Electrodynamics of a split-transpolar aurora


Received 14 July 2006; accepted 21 September 2006; published 23 November 2006.

We report new results on the relation between drift velocity shear, average inverted electric field of two sunward flow channels that were separated by an intermediate region of much weaker antisunward flow. The flow shear consisted of differences mainly in the magnitude of the sunward drift velocity. The cross-track disturbance magnetic field was in phase with the drift velocity fluctuations in such a way that two upward field-aligned currents coincided with the peak average energy of the electron precipitation that generated the two polar arcs while a downward field-aligned current was observed in the intermediate region. The observed transverse arc separation is consistent with a reported linear dependence between the average energy of the precipitating electrons of the two arcs and the arc separation. We propose that this relation mainly follows from a local Pedersen current closure requirement. The greater the upward field-aligned current density of the two arcs, the wider the transverse region of the intermediate downward field-aligned current needs to be in order to supply a sufficient amount of current carriers to the bifurcated arc current circuit and thus to balance the Pedersen current.


1. Introduction

Single and multiple auroral arcs are often observed at very high latitudes during northward interplanetary magnetic field (IMF) conditions [Lassen and Danielsen, 1978; Burke et al., 1982; Carlson et al., 1988; Valladares et al., 1994]. Such arcs are generally aligned in the Sun-Earth direction and they are typically caused by precipitating electrons with \( \leq 2 \) keV average energy. In the literature they are referred to as Sun-aligned arcs, polar cap arcs, transpolar arcs (TPA), or theta aurora. Burch et al. [1979] first reported that polar arcs occur at flow shears where the corresponding dawn-dusk convective electric field points toward the center of the electron acceleration region. Subsequent reports have confirmed that the arcs typically coincide with a localized upward field-aligned current (FAC) sheet at a flow shear with a converging electric field [Burke et al., 1982; Carlson et al., 1988; Obara et al., 1993; Carlson and Cowley, 2005].

Obara et al. [1996] reported 17 events of pairs of adjacent inverted V electron precipitation in the high-latitude northern polar region using Akebono satellite measurements. Each inverted V pair was assumed to correspond to a pair of polar arcs on the basis of the electron energy flux alone. Akebono generally confirmed that the two arcs coincided with upward FAC sheets within regions of converging electric field that were separated by a downward FAC. Obara et al. [1996] also found a linear relation between the dawn-dusk transverse separation of the two arcs (30–100 km at 120 km altitude) and the mean of the average energy of the electron precipitation (0.3–1.1 keV). A larger average energy was observed to result in a greater separation. An indirect dependence is thus expected between the arc separation and the Hall-to-Pedersen conductance ratio, since this ratio depends on the average energy [e.g., Spiro et al., 1982; Robinson et al., 1987]. This result was indeed reproduced in a magnetosphere-ionosphere (M-I) coupling simulation of multiple polar arcs [Zhu et al., 1994; Obara et al., 1996]. However, no satisfactory explanation has been proposed for the original average energy dependence of the observed dual-arc separation.

The Zhu et al. [1993] M-I coupling model of multiple polar arcs assumes an initial magnetospheric flow velocity shear [e.g., Lyons, 1980; Sojka et al., 1994] that generates an initial upward FAC and a primary arc in the ionosphere. Zhu et al. [1993] proposed that the adjacent downward FAC and a second upward FAC (the secondary arc) would result...
due to the conductivity enhancement caused by the primary arc as the M-I system approaches steady-state.

[5] Large-scale ~200–400 km wide TPAs may occasionally also bifurcate along the nightside section or even along their entire noon-midnight extension into two parallel polar arcs separated by a region of much lower luminosity [Craven et al., 1991; Eriksson et al., 2005]. This paper examines the electrodynamics of such a split-TPA feature observed by the Polar UVI instrument [Torr et al., 1995] and recorded by the DMSP F13 satellite in the Northern Hemisphere (NH) on 14 February 2003. We discuss a possible physical explanation of the arc separation based on the average energy, a local self-consistent Pedersen current closure requirement, and the Zhu et al. [1994, 1996] M-I coupling model results.

2. Observations

[6] Figure 1 displays the IMF conditions (GSM components and YZGSM clock angle) in the solar wind (ACE) and in the magnetosheath (Cluster C1) during the 2013–2140 UT interval on 14 February 2003. The X, Y, Z components are color coded as black, green, and red, respectively, showing that the IMF was northward after 2017 UT with IMF B_x > 0 and IMF B_z < 0. The bottom panel shows that the upstream magnetosheath flow was mostly sub-Alfvénic along this Cluster C1 trajectory from (X, Y, Z) = (4.4, 0.5, 9.1) to (6.3, 0.7, 9.4) R_E. These conditions are favorable for antiparallel lobe reconnection poleward and duskward of the NH cusp and the generation of sunward E × B convection [e.g., Gosling et al., 1991; Eriksson et al., 2005] in the vicinity of the reconnection site. A flow shear region should develop between such a sunward flow and the magnetosheath flow. The gray area in Figure 1 corresponds to a period when the Polar UVI instrument observed a clear signature of a dusk-side TPA in the NH that eventually bifurcated while the vertical red bar at 2111–2112 UT marks when the DMSP F13 satellite encountered this split-TPA.

[7] Figure 2 displays the Polar UVI observation of the bifurcated TPA at 2110:44 UT (red color indicates higher photon flux). The Polar s/c was at 1.88 R_E altitude when the field-of-view (FOV) of the UVI instrument captured this section of the split-TPA over northern Greenland. The auroral oval was not in the UVI FOV due to the low s/c altitude. The dual-arc UVI observation was confirmed at 2110 UT by the ITACA2 all-sky camera in Daneborg, northeastern Greenland (not shown).

[8] Figure 2 also shows the 2110–2112 UT interval of the global SuperDARN convection pattern displayed here as equipotential contours [Ruohoniemi and Baker, 1998]. There was sufficient radar backscatter to confirm a sunward E × B drift over the split-TPA at this time. The DMSP F13 cross-track E × B drift velocity vectors are also shown along this 2107:08–2119:42 UT dusk-to-dawn satellite trajectory. The SuperDARN and DMSP F13 drift information suggest that the split-TPA occurred at a structured sunward flow section of a clockwise lobe cell that covered most of the high-latitude polar cap. Colored along-track F13 segments correspond to the various magnetospheric source regions as identified from the measured DMSP F13 particle precipitation shown in Figure 3.

[9] Figure 3 shows the cross-track magnetic field perturbation (ΔB_z, solid line), particle precipitation, and cross-track drift velocity (solid line) recorded by DMSP F13 along the duskside 2107–2114 UT interval. A positive (negative) ΔB_z slope along the direction of motion corresponds to a downward (upward) FAC sheet. The electron and ion energy flux were measured by a low-energy (32 eV to 1 keV) and a high-energy (1 keV to 32 keV) pair of electrostatic particle analyzers of the DMSP F13 SSJ/4 plasma instrument [Hardy et al., 1984] whose entrance aperture points toward local zenith. We note that the low-energy ion detector has degraded over time and therefore that low fluxes of low-energy ions may be undetected.
Several plasma source populations are indicated between the vertical dotted lines in Figure 3 such as a central plasma sheet (CPS) and a boundary plasma sheet (BPS). The most poleward region is identified as the polar rain of the polar cap. DMSP F13 observed the center of two 1–3 keV inverted V electron precipitation regions at 2111:24 and 2111:51 UT that generated the two visual polar arcs shown in Figure 2. The two arcs were separated by 201 km along the F13 orbit in a boundary region labeled TPA between the poleward part of the BPS and a region that we identify as a mantle population (MTL) on the basis of its high-energy electron precipitation coincident with polar rain-type electron precipitation [Newell et al., 1991].

There was a clear correlation between the cross-track $\mathbf{E} \times \mathbf{B}$ drift velocity and $\Delta B_z$ (solid lines). The two arcs appeared on the poleward side of two distinct sunward flow channels in a converging electric field region that was dominated by a sunward flow sheaf. The corresponding $\Delta B_z$ indicated an individual upward FAC at each arc and a downward FAC separated the arcs. This system of mesoscale upward and downward FACs related to the two polar arcs occurred within a large-scale upward FAC region (dark gray area in Figure 3) that reached poleward into the polar rain. A large-scale downward FAC (light gray) was found equatorward of the split-TPA. We identify this pair of largescale FACs as a structured NBZ current system [Iijima and Shibajii, 1987] offset toward the duskside of the polar cap in agreement with the positive IMF $B_z$ and northward IMF [Eriksson et al., 2005, and references therein].

[12] Detailed electron precipitation observations during the 2111:05–2112:05 UT interval are shown in Figure 4. The average energy of the electrons is defined as $E = J_E/J_{NE}$ where $J_E$ is the energy flux (see Figure 4a) and $J_{NE}$ is the number flux (not shown) of the electrons. The peak of the average energy was $E = 2.26$ keV and $E = 1.19$ keV at the 2111:24 and 2111:51 UT times of the two arcs, respectively, corresponding to an average $E = 1.72$ keV of this bifurcated arc system. The intermediate region between the two arcs was characterized by a low average Pedersen conductance $\Sigma_P \sim 0.9$ mho on the basis of a quantitative M-I coupling model result of [Spiro et al. 1982]

$$\Sigma_P = (20E/4 + E^2) \sqrt{1.6 \cdot 10^{-12} \pi J_E}$$

(1)

while the Robinson et al. [1987] expression

$$\Sigma_P = (40E/16 + E^2) \sqrt{1.6 \cdot 10^{-12} \pi J_E}$$

(2)

resulted in an average $\Sigma_P \sim 0.5$ mho.

[13] Obara et al. [1996] illustrated a dependence between the estimated dual-arc separation and the observed mean of the average electron energy of the two inverted Vs. We derived a linear fit

$$E = 10.6y - 83.7$$

(3)

on the basis of their Figure 4, where $y$ is the transverse separation of the two arcs in km (mapped to 120 km altitude) and $E$ is the mean of the average energy of both arcs in eV. The wider the arc separation, the greater the mean average energy. This Akebono relation is consistent with the observed mean $E = 1.72$ keV and the $\Delta t = 27$ s along-track arc separation on 14 February 2003 which corresponds to a 162 km perpendicular distance at 848 km DMSP F13 altitude ($v_{sc} = 7.43$ km/s) or 146 km at 120 km altitude. We used an $\alpha = 36^\circ$ angle of incidence between the DMSP F13 trajectory and the TPA normal (see Figure 2). The top panel of Figure 5 illustrates this comparison between the DMSP F13 event (open circle) and the Akebono data (black dots) that we reproduced from Figure 4 by Obara et al. [1996]. The solid line corresponds to equation (3).

[14] The bottom panel of Figure 5 compares the arc separation and the $\Sigma_{eff}/\Sigma_P$ conductance ratio using equation (3) in the Spiro et al. [1982] expression

$$\Sigma_{eff}/\Sigma_P = E^{5/8}$$

(4)

where $E$ is in keV. The general nonlinear form of the conductance ratio using either equation (4) or the Robinson et al. [1987] result

$$\Sigma_{eff}/\Sigma_P = 0.45E^{0.85}$$

(5)
where \( E \) is in keV, is lower than the 1–2 range predicted by Zhu et al. [1994] for a corresponding 50–100 km dual-arc separation.

3. Discussion

[15] The two polar arcs that DMSP F13 intersected were related to a flow shear corresponding to a converging electric field directed toward the center of each upward FAC which was carried by the earthward accelerated electrons of the two inverted Vs [Burch et al., 1979; Burke et al., 1982; Carlson and Cowley, 2005]. Moreover, the Obara et al. [1996] relationship for the 0.3–1.1 keV average energy double arcs appeared to hold for even higher energy and greater separation. The question is how this relation may be explained.

[16] We first examine whether the high-latitude bifurcated arc system poleward of the duskside region 2 current is a locally balanced current circuit as suggested by Zhu et al. [1993]. We assume that the region 2 FAC density is negligible as indicated by the DMSP F13 \( D_B \) observations (see Figure 3). A closer inspection of the along-track FAC budget between the CPS and the polar rain is summarized in Table 1 using an infinite current sheet approximation. This is a valid assumption, since the two horizontal disturbance magnetic field components (see Figure 3) are either in phase or out-of-phase. There were no bipolar along-track signatures which are expected at local current carrying flux tubes. Table 1 lists the estimated time intervals \( \Delta t \) of each significant FAC segment and the FAC densities using

\[
\mathbf{j}_k = \mathbf{D}_y / (\mathbf{m}_0 \mathbf{D}_x),
\]

where \( \mathbf{D}_y = \mathbf{B} - \mathbf{B}_{\text{IGRF}} \), \( \mathbf{D}_x = \mathbf{v}_{sc} \Delta t \), and \( \mathbf{v}_{sc} = 7.43 \text{ km/s} \) is the DMSP F13 speed.

[17] Current continuity [e.g., Lyons, 1980; Milan et al., 2003] relates the height-integrated Pedersen current \( J_P \) and \( \mathbf{j}_\parallel \) by

\[
J_P = - \int_{x_1}^{x_2} \mathbf{j}_\parallel dx
\]

where \( x \) is the DMSP F13 along-track distance (\( x_2 > x_1 \)), \( \mathbf{j} = \mathbf{j}_\parallel \mathbf{z} \), and \( \mathbf{z} \) is positive in the upward direction or antiparallel to the NH magnetic field. \( J_P > 0 \) corresponds to a Pedersen current directed along the direction of motion \( \mathbf{x} \). The along-track electric field \( E_x \) that drives this Pedersen current is \( E_x = J_P / \Sigma_P \) while the cross-track drift velocity corresponding to \( E_x \) is \( V_x = E_x / B_0 \) under the assumption that the total field is
vertical $\mathbf{B} = -B_0 \mathbf{z}$ and $B_0 = 50 \mu T$. A positive $V_y$ corresponds to a sunward drift velocity. The bottom panels of Figure 6 display the resulting along-track $J_P$, $E_x$, and $V_y$ [see also Milan et al., 2003, Figure 4] during a 5-min section of the DMSP F13 orbit from 2108:35 UT using the observed $j_k$ (see Figure 6c and Table 1). An effective $\Sigma_P = \Sigma_P + \Sigma_{Pb}$, where $\Sigma_{Pb} = 1 \text{ mho}$ is an additional background conductance, was employed in order to retrieve realistic $E_x$ and $V_y$. We have also assumed that the average energy $E$ of the electron precipitation (see Figure 6a) may be used directly in equation (1) (see Figure 6b). We conclude two important results from Figure 6. First, we find that the Pedersen current $J_P = J_P \cos \alpha$ transverse to the split-TPA (thin line) is balanced to zeroth order. Second, it is clear that the enhanced $\Sigma_P$ below the two polar arcs suppresses $E_x = J_P/\Sigma_P$ and that this contributes to the structured sunward ionospheric drift velocity $V_y$ related to $J_P$. The resulting drift $V_y$ shown in Figure 6f compares favorably with the observed cross-track drift (c.f. Figure 3).

[18] Assume now that the magnitude of $j_k$ increases at the equatorward or primary 2111:24 UT arc and for simplicity that nothing else changes. This will result in a nonbalanced Pedersen current. It is well-known that density cavities develop after some finite time period beneath downward current regions. This is caused by a depletion of ions that carry the Pedersen current away from the downward FAC and the upward escaping electrons that carry the downward FAC [Karlsson et al., 2005]. We therefore propose that the intermediate downward current region between the two arcs needs to expand in order to supply a sufficient amount of current carriers to the bifurcated arc current circuit and thus to balance the Pedersen current.

[19] Figure 7 demonstrates this fact on the basis of the observed and derived electrodynamic quantities on 14 February 2003. There is a linear relation between the
magnitude of the primary upward FAC density and the required transverse width of the intermediate downward FAC in order to balance the bifurcated arc system by Pedersen currents alone. Lyons [1980] showed in his numerical solution results of a single auroral arc (his Figure 4) that an increased field-aligned potential drop $\phi$ typically corresponds to an increased upward FAC density $j_\parallel$ [Knight, 1973] as well as an enhanced precipitating electron energy flux $J_E$ [Lundin and Sandahl, 1978], since both $j_\parallel$ and $J_E$ (see equation (3) and equation (10) as stated by Lyons [1980]) are assumed to depend on $\phi$ in a similar form.

Figure 7 thus provides a possible explanation for the arc separation dependence on the average energy $E$ under the assumption that the upward FAC density $j_\parallel$ is proportional to the average energy $E$ of the accelerated electrons that carry the upward FAC. This scenario is in agreement with the observed and modeled linear dependence between the average energy of the accelerated electrons of a bifurcated arc system and the arc separation [Zhu et al., 1994; Obara et al., 1996].

4. Summary and Conclusions

[20] The split-TPA event that was observed by DMSP F13, SuperDARN, and Polar UVI on 14 February 2003 displayed a transverse dual-arc spacing of 146 km at 120 km altitude with an average $E = 1.72$ keV inverted V energy distributed between the two polar arcs. The bifurcation of the original TPA is in agreement with the linear dependence that Obara et al. [1996] reported between the average energy and the arc separation. We propose that this relation is caused primarily by a local Pedersen current closure requirement and related to the dynamics of the intermediate downward FAC and the density cavity that develops beneath it. Our hypothesis is that the width of this downward FAC region is determined by a need to supply

Table 1. Estimated DMSP F13 FAC Density for Each Time Interval Poleward of the R2 Current System on 14 February 2003$^a$

<table>
<thead>
<tr>
<th>Start Time, UT</th>
<th>Stop Time, UT</th>
<th>$j_\parallel$, $\mu$A/m$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2108:35</td>
<td>2109:49</td>
<td>0.20</td>
</tr>
<tr>
<td>2109:49</td>
<td>2110:09</td>
<td>-0.61</td>
</tr>
<tr>
<td>2110:09</td>
<td>2110:31</td>
<td>0.85</td>
</tr>
<tr>
<td>2110:31</td>
<td>2111:20</td>
<td>-0.79</td>
</tr>
<tr>
<td>2111:20</td>
<td>2111:28</td>
<td>1.60</td>
</tr>
<tr>
<td>2111:28</td>
<td>2111:44</td>
<td>-0.80</td>
</tr>
<tr>
<td>2111:44</td>
<td>2111:58</td>
<td>0.91</td>
</tr>
<tr>
<td>2111:58</td>
<td>2112:10</td>
<td>-0.40</td>
</tr>
<tr>
<td>2112:25</td>
<td>2112:49</td>
<td>0.38</td>
</tr>
</tbody>
</table>

$^a$Positive values mark upward currents.
a sufficient ion source population to balance the upward FAC system of the two adjacent polar arcs via Pedersen currents.

[21] The split-TPA feature also appears to be consistent with the physics contained in the Zhu et al. [1993] M-I coupling model of multiple polar arcs. However, the main difference between this model and the 14 February 2003 split-TPA event is related to the initial state and the subsequent evolution of the dual-arc system. The split-TPA and the mesoscale structure observed by DMSP F13 evolved as a bifurcation of a preexisting large-scale TPA [see also Craven et al., 1991] and the transverse width of the split-TPA was comparable to the width of the original TPA. The Zhu et al. [1993] model, however, gradually evolves from one mesoscale primary arc into multiple arcs distributed over an increasingly wider region until a steady state width is achieved. In summary, although a local Pedersen current closure requirement probably determines the width of the intermediate downward current region, we still need to understand what initiates the development of a downward current at the center of the primary TPA in the first place if we assume that the TPA coincided with an initial large-scale upward FAC.

[22] The two arcs of the split-TPA presented here occurred at a drift velocity shear which was dominated by a sunward component with a narrow intermediate region of weak antisunward flow. It may be argued that the enhanced Pedersen conductance \( \Sigma_p \) (caused by the downward accelerated electrons of the two arcs) eventually contributed to the deceleration of the sunward flow at the two arcs and resulted in a more severe and localized sunward flow shear in the ionosphere than what was perhaps originally imposed on it from the magnetosphere. We suspect that the sunward flow at the arcs and the corresponding high-latitude convection pattern were generated at a magnetopause source region in the vicinity of a lobe reconnection site [e.g., Eriksson et al., 2005] that resulted in the original flow shear [e.g., Lyons, 1980] during these northward IMF conditions.

References
Lyons, L. R. (1980), Generation of large-scale regions of auroral currents, electric potentials, and precipitation by the divergence of the convection electric field, J. Geophys. Res., 85, 17.

Acknowledgments. We thank Steve Petrinec for making us aware of the Obara et al. [1996] reference and Stan Cowley for useful comments on the manuscript. Polar UVI data were obtained via CSDS UVI Online Search Tool at http://csds.uah.edu/uvii-ost/index.asp and ACE Level 2 data were retrieved from http://www.srl.caltech.edu/ACE/ASC/level2/. This work was supported by NASA grant NNG04GH82G at the University of Colorado at Boulder.

Wolfgang Baumjoehann thanks Lie Zhu and another reviewer for their assistance in evaluating this paper.

M. W. Dunlop, Space Sciences Division, Space Science and Technology Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK.
S. Eriksson and J. T. Gosling, Laboratory for Atmospheric and Space Physics, University of Colorado, 1234 Innovation Drive, Boulder, CO 80303-7814, USA. (eriksson@lasp.colorado.edu)
M. Lester, S. E. Milan, and G. Provan, Department of Physics and Astronomy, University of Leicester, University Road, Leicester, Leicestershire, LE1 7RH, UK.
S. Massetti, Istituto di Fisica dello Spazio Interplanetario, Via del Fosso del Cavaliere, 100, I-00133 Roma, Italy.
H. Réme, Centre d’Etude Spatiale des Rayonnements, 9 Avenue du Colonel Roche, B.P. 4346, F-31028 Toulouse, France.
F. J. Rich, Air Force Research Laboratory, AFR/L/VSBXP, 29 Randolph Road, Hanscom AFB, MA 01731-3010, USA.