model calculation in a qualitative fashion and found that model results are quite consistent with the Akebono observations. The observational results from Akebono indicate the importance of the M-I coupling processes in which the ionosphere plays an active role in the formation of the multiple polar cap arcs. This initial study has demonstrated the close agreement between model and observations of Sun-aligned polar cap arcs. Furthermore, it shows that the observations from Akebono are comprehensive enough to be used to constrain future M-I model simulations.

There is, however, still another possibility that multiple polar cap arcs are due to structured plasma sources in the magnetosphere. In order to understand the physics of the multiple polar cap arcs, more detailed studies together with all-sky images are needed. The follow-up studies will determine whether assumptions used in the formulation of the magnetohydrodynamic M-I coupling model [*Zhu et al.*, 1993] are adequate.

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