Responses of the open-closed field line boundary in the evening sector to IMF changes: A source mechanism for Sun-aligned arcs

N. C. Maynard,[1] W. J. Burke,[2] J. Moen,[3] D. M. Ober,[1] J. D. Scudder,[4] J. B. Sigwarth,[4] G. L. Siscoe,[5] B. U. Ö. Sonnerup,[6] W. W. White,[1] K. D. Siebert,[1] D. R. Weimer,[1] G. M. Erickson,[2] L. A. Frank,[4] M. Lester,[7] W. K. Peterson,[8] C. T. Russell,[9] G. R. Wilson[1] and A. Egeland,[3]

Abstract

Simultaneous measurements from the Polar satellite and by ground-based optical sensors suggest that brief variations of the poleward auroral boundary on the night side correlate with changes in the interplanetary magnetic field (IMF) about an hour after a structure propagates in the solar wind to the bow shock. Short-lived sun-aligned arcs may emerge along the open-closed magnetic field line boundary (OCB) and then disappear after ~10 minutes. The arcs are fueled by energetic particles whose spectral characteristics are similar to those of the of boundary plasma sheet. Polar measurements confirm that these auroral protrusions into the polar cap occur on nearly isolated closed magnetic flux. Optical emissions from these arcs appear strongest at their intersection with the poleward boundary of the auroral oval. A salient feature from detailed magnetohydrodynamic (MHD) simulations of interactions near the dayside magnetopause as the dominant IMF component (B_Y) changed sign is the occurrence of merging between interplanetary field lines located near the reversal, within the magnetosheath [*Maynard et al.*, 2001]. Newly formed loops of interplanetary flux are swept past the Earth without interacting with the magnetosphere. Here we consider some consequences within the distant magnetotail as the loops of disconnected flux propagate to $X_{GSM} \approx -200$ R$_E$. The MHD simulations indicate that about an hour after intra-IMF merging events, fingers of closed field lines protrude from the OCB into the polar cap. Like the observed sun-aligned arc, these simulated auroral features grow and decay on scales of ~10 min and have ionospheric footprints that are nearly surrounded by open magnetic flux. The simulated auroral fingers are conjugate to high-pressure channels in the distant plasma sheet. We suggest that the short-lived Sun-aligned arcs are created via an interchange process similar to that proposed by *Kan and Burke* [1985] to explain a class of theta auroral forms. The continuity of magnetotail currents across a high-pressure channel requires the development of field-aligned currents carried by obliquely propagating Alfvén waves. Plasma drifts associated with the dusk-to-dawn electric fields of the Alfvén waves are away from the Earth in the magnetotail and poleward in the nightside ionosphere. The correlation of phenomena at the nightside OCB with variations in the IMF indicate that processes other than substorms influence boundary dynamics. Effects of self-interactions of the IMF within the dayside magnetosheath may be felt along the OCB as much as 1 hour later.

1. Introduction

Maynard et al. [2001b] (M-01) analyzed the response of ionospheric convection to a reversal in the interplanetary magnetic field (IMF) Y component. The study utilized the Integrated Space Weather Model (ISM) which simulates the coupled magnetosphere system from 40 R_E in the front of the Earth to 300 R_E in the deep tail and to the base of the ionosphere at 100 km altitude [*White et al.*, 1998; 2001]. M-01 indicates that merging begins quickly after a B_Y reversal reaches the subsolar magnetopause. Like observations reported by *Ridley et al.* [1997; 1998], the simulated reversal of global convection began about 8 minutes later. The currents in the magnetospheric boundary layers above and below the cusp had to reverse, in order to reverse the cusp-mantle current system, before the major change in the convection pattern could begin. Before the directional discontinuity impacted the magnetopause, the planar reversal front in the IMF became distorted and compressed in the magnetosheath. Magnetosheath merging was initiated in the simulation between IMF field lines of new and old polarities. Consequently, a region formed in the magnetosheath in which the IMF became totally disconnected from the magnetosphere. As the reversal front moved past the Earth, the detached flux convected tailward in the magnetosheath. A several-minute period of disconnection between the IMF and the magnetosphere occurred before new open flux was added to the polar cap.

The open-closed field line boundary (OCB) is the separatrix between open and closed field lines. It is also the footprint of the reconnection line in the magnetotail at local times where reconnection is active. The amount of flux crossing that boundary per unit time may be used to infer the reconnection rate [*Blanchard et al.*, 1996; *Ober et al.*, 2001]. *Blanchard et al.* [1996] examined the relationship between the nightside reconnection rate and the IMF. They found a peak correlation coefficient of 0.46 with a lag of 70 min between the reconnection rate and the solar wind electric field determined by the half-wave-rectifier formula VB_S where $B_S = B_Z$ if B_Z is negative and zero otherwise. Since 70 min is a typical propagation time from the cusp across the polar cap to the nightside boundary, they concluded that the nightside reconnection rate is influenced by the rate at which open magnetic flux is added on the dayside.

Reconnection may occur at a distant X-line (on average near $X_{GSM} = -130$ R$_E$ [*Nishida et al.*, 1996]), or at one located much nearer Earth (20 to 40 R$_E$) during substorms. In comparing Geotail with ground-based data *Maynard et al.* [1997] showed that both X-lines can operate simultaneously. However, the distant X-line controls the OCB until lobe flux starts to reconnect along the near Earth X-line (NEXL). Even if the reconnection begins in the plasma sheet immediately, it may be some time before the reconnection reaches the open field lines of the lobe [*Maynard et al.*, 1997; *Russell*, 2000], but in a strong substorm this may happen quickly. If flux is added at the same rate on the dayside as it is removed on the nightside, the OCB remains stationary. If no flux reconnects in the tail, the boundary expands equatorward to accommodate the additional flux from the dayside [*Russell*, 1972; *Siscoe and Huang*, 1985]. Conversely, the nightside OCB may locally, or more globally, contract poleward if open flux is not added on the dayside but is removed by reconnection in the magnetotail, depending of the spatial extent of the process. When an active NEXL rapidly reconnects lobe flux during an intense substorm, the nightside OCB expands poleward in the midnight region while open flux is quickly removed from the polar cap [e. g. *Frank et al.*, 1998; *Ober et al.*, 2001].

The dynamics of the nightside OCB reflect those of the magnetotail. The OCB location in the ionosphere depends on the historical balance between flux opening on the dayside and reconnecting in the magnetotail. Since significant reconnection may occur on the flanks as well as the central tail [*Maynard et al.*, 2001b], boundary response may vary with local time. Depending on the polarity of IMF B_Y, the magnetotail's current sheet becomes tilted, [*Kaymaz and Siscoe*, 1998; *Maezawa and Hori*, 1998]. As the IMF orientation changes, the tilt of the current sheet must adapt accordingly.

Sun-aligned arcs in the polar cap were first recognized by *Mawson* [1916] during an Australian expedition to Antarctica. *Berkey* [1976] showed that they preferentially developed when IMF B_Z was northward. However, *Valladares et al.* [1994] observed that 20% of the polar cap arcs occurred while B_Z was southward. These divergent reports can be reconciled if we allow for delays as global magnetopause currents reorganize in response to changes in the IMF orientation. *Valladares et al.* [1994] found that it took ~30 min after a southward turning of the IMF to empty the polar cap of Sun-aligned arcs. Under some conditions, these arcs span the polar cap to form a "theta" configuration [*Frank et al.*, 1986]. Horse-collar configurations may also develop with transpolar arcs on both the dawn and dusk sides of the polar cap separated by a dark region of open field lines [*Hones et al.*, 1989]. In the Northern (Southern) hemisphere transpolar arcs drift in the direction of B_Y ($-B_Y$) [*Craven et al.*, 1991]. *Peterson and Shelley* [1984] showed that energetic O^+ ions precipitating into theta aurora indicate that the emissions come from closed magnetic field lines that thread the outer plasma sheet, a conclusion confirmed by *Eliasson et al.* [1987]. *Huang et al.* [1987] found that during periods of northward IMF filaments protrude into the tail lobes from the central plasma sheet. In one case the DE 1 satellite imaged a theta auroral arc while ISEE 1 was encountering a protruding filament [*Huang et al.*, 1989].

From Viking images *Murphree et al.* [1987] demonstrated that polar cap arcs are often associated with optical intensifications at the poleward edge of the oval, and that they can fade or disappear in a few minutes. *Murphree et al.* [1989] reported cases of Sun-aligned arcs that rapidly formed and decayed. The arcs extended from, then retracted to, the nightside boundary of the polar cap at rates of $\sim$5 km s^{-1}. In one case the entire life cycle lasted only 15 min.

Chang et al. [1998a, 1998b] distinguished between two types of theta auroral arcs, both associated with prolonged periods of northward IMF. The first and more common type begins as a sun-aligned arc separates from the high-latitude flanks of the contracted auroral oval, then drifts into the central polar cap. They appear to initiate in response to southward swings of IMF B_Z [*Newell et al.*, 1995] or to sudden changes in IMF B_Y [*Chang et al.*, 1998a]. As such they are related to the dynamics of the dayside magnetopause at high magnetic latitudes. The second type begins along the night side boundary of the auroral oval then propagates to the dayside across the polar cap. *Kan and Burke* [1985] suggested that self-sustaining arcs of this type form in response to magnetic flux transport constraints in the magnetotail during periods of northward IMF. Their analysis of high-latitude electric fields indicates that reconnection continues along the distant X line, which becomes most active near the dawn and dusk flanks of the magnetotail. To accommodate the presence of newly closed flux a channel of old, closed-magnetic flux migrates tailward via an interchange instability. Its footprint in the ionosphere would appear to extend poleward from the high latitude boundary of the nightside auroral oval.

Relationships between auroral electron precipitation and magnetospheric sources have been obscured by nomenclature differences. Based on spectral characteristics of auroral precipitation into the high latitude ionosphere *Winningham et al.* [1975] introduced a phenomenological distinction between electrons originating in the boundary plasma sheet (BPS) and the central plasma sheet (CPS). BPS electron precipitation tends to be highly structured and relatively low (<1 keV) energy while CPS electron fluxes vary smoothly and have mean thermal energies > 1 keV. The BPS electrons have spectral characteristics similar to those observed in the plasma sheet at lunar distance [Rich et al., 1973]. *DeCoster and Frank* [1979] noted that when the ISEE spacecraft entered the plasma sheet from the lobes of the magnetotail it encountered field-aligned beams of velocity dispersed ions. Ion fluxes generally become isotropic deeper into the plasma sheet. On the basis of these magnetospheric measurements a phenomenological distinction was introduced between the plasma sheet boundary layer (PSBL) and the central plasma sheet (CPS). A simple identification of the BPS with the PSBL led to confusion that was eventually resolved through analysis of occasional satellite detections of velocity-dispersed ion precipitation at the poleward boundary of the auroral oval [*Zeleyni et al.*, 1990; *Saito et al.*, 1992; *Burke et al.*, 1994]. When present, the PSBL maps along the open-closed boundary, poleward of BPS precipitation.

The passage of Polar over Svalbard on December 5, 1997 offered an opportunity to examine the formation and decay of a short-lived sun-aligned arc simultaneously detected by the all-sky camera at Ny-Ålesund and the VIS imager on the spacecraft. *In situ* particle and field measurements provided information about the source of the sun-aligned arc and associated plasma convection. Following an overview of the instrumentation in section 2, we present observations suggesting that the OCB dynamics correlate with IMF variations. To help understand this correlation, in section 4 we utilize the ISM simulation reported by M-01 to explore magnetotail and OCB responses to IMF directional changes. Section 5 compares the empirical and simulated results. We suggest that ephemeral sun-aligned arcs, emerging from the nightside OCB, reflect the distant reconnection line's responses to the passage of disconnected IMF packets. In the actual case and in the simulation the IMF component reversals would have propagated to $X_{GSM} \approx -200$ R$_E$ in the unperturbed solar wind.

2. Instrumentation

In early December 1997 the Polar orbit plane was oriented such that the satellite was moving poleward near 2100 MLT, approaching an apogee of 9 R_E over the northern polar cap. Between 1800 and 2000 UT on December 5 the Polar's footprint passed near Svalbard. Several Polar instruments are used in this study. Optical images of 557.7 nm auroral emissions come from the VIS low-resolution camera [*Frank et al.*, 1995]. The camera is mounted on a despun platform for continuous monitoring of the aurora with a cadence of 246 s at this wavelength and a field of view of 6° x 6°. The Hydra Duo Deca Ion Electron Spectrometer (DDIES) [*Scudder et al.*, 1995] consists of six pairs of electrostatic analyzers looking in different directions to acquire high-resolution energy spectra and pitch angle information. Full three-dimensional distributions of electrons between 1 eV and 10 keV and ion fluxes with an energy per charge ratio of 10 eV q^{-1} to 10 keV q^{-1} were sampled every 13.8 s. The electric field instrument (EFI) [*Harvey et al.*, 1995] uses a biased double probe technique to measure vector electric fields from potential differences between 3 orthogonal pairs of spherical sensors. In this paper we present measurements from the long wire antennas in the satellite's spin plane. The Magnetic Field Experiment (MFE) [*Russell et al.,* 1995] consists of two orthogonal triaxial fluxgate magnetometers mounted on nonconducting booms.

Measurements from the Wind spacecraft located 198 R_E in front of the Earth monitored interplanetary conditions. Plasma observations determined the solar wind density and velocity [*Ogilvie et al.*, 1995] and a tri-axial fluxgate magnetometer measured the vector magnetic field [*Lepping et al.*, 1995].

Ground-based instrumentation at Ny-Ålesund, Svalbard measured the intensity and distribution of auroral emissions at wavelengths of 630.0 and 557.7 nm. The sensors included a meridian scanning photometer (MSP) aligned with the magnetic meridian and an all-sky camera that acquired new images about every 30 s. The CUTLASS Iceland radar, part of the SuperDARN network [see *Greenwald et al.*, 1995], measured longitudinal drifts (toward and away from the radar) over the North Atlantic Ocean and Svalbard.

3. Observations

3.1. Meridian scanning photometer overview

Figure 1 contains a stack-plot representation of 630.0 nm emissions observed by the MSP at Ny-Ålesund between 1800 and 2030 UT. The interval began with emissions near both horizons. Beginning at 1825 UT, during the interval labeled A, the poleward band of emissions moved equatorward, reaching the southern horizon near 1853 UT. Emissions remained to the south of the station until the interval B. Starting at 1914 UT, an auroral form moved to the center of the scan and then retreated to south of zenith. At about 1927 UT auroral emissions filled the whole scan then retreated equatorward starting at 1935 UT. The retreat stopped at 1943 UT with a brief enhancement before emissions moved below the equatorward horizon. These features are labeled 1, 2, and 3 in Figure 1. The period of concern ended as the auroral forms rapidly expanded poleward at 2015 UT during a substorm. The poleward boundary of the 630.0 nm emissions has been related to the open-closed magnetic field line boundary [*Blanchard et al.*, 1997; *Ober et al.*, 2001]. To explain their temporal evolution, we compare the measurements in Figure 1 with allsky images, optical and *in situ* measurements from the Polar spacecraft, as well as with interplanetary inputs to the magnetosphere-ionosphere system determined from measurements by the Wind spacecraft. The dots to the left of the meridian scans mark times of all-sky and Polar images presented in Section 3.2.

3.2. Interplanetary conditions

Figure 2 provides Wind measurements from the interval 1630 to 1930 UT. From top to bottom the plots give the three components of the IMF in GSM coordinates, the X_{GSM} component of the solar-wind velocity and the clock angle of the IMF in the YZ plane. B_Y was positive throughout the interval; B_Z changed polarity several times. B_X was small in magnitude and generally negative. Prior to 1830 UT four IMF B_Z features stand out. First is the reversal of B_Z from north to south between 1655 and 1700 UT, labeled A. There are three brief northward turnings labeled 1, 2 and 3 spanning the interval B. The northward turnings or dips in the clock angle cover a 30-min interval, as do the features marked by similar labels in Figure 1.

If, for the sake of argument, we associate the intervals labeled B in Figures 1 and 2, then the southward turning starting near 1655 UT (labeled A) would correspond to the equatorward auroral retreat seen in Figure 1 near 1840 UT. Such a hypothesis requires a time delay of $\sim$108 min for the southward turning to correspond to the auroral movement to lower latitudes and for the features labeled B to be aligned. Note that with this lag, impacts of the northward turning observed after 1835 UT in Figure 2 on the OCB from reconnection in the magnetotail would occur subsequent to the meridian-scan data presented in Figure 1. This does not exclude the possibility that the rapid poleward expansion of the OCB after 2015 UT could be from substorm effects derived from reconnection nearer the Earth. The 108-min delay is indicated at the bottom of Figure 2. The normal advection lag from the position of Wind to the bow shock at 15 R_E using the average V_X of 390 km s^{-1} is 49 min. After 108 min, plasma elements in the unperturbed solar wind would have propagated to $X_{GSM} = -204$ R_E. We will further evaluate the association of IMF data with photometer data in the intervals A and B in the Discussion section.

3.3. Auroral Image Comparisons

MSP data provide synoptic pictures of auroral evolution, but are incomplete if the auroral forms have irregular shapes, as is the case here. All-sky images from Ny-Ålesund and images from Polar provide two-dimensional temporal/spatial histories on regional and global scales, respectively. Plates 1, 2, and 3 present sequences of images from Polar at 557.7-nm and the all-sky camera at 557.7-nm and 630.0-nm. Images in Plate 1 were acquired near 1813, 1817, and 1829 UT. Solid (blue) dots superposed on the all-sky images indicate the footprint of Polar magnetically mapped to the ionosphere using the Tsyganenko T96 magnetic field model [*Tsyganenko and Stern*, 1996]. The assumed altitudes for 557.7-nm and 630.0-nm emissions in the all-sky images are at 150 and 200 km, respectively. Thus, the spatial coverage for 557.7 nm emissions is less than that for 630.0 nm. The emission altitudes of the aurora in the all-sky images were chosen to match the associated Polar observations. The open (white) dot in the Polar images represents the location of Ny-Ålesund, equivalent to the centers of the all-sky images.

The main feature seen in the all-sky images in Plate 1 is an auroral form that extends poleward from the main auroral oval. The Polar images show this as a curved structure protruding into the polar cap. The form's intensity decreased between the second and third set of images. The Polar footprint lies within the region of auroral emissions, and moves toward the featureless region between the oval and the poleward extending form. This feature, and another located to the west of it in the all-sky images, might normally be considered sun-aligned arcs. More often these are local features, extending a short distance into the polar cap from the main auroral oval. Images in Plate 1 match the times of the first three dots located beside MSP data in Figure 1. We see that the weak emissions observed near MSP zenith reflect the region between the auroral forms, suggesting that the OCB lies poleward (and/or to the east) of the scan line.

Plate 2 shows images corresponding to the second set of three dots in Figure 1, at 1842, 1854, and 1902 UT. During this interval auroral emissions retreated to the south. The top of each of the all-sky images as well as the corresponding parts of the Polar images are devoid of emissions, consistent with a location in the open field line region of the polar cap. This places the Polar footprint at 1854 and 1902 UT within the open field line portion of the polar cap, a conclusion substantiated by the *in situ* measurements presented in Section 3.3. We conclude that the equatorward retreat of the 630.0 nm emissions in interval A of Figure 1 also indicates an equatorward expansion of the OCB to south of the Ny-Ålesund observing area.

Plate 3 shows a third set of images taken near 1910, 1931, and 1935 UT. They show that in the interval B of Figure 1 a sunward arc emerged from the OCB and extended poleward intersecting the footprint of the Polar trajectory. At 1910 UT the aurora is far to the south. By 1930 UT a sun-aligned arc extended poleward through the all-sky field of view. The Polar image shows that the arc was situated to the north of Ny-Ålesund and extended toward magnetic north. Auroral emissions are enhanced at the location of the arc's connection to the auroral oval. The Polar image indicates that by 1935 UT the arc had started to dim. The corresponding all-sky image shows that emissions had spread across the Polar footprint.

3.4. In situ Polar measurements

Plate 4 shows electron fluxes and electric and magnetic fields measured by Polar as it moved poleward between 2100 and 2200 MLT. Plate 4a shows the omnidirectional average of the differential energy flux. The gray area represents a Hydra data dropout. Plate 4b shows the electron anisotropy with yellow-red (blue-purple) indicating a preponderance of parallel (perpendicular) flux. The color coding is in signal to noise units of anisotropy detection, with black corresponding to isotropic within noise limitations. Plates 4d and 4e give the electric field along the Polar velocity vector and the integrated potential along the orbit. Positive (negative) electric field values indicate a component of sunward (anti-sunward) flow. The increasing potential indicates that the Polar trajectory was moving away from the negative cell minimum toward the positive (morning side) potential cell. The trace in Plate 4c represent the component of the magnetic field normal to the orbit plane (B_{56}), positive toward dusk (westward). Variations in this component of the magnetic field can be used to infer FAC structures.

From 1730 to 1810 UT, electron fluxes extended into in the keV range and the most intense fluxes were primarily trapped as indicated by the blue color in Plate 4b. After the data gap the fluxes were lower in energy and field-aligned (yellow and red in Plate 4b), probably indicating a transition into the boundary plasma sheet [*Winningham et al.*, 1975]. This corresponds to Polar crossing of the boundary arc in Plate 2a and to the equatorward expansion of the auroral emissions seen in Figure 1. From 1845-1930 and 1940-2030 UT electron fluxes were very weak, characteristic of polar rain on open field lines. Plates 2b, 2c, and 3a show a correlated lack of emissions at the footprint of Polar, consistent with a location on open field lines. We infer that the OCB is near the poleward edge of the arcs to the south. The electric field is negative during these times indicating that the convection had an antisunward component in these regions of polar rain, typical of polar cap convection with southward IMF [e.g., *Heppner and Maynard*, 1987].

Plate 5 expands the electron fluxes and electric and magnetic fields displayed in Plate 4 between 1920 and 1950 UT. Plates 5a-d displays the magnetic field along the spin axis positive toward dusk, the electric field along the velocity vector, the electron skew and the omnidirectional electron flux. The electron skew ratios the electron fluxes that parallel to those that are antiparallel. Parallel (antiparallel) fluxes are indicated by red (blue) tones. Corresponding field-aligned currents would be out of the ionosphere for red and in for blue. At 1930 UT the electric field approaches zero and became slightly positive (indicating a component of sunward flow), while the electron fluxes had the same characteristics as observed at the OCB. Plates 3b and 3c indicate that the Polar trajectory mapped to the sun-aligned arc at these times. A negative slope in B_{56} signifies a field aligned current into the ionosphere. The B_{56} trace indicates that Polar first crossed a sheet of downward FAC as it entered the arc's western boundary, which changed to an upward FAC at about 1934 UT in plate 5a and continued to the arc's eastern boundary. Within the region of most intense electron precipitation the FAC was out of the ionosphere. The skew in Plate 5c confirms this. While upward and downward dominated fluxes are seen throughout the interval of precipitation, prior to 1934 UT the general tone is blue, corresponding to downward current, and after 1934 UT it is more red, corresponding to upward current. In the sun-aligned arc region the Polar TIMAS instrument [*Shelley et al.*, 1995] observed upward-flowing field-aligned fluxes of H^+ and He^+ as well as isotropic hydrogen typical of the plasma sheet. The ion fluxes were similar to those observed at the OCB and are consistent with the field lines in the sun-aligned arc being closed [*Peterson and Shelley*, 1984; *Rich et al.*, 1973].

EFI measurements indicate that convective flow within the sun-aligned arc was either sunward or very weak. Plasma in surrounding regions flowed antisunward. The sunward component of flow was confirmed by the TIMAS velocity moments of the H^+ distribution. Along the orbit track the TIMAS velocity had a component toward dawn at the OCB and toward dusk at the sun-aligned arc. The components of the flows estimated by EFI and TIMAS are qualitatively consistent with the single component velocity distribution measured by the Cutlass radar in Iceland [*Greenwald et al.*, 1995]. These ground measurements are mentioned only to establish the general consistency of the data set, and are not discussed further.

3.5. Summary of Observations

Our comparison of Polar measurements in the high-latitude magnetosphere with ground-based optical measurements has confirmed or established that:

(1) The poleward boundary of 630.0 nm auroral emissions approximates the open-closed field line border [e.g., *Blanchard et al.*, 1996; *Ober et al.*, 2001].

(2) The boundary may vary in a time-dependent, irregular way with the emergence of sun-aligned arcs, fed by particles fluxes whose spectral characteristics are similar to those of the of boundary plasma sheet. These arcs may be short-lived, lasting for about 10 minutes before disappearing. The *in situ* measurements confirm that the protrusion into the open polar cap is on closed field lines.

(3) Comparison of Plates 1 and 3 indicate that the emissions from these arcs may be enhanced at their intersection with the poleward boundary of the auroral oval.

Returning to the IMF data, recall that we asserted that variations in the auroral boundary may be correlated with variations in the interplanetary magnetic field with lag times about an hour longer than the advection time for the solar wind to propagate to the bow shock. During this time the IMF features would have propagated in the unshocked solar wind to ~200 R_E behind the Earth. The Polar data indicate that the field lines are open, therefore connecting to the IMF, in the intervals before and after the Sun-aligned arc. This suggests that open field lines in the high latitude ionosphere just poleward of the OCB extend to a location in the solar wind ~ -200 R_E downstream.

4. Comparisons with MHD Modeling

Can changes in orientation of the IMF influence dynamics of the nightside OCB by stimulating short-lived sun-aligned arcs? The MHD modeling results of M-01, using the Integrated Space Weather Model (ISM), can be used to elucidate observations reported in the previous section. M-01 showed that distortions introduced during the passage of an IMF B_Y polarity reversal across the magnetosheath produced intra-IMF merging in front of the magnetopause. This effectively disconnected a segment of the IMF from contact with the magnetosphere (Plates 3 and 13 of M-01). Using V_X = 350 km/s M-01 showed that an hour after first contact with the magnetopause, the disconnected region had propagated in the solar wind to $X_{GSM} \approx$ -200 R_E.

It is important to recognize that M-01 described effects from a reversal in B_Y. In the previous section we have related auroral features to a reversal in B_Z, while B_Y remained positive. We believe that results from M-01, described below, establish a conceptual framework for understanding how sun-aligned arcs grow in response to a range of changes in the IMF direction. To test this conjecture we ran two other simulations. In the first B_Z was reversed from negative to positive. In the second a constant B_Y was included with the B_Z reversal. Preliminary results show qualitatively similar temporal features at the nightside OCB. A more detailed analysis of these runs is in progress. We thus present magnetotail effects seen during the M-01 simulation, taking advantage of the extensive and readily available analyses performed for that case. In the discussion we compare our observations with the results of this simulation.

Plate 6 presents two external views of the magnetosphere acquired during the simulation, at six discrete times t = 40, 45, 50, 55, 60, and 65 min. These times are designated in the lower right corners of the panels and are references to the time when the IMF reversal first contacted the nose of the magnetosphere. Plates 6 a-f present views of the magnetosphere from above the north pole. In Plates 6 g-l the magnetosphere is viewed from the sun. A common color code for traced magnetic field lines is used in all panels with green representing purely interplanetary magnetic field lines. The colors blue and red represent open magnetic field lines connected to the northern and southern high-latitude ionospheres, respectively. Plates 6a-f show magnetic field lines traced from both the dusk and dawn edges of the simulation at X_{GSM} distances of -160 and -190 R_E. The background plane is colored by B_Y with positive (negative) represented by brown (blue). The bow shock is located at the edge of the darker blue region at the bottom of each panel. Red dots represent the starting points for the traces in all six panels. Blue dots indicate the X_{GSM} locations of the imposed IMF B_Y reversal. Field lines that passed beneath the XY plane are obscured, so that open field lines connected to the Southern Hemisphere are generally not visible. Plates 6g-l provide views of IMF coupling to both hemispheres. Connection to the northern ionosphere is initially through the dawn flank. The first connection from the trace points to the dusk flank appears at t = 55 min (Plates 6d, 6j). Thus, connection of open field lines to the polar cap changes as the IMF reversal front passes down stream by $\sim$200 R_E. Green interplanetary field lines that merged in the magnetosheath near the polarity reversal are clearly seen on the dawn flank in Plate 6b-f. Similar field lines on the dusk flank pass below the plane and are obscured. These field lines are seen in Plates 6g-l as green lines that do not pass between the dusk and dawn edges of the magnetotail, but curl back to the side of origin.

The simulated ionospheric projection of the OCB is shown in Plate 7. The OCB was found in each hemisphere by tracing outward from a matrix of points every 0.2° in latitude and longitude. The last closed field line boundary is determined and the first open field line boundary is set in the poleward direction, 5 km perpendicular to the closed boundary at ionospheric altitudes. Blue (red) points are from the Northern (Southern) Hemisphere determination. The Southern Hemisphere pattern and boundaries should be mirror images with the large convection cell on the dusk side. Plate 7a shows the Northern Hemisphere convection pattern at t = 38 min. Plate 7b expands the region within the box in Plate 7a. Plates 7c-l show this same segment of the pattern at subsequent times given in the lower left portion of each panel. The circle near the center of each panel is located at 76° Mlat and 2100 MLT. The OCB gradually moves poleward. However, a finger of closed flux tubes develops and intrudes into the polar cap between t = 50 and 60 min. Its extension into the polar cap maximizes at t = 56 min, then retreats. At its maximum incursion into the polar cap, the feature extends over 2 hrs in MLT and is separated in latitude from the rest of the boundary by more than 2° at its tip. Comparison of Plates 7f and 6d suggests that the finger may be associated with the passage downtail of the disconnected region and the switching of the open field line connectivity from dawn to dusk sides of the dayside magnetopause (compare Plates 6c and 6e).

To illustrate magnetotail dynamics at this time, Plates 8-10 present the mappings of three sets of 20 field lines associated with the auroral finger at t = 56 min (Plate 7g). The first set maps to near the root of the finger, as shown in Plate 8a. Plates 8b-f present paired open field lines in blue and nearby closed field lines in yellow. The background colors depict the variations in the log of the magnetic field strength (Plates 8b and 8f), energy density (Plates 8c and 7e), and the magnitude of B_Y (Plate 8d). Attention is directed to locations where open field lines separate from their closely matched closed field lines (compare Plate 8b with 8d). The separation region is near $X_{GSM} = -60$ R_E and $Z_{GSM} = 2$ R_E, represented by a white circle. The orange circles in Plates 8d-f indicate positions of the B_Y reversal front from positive to negative. Plates 8b and 8c show the YZ plane at X = -60 R_E colored with the log of B and ion energy density, respectively. Ion energy density in the model is the average ion energy multiplied by the number density. A cross-tail S with a negative slope in the plasma sheet [*Kaymaz and Siscoe*, 1998; *White et al.*, 1998] characteristic of negative IMF B_Y is apparent in these plots. However, the central part of the plasma sheet is tipped upward with a positive slope in the direction expected for positive B_Y. The mapped site for the root of the auroral finger is located at the bend in the plasma sheet in a region of high energy density, where the effects of the new IMF polarity are interfacing with those of the old polarity. That the white dot locates a high energy density region is confirmed by the hinge point of the plasma sheet at negative Y in this simulation which has mirror symmetry.

Plates 8d-f present B_Y, ion energy density, and log B in the XY plane at $Z = 2$ R_E, which passes through the bend in the plasma sheet. Plates 8e and 8f place the mapped site in a region of high particle energy density and low B. Note however that this is also a region where two troughs of low B merge. One extends to the B_Y reversal (compare the orange circles in Plates 8d and 8f), and the other is the plasma sheet. The open field lines map to the dusk flank as seen in Plates 8d and 8e. The root of the finger is thus connected to a region of high energy density plasma near 60 R_E down tail in the simulation. We also note that field lines just to the west of the finger in Plate 8 reconnect in a segment of the plasma sheet with lower ion energy density.

Plate 9 presents mappings of 20 paired open and closed field lines that emerge from the ionosphere near the tip of the auroral finger (Plate 9a). The format is similar to that used in Plate 8. In this case the ZY cross-sectional plane is at $X_{GSM} = -83$ R_E and the XY plane is at $Z = 6$ R_E. These values were chosen to pass through the inferred divergence region where the blue and yellow field lines separate, indicated by solid arrows. The closely-spaced open field lines (blue) map to three distinct locations. The first group maps to the reversal front (Plate 9d). The second group passes through the dawn side of the magnetotail. The third group follows closed field lines back to the Southern Hemisphere dusk sash merging region where they turn out into the magnetosheath and solar wind (dashed arrows). Note that the upward tilt (positive slope) of the central plasma sheet region is stronger; however, the ion energy density at the bend is weaker as indicated by the more yellow-orange color. The same low-field high-density channel seen in Plates 8e and 8f connects from the directional discontinuity in the solar wind to the plasma sheet at the bend.

Plate 10 completes the sequence examining field lines that map from the dawn/poleward side of the auroral finger (Plate 10a). The inferred region where the open and closed field lines diverge for these field lines is still further down tail near X = -125 R_E. Most of the open lines extend down tail and toward the dawn side as seen in Plate 10e. Some of the open field lines do thread back to the Southern Hemisphere dusk sash before turning out into the magnetosheath (noted by the dashed arrows). Plates 10b-10d depict the YZ, XZ, and XY planes which pass through the divergence region. The XY plane that passes through the inferred reconnection site is now at $Z = 8$ R_E, while the Y location is at 12 R_E. From the position of the solid arrow in Plate 10d, the location is seen to be just tailward of the mapping of the high energy density tongue that extends inward from the reversal front (compare Plate 8e with Plate 8d). Note in Plate 10b the plasma sheet is strongly tilted upward, having the direction typical for the old IMF direction. The new tilt from the negative B_Y is just starting to affect the plasma sheet as evidenced by the bend back to horizontal, starting at the reconnection site. The ion energy density in the region of reconnection continues to decrease with distance down tail.

4.1. Summary of pertinent observations from the simulation

In a simulation in which B_Y reversed polarity M-01 demonstrated that segments of the IMF near the reversal merged within the magnetosheath then propagated in the plasma flow past the Earth. This eliminated connection between the magnetosphere and the IMF in this region around the directional discontinuity in the magnetosheath. This disconnected region propagated downtail in the magnetosheath. Open field lines on either side would connect to the polar cap. Plates 6-10 suggest that, as the disconnected region passed down the tail near -200 R_E, a finger of closed field lines extended into the polar cap. This feature grew and decayed in about 10 min. The ionospheric footprint followed the equipotentials and was similar in shape to the sun-aligned arc. Since the plasma energy density is more intense near the root, we expect that the arc should be brightest where it attached to the oval and diminishes in intensity with distance from the oval. Note that field lines were identified as being open on both sides of the arc. The auroral finger connected to the plasma sheet where the old B_Y tilt was converting to the new tilt. A low magnetic field channel extended between the plasma sheet and the B_Y reversal boundary down the magnetotail (compare Plates 8d and 8f with 9d). The ionospheric footprint is associated with this channel.

5. Discussion

In section 3 we suggested that the creation and decay of sun-aligned arcs at the poleward boundary of the auroral oval near 2100 MLT may be associated with IMF variations as they propagated to about -200 R_E in the unperturbed solar wind. In section 4 the ISM simulation indicated that a change in the IMF influenced the shape of the nightside OCB as disconnected IMF flux propagated to a similar distance. The distorted boundary resulted in a tongue of closed magnetic flux that briefly extended into the polar cap to produce a Sun-aligned arc. The similarity of the two results from independent sources is striking. In the following subsections we use simulation results to suggest that (1) the OCB is partially controlled by the influence of the IMF on the distant magnetotail, and (2) resultant plasma sheet contortions are the sources of auroral brightening along the boundary and short-lived Sun-aligned arcs. We first discuss the influence of the IMF, then relate the magnetotail structure and its temporal evolution with the observed characteristics of the Sun-aligned arc. It is important to keep in mind that the simulation was for a complete reversal in IMF B_Y, while our auroral observations appear to be related to brief northward turnings of IMFB_Z. This is addressed in the final section with initial results from 2 other simulations. We believe that disconnection between the interplanetary medium and the magnetosphere, subsequent to intra-IMF merging in the magnetosheath, provides a framework for understanding the generation of ephemeral Sun-aligned arcs. It is conceptually similar to an interchange process invoked by *Kan and Burke* [1985] to explain the formation of theta auroral arcs whose footprints begin on the nightside OCB and march across the polar cap to the dayside cusp.

5.1. IMF control

The solar wind and IMF influence many statistical properties of the magnetosphere-ionosphere system. The shape and magnitude of the ionospheric convection pattern are directly related to the magnitudes and directions of the IMF and the solar wind velocity [*Weimer*, 2001a]. The field-aligned current system that couples the magnetosphere and ionosphere depends on the same parameters [*Weimer*, 2001b]. Sun-aligned arcs prevalently occur during periods of northward IMF B_Z [*Berkey et al.*, 1976]. Field lines in the polar cap are open, convect in the antisunward direction, and carry weak polar-rain electron fluxes [*Winnigham and Heikkila*, 1974]. In the magnetotail the plasma sheet tilt depends on B_Y [e. g., *Kaymaz and Siscoe*, 1998; *Maezawa and Hori*, 1998]. These all provide general associations with the IMF without being specific as to their nature.

Many investigators have established correlations between variations in the IMF and in ionospheric phenomena. Even small fluctuations in the geoeffective interplanetary electric field correlate with dayside ionospheric convection, optical emissions and currents [*Maynard et al.*, 2000, 2001b; *Farrugia et al.*, 2000]. Reported correlations between the IMF and nightside ionospheric phenomena such as the OCB are limited. Using cross-correlation analysis of the estimated reconnection electric field at the nightside poleward boundary with the half-wave rectifier expression, VB_S, from IMP-8 data, *Blanchard et al.* [1996] found the most probable lag to be 72 min. *Lyons et al.* [1999] argued that substorms are triggered by northward turnings of the IMF (see also references therin). However, in their model substorm triggering results from current disruption in the inner magnetosphere and does not involve the

OCB. *Russell* [2000] suggested in his scenario for substorm onsets that reconnection ceases at the distant neutral line soon after the IMF turns northward. Our results indicate that reconnection at the distant neutral line and/or magnetotail dynamics may be influenced by variations of the IMF that occurred as much as an hour before those influencing merging at the nose.

We have compared brief temporal fluctuations in IMF B_Z with optical variability near the auroral oval's poleward boundary. The region of auroral emissions observed by the MSP (Figure 1) followed the patterns of polar cap expansion and contraction expected from the statistical studies. When B_Z turned southward the boundary moved equatorward as the polar cap expanded. The unique feature of our data set is the potential association of brief northward IMF turnings with localized poleward motions of auroral emissions observed by the MSP. At the times when these occurred, the IMF turnings had propagated to $X_{GSM} \approx -200$ R_E in the unperturbed solar wind. The all-sky and Polar images show that the optical emissions came from a localized Sun-aligned arc. *In situ* Polar measurements indicate that magnetic field lines were open on both sides of the arc. There the satellite detected antisunward convection and polar-rain electron fluxes. The dynamics of this local arc are unrelated to rapid poleward expansions of the auroral boundary observed during substorms [*Ober et al.*, 2001]. A substorm did in fact develop later the same night, well after the Sun-aligned arc disappeared. The correlation between the Wind observations and the Polar and ionospheric data suggest that the IMF influenced the dynamics of the OCB until connection with the ionosphere was cut off due to reconnection in the magnetotail. The simulations suggest that the reconnection location is closer to the Earth than the distance to which the directional discontinuity has propagated to in the solar wind. We have no other examples with coordinated data from Polar and ground-based sources. However, the similarity between observed and simulated arc dynamics suggests that the causal links were analogous to those followed in the ISM simulation. If it is true that this class of Sun-aligned arcs is related to a northward IMF turning, then the simulation may suggest how and why the arc formed.

5.2. Relationships between magnetotail events and the Sun-aligned arc

Plate 7 shows that a finger of closed magnetic flux protruded into the polar cap from the OCB. The finger developed and decayed over ~10 minutes. This is similar to the development and decay of the Sun-aligned arc seen in the ionosphere between 1928 and 1940 UT by the Polar and all-sky imagers. By comparing the diverging traces of the last closed field line with the first open field line, the simulation located both the plasma sheet sources and the connections to the solar wind.

Plate 8 provides three important clues concerning the origin of the Sun-aligned auroral arc. First, the root of the finger maps to a kink in the simulated plasma sheet, where its tilt shifts from B_Y positive to B_Y negative control. At this point the energy density of the plasma sheet ions maximized (Plate 8e). Flux tubes with a relative superabundance of energetic plasma are unstable to the development of interchange processes that cause them to migrate further from the Earth. We also expect that such a local enhancement should be manifest in the energy flux of particle precipitation into the conjugate ionosphere. This is consistent with the auroral brightening observed near the base of the Sun-aligned arc (Plate 3). However, we should not expect the enhancement or shape of the protrusion in the conjugate hemisphere to be identical in this B_Y dominated case, as the basic patterns in the ionosphere and magnetosphere are quite different in each hemisphere, and the dynamics will influenced differently. Similar optical enhancements at the intersection of Sun-aligned arcs with the auroral oval are common [*Murphree et al.*, 1987]. Second, the kink is embedded in a region of low magnetic field (Plate 8f), that extends outward to the location of the IMF-reversal front deeper in the magnetotail (orange dots in Plates 8d and 8f). Recall that close to the reversal in the simulation interplanetary field lines turn in the magnetosheath and connect to similar interplanetary field lines (Plate 6e and M-01). Third, ionospheric convection is antisunward (Plate 8a). Open field lines near the base of the auroral finger that are approaching the OCB and must soon reconnect somewhere in the magnetotail, are tied to the IMF far downstream (Plate 8d).

Plate 9 investigates connectivity to the magnetotail along the Sun-aligned arc's western wall. This region is comparable to the place where Polar crossed the arc. Plate 9 indicates that the open field lines map near the kink in the plasma sheet out to $X_{GSM} \approx -83$ R_E. The kink becomes sharper as the magnetotail becomes more strongly tilted away from its initial B_Y condition. The implication is that associated auroral particle fluxes must originate in the local plasma sheet. This conclusion is confirmed by Polar electron and ion flux measurements (Plate 4). Plate 9d shows that the first open field lines map to many places. Some map to the dawn side of the magnetotail, while others exit to the solar wind through the dusk magnetopause, and still others map to the vicinity of the IMF reversal. The simulation ties the emergence of the auroral finger to the passage of the reversal front nearly 200 R_E down the distant magnetotail. The IMF disconnection appears to correlate with the observed Sun-aligned arc when the IMF northward turning had propagated to similar distances of -200 R_E in the unperturbed solar wind. This observed similarity with the simulation suggests that the emergence of the Sun-aligned arc is also tied to the passage downstream of an IMF change. Plate 10 continues the comparisons placing the divergence region for open field lines on the eastern side of the finger near -125 R_E, at the kink in the plasma sheet and associated with field lines that project to the dawnside of the magnetotail.

ISEE-1 detected intrusions of the plasma sheet extending to high latitudes into the lobe of the magnetotail [*Huang et al.*, 1987]. In one instance the intruding plasma mapped to a transpolar Sun-aligned arc (theta aurora) detected by the DE-1 imager [*Huang et al.*, 1989], indicating a plasma sheet source for Sun-aligned auroral forms. *Craven et al.* [1991] showed that these arcs can occur simultaneously in both hemispheres. The theta arcs move in the same (opposite) direction as B_Y in the Northern (Southern) Hemisphere. We note that the kink in the simulated plasma sheet also migrates toward the center of the magnetotail as control passes to the new negative B_Y. Plates 7k and 7l show a new finger of closed field lines starting to develop nearer midnight. Note that the origin of the theta aurora may be different from these short-lived arcs that we are observing here, as noted in the introduction [e. g., *Chang et al.*, 1998a].

The initial apparent movement of the Sun-aligned arc that we see is sunward. The tailward propagation of a region disconnected from the solar wind provides a mechanism for the filamentary structures seen by *Huang et al.* [1987]. However, in the collapse of the arc, the movement would be antisunward. *Rodriguez et al.* [1997] showed that Sun-aligned arcs retreat in the antisunward direction, as convective motion resumes due to growing dayside merging. *Bonnell et al.* [1999] also observed antisunward flow associated with the arcs with FAST data, investigating cases when the IMF was northward for more than an hour. They discussed three possible source regions: lobe reconnection, the plasma sheet either through bifurcation of the lobe [*Huang et al.*, 1987, 1989] or through expansion of the plasma sheet into the lobe [*Murphree et al.*, 1994], and the low latitude boundary layer [*Elphinstone et al.*, 1994]. The LLBL source was ruled out as requiring a bipolar flow. They preferred lobe reconnection, although they could not rule out the plasma sheet as a source if it were tied to bursty bulk flows (BBF's). *Lyons et al.* [1999] have correlated BBF's to equatorward moving forms within the oval, not poleward of it. While some optical enhancements on the poleward border can be associated with BBF's, they would move equatorward and not be associated with a Sun-aligned arc. Our source region is clearly associated with the plasma sheet, but definitely not with BBF's. The depth of arc intrusion into the polar cap and the rate of renewed dayside merging should determine how rapidly the arc disappears.

5.3. Other types of IMF changes

M-01 showed that during a polarity reversal a segment of the IMF became disconnected from the magnetosphere. The simulated disconnection remained intact as it moved back along the flank. We have shown that the appearance of the auroral finger occurred at about the time when information about the disconnected field lines would influence the dynamics of the reconnection line in the distant magnetotail. We suggest that any change in the IMF that temporarily turns off dayside merging should have similar effects as it propagates down the tail. To check this conjecture, we ran a second simulation in which the clock angle of the IMF was switched from 180 to 0°. Again a portion of IMF near the reversal had no connection with the magnetosphere, due to merging between IMF field lines of opposite polarities in the magnetosheath. A similar finger of closed magnetic flux extending into the polar cap appeared for a brief period when the disconnected IMF propagated to beyond -220 R_E in the unshocked solar wind. The open-closed magnetic divergence region was near 160 R_E. The IMF reversal produced a channel low magnetic field strength near the juncture with plasma sheet. A third simulation was run in which the IMF was switched from 135° to 45° for 20 min and then returned to its original orientation. Auroral protrusions into the polar cap in this case also were associated with the IMF reversal. However the fingers were not as long. They were similar to features found at the OCB in the larger convection cell in the M-01 simulation. We note that in the third simulation longer protrusions extended from the OCB in the post-midnight sector.

These additional simulations provide evidence that protrusions of closed field line regions into the polar cap from the nightside OCB are common features associated with large changes in the IMF. The association of these with Sun-aligned arcs is natural as they are connected to the plasma sheet [*Huang et al.*, 1987]. *Kan and Burke* [1985] proposed a mechanism to explain the formation of Sun-aligned theta arcs that begin near the OCB. They suggested that under northward IMF conditions reconnection should continue along the flanks of the magnetotail. With no merging occurring along the sub-cusp magnetopause, closed flux from the night side could not easily move toward the dayside. As newly reconnected flux pushed Earthward, older closed flux with relatively high-pressure plasma would be forced tailward. In time the footprints of the flux tubes, containing high-pressure plasma, should migrate across the polar ionosphere to the cusp. Magnetic merging of the northward interplanetary flux at the poleward boundary of the cusp would provide the energy needed to maintain the theta auroral circulation pattern.

We suggest that as the interval of disconnection from the IMF, similar interchange processes operate to drive high-pressure flux tubes near the distant X-line in the antisunward direction in the magnetotail. Their footprints expand poleward from the OCB into the polar-cap ionosphere. The main difference with the *Kan and Burke* [1985] model is that in the cases studied here the interchange processes only operate during the disconnection interval. The protrusion is thus limited by the IMF reversal time scale.

Figure 3 gives a simplified representation on currents carried by plasmas in closed magnetospheric flux tubes near the open-closed boundary when local reconnection shuts off. The ionospheric configuration is shown in Figure 3a, where it is schematically compared to the central VIS image in Plate 3. The corresponding magnetospheric configuration is shown in Figure 3b.

The envisaged scenario has three elements: First, as the influence of IMF disconnection passes downstream, the cross-tail electric field driving magnetic reconnection would vanish locally. The governing equations are the required force balance $\nabla p = \mathbf{j} \times \mathbf{B}$ and current continuity $\nabla \cdot \mathbf{j} = 0$. Where the symbols p, $\mathbf{j}$, and $\mathbf{B}$ represent the local plasma pressure, the current density and the magnetic field.

Secondly, following the ISM results, we assume plasma pressure within the channel marked by slanted lines in Figure 3b is higher than to its east and west. Within the high-pressure channel the current carried by gradient-curvature drifting ions and electrons exceeds that outside it. *Vasyliunas* [1970] showed that such a configuration of magnetized plasmas generates FACs that couple the magnetosphere to the conjugate ionospheres. In steady state the FAC reaching the ionosphere is

$$j_{\|} = \frac{B_i}{2B_e}(\nabla p \times \hat{\mathbf{B}}_{\mathbf{e}}) \cdot \nabla \int \frac{ds}{B}$$

Subscripts i and e reference magnetic field values at the ionosphere and the equatorial plane of the magnetosphere, respectively. The pressure gradient has a strong eastward (westward) component at the eastern (western) boundary of the channel. The gradient of the flux tube volume ($\int ds/B$) is in the downtail direction. To satisfy Kirchoff's law FAC flows toward the equatorial plane (out of the ionosphere) along the eastern edge of the high-pressure channel, and away from the equator (toward the ionosphere) on the western edge.

Thirdly, since insufficient time is available to establish steady state conditions the FAC is carried by obliquely propagating Alfvén waves [*Kan and Sun*, 1985]. Currents associated with these waves are represented by

$$\mathbf{j_A} = \pm\Sigma_A[-\hat{\mathbf{B}}(\nabla \cdot \mathbf{E}) + (\hat{\mathbf{B}} \cdot \nabla)\mathbf{E}]$$

The term $\Sigma_A = 1/(\mu_0 V_A)$ is the Alfvén conductance of the plasma and V_A the Alfvén speed. The FAC is represented by space charge distributed along field lines to give them their appropriate equipotential values. The second term is a polarization current the flows at the leading edge of the Alfveén wave. The resultant polarization electric field is opposite to the direction of the cross-tail current as expected for a generator region. E_P causes plasma in the equatorial portion of the flux tube to move in the antisunward direction. Projected to the ionosphere E_P plasma motion is poleward. The FAC is directed away from (toward) the ionosphere on the flux tube's eastern (western) wall of the flux tube. We have seen that within the Sun-aligned arc, the EFI on Polar detected a weak eastward electric field responsible for poleward motion of the arc. Attention is redirected to the Plate 4e that shows the δB_{56} component of the magnetic perturbation. As predicted from the requirement of current continuity in the magnetosphere, FAC flows into the ionosphere on the western side of the sun-aligned arc and out on its eastern side. This is consistent with the cartoon in Figure 3a and with the Polar *in situ* measurements.

6. Conclusions

Through observational evidence from Polar measurements in the high-latitude magnetosphere and ground-based optical measurements we have confirmed or established that:

(1) The poleward boundary of 630.0 nm auroral approximated the open-closed field line border [e. g., *Blanchard et al.*, 1996; *Ober et al.*, 2001].

(2) The boundary may vary in a time-dependent, irregular way with the emergence of sun-aligned arcs, fed by particles fluxes whose spectral characteristics are similar to those of the of boundary plasma sheet. These arcs may be short-lived, lasting for about 10 minutes before disappearing. The *in situ* measurements confirm that the protrusion into the open polar cap is on closed field lines [e. g., *Peterson and Shelley*, 1984].

(3) Emissions from these arcs may be enhanced at their intersection with the poleward boundary of the auroral oval [*Murphree et al.*, 1987].

(4) Variations in the auroral boundary may be correlated with changes in the interplanetary magnetic field occurring over 10 minute time scales with lag times about an hour longer than the advection time for the solar wind to propagate to the bow shock. During this additional time the IMF reversal propagates to ~200 R_E behind the Earth in the unshocked solar wind.

Our simulations show that reversals in the IMF lead to the creation of auroral fingers on closed field lines extending from the OCB into the polar cap. These arcs grow and decay on scales of about 10 min. Open field lines surround these sun-aligned arcs. The auroral fingers connect low intensity magnetic field channels in the distant plasma that are under the control of neither IMF polarity. Similar auroral features emerged from the OCB in all three simulations, indicating that Sun-aligned arc formation is robust and only weakly depends on specific IMF change of directions. Merging between IMF field lines with different orientation in the dayside magnetosheath provides an interval of no IMF coupling to the magnetosphere. As this propagates down tail, the channel of weak magnetic field and relatively high plasma pressure develops. The associated interchange mechanism for creating this short-lived type of Sun-aligned arc is quite similar to that proposed by *Kan and Burke* [1985] to explain the formation of theta auroral forms originating in the midnight sector.

This study implies that the OCB, magnetotail dynamics, and reconnection at the distant neutral line respond in part to IMF variations that passed the magnetopause up to 1 hour earlier. While the nature of the response is complex and obviously includes more factors than the mechanism for Sun-aligned arcs reported here, our results suggest that IMF that has previously interacted with the magnetopause must be considered in understanding magnetotail processes. The observation that the distant neutral line may continue to control the OCB for 20 to 30 minutes after substorm onset [*Maynard et al.*, 1997] is another indicator that magnetotail dynamics are controlled by past activity until the tail is severed by a near-Earth neutral line reconnecting lobe flux.

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W. J. Burke, Air Force Research Laboratory, 29 Randolph Rd., Hanscom Air Force Base, MA 01731

A. Egeland and J. Moen, Physics Department, University of Oslo, P. O. Box 1048, Blindern, N-0316 Oslo, Norway

G. M. Erickson and G. L. Siscoe, Center for Space Physics, Boston University, 725 Commonwealth Avenue, Boston, MA 02543

L. A. Frank, J. D. Scudder, and J. Sigwarth (Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242

M. Lester, Department of Physics, University of Leicester, Leicester LE1 7RH England, United Kingdom

N. C. Maynard, D. M. Ober, D. R. Weimer, W. W. White, and G. R. Wilson, Mission Research Corporation, One Tara Boulevard, Suite 302, Nashua, NH 03062 (e-mail: nmaynard@mrcnh.com)

W. K. Peterson, Lockheed Martin Advanced Technology Center, Palo Alto, CA 94304

C. T. Russell, IGPP, UCLA, Los Angeles, CA

B. U. Ö. Sonnerup, Thayer School of Engineering, Dartmouth College, Hanover, NH 03755 (email: sonnerup@dartmouth.edu)

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[1]Mission Research Corporation, Nashua, New Hampshire.

[2]Air Force Research Laboratory, Hanscom Air Force Base, Massachusetts

[3]Physics Department, University of Oslo, Oslo, Norway

[4]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa

[5]Center for Space Physics, Boston University, Boston, Massachusetts.

[6]Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire.

[7]University of Leicester, Leicester, England

[8]Lockheed Martin Advanced technology Center, Palo Alto, California

[9]IGPP, UCLA, Los Angeles, California

Figure 1. Components of the IMF, the solar wind velocity, and the clock angle of the IMF versus time as measured by the Wind spacecraft on 5 December 1997. Scales for both UT and the optimum delayed time for the correlations are indicated.

Figure 2. Stack plots of 630.0 nm meridian scanning photometer data for December 5, 1997, recorded at Ny-Ålesund. The intervals A and B and the times of the all-sky images used in Plates 1-3 are noted in the margins.

Figure 3. a. Cartoon showing the ionospheric configuration of velocities, electric and magnetic fields and field aligned currents associated with the Sun-aligned arc in the central image of Plate 3. b. Cartoon of the pressure channel and associated currents and polarization electric field in the magnetosphere, inferred from the ISM results. The downward current maps to the western edge of the Sun-aligned arc while the upward current maps to the poleward edge of the arc.

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Plate 1. Comparisons of the Polar VIS image at 557.7 nm with all-sky photometer images at 557.7 and 630.0 nm near 1813, 1817, and 1829 UT. The all-sky images are mapped to 150 and 200 km, respectively. The mapped Polar trajectory is indicated by the black trace, with the location at the time of the image noted by the black dot. The white dot at the center of the all-sky images and in the VIS images identifies the location of Ny-Ålesund. The direction of the meridian scan is approximately parallel to the magnetic longitude lines overlaid on the allsky images. The times of these images are noted in the meridian scan record in Figure 2, and represent the configuration during the initial period of northward IMF.

Plate 2. Comparisons of the Polar VIS image at 557.7 nm with all-sky photometer images at 557.7 and 630.0 nm near 1842, 1854, and 1902 UT. See caption for Plate 1. These images illustrate the expanding polar cap area during the period of southward IMF. Near the first time the boundary arc moves across the mapped Polar location, while the in situ fluxes at Polar in Plate 4 are indicative of boundary plasma sheet precipitation.

Plate 3. Comparisons of the Polar VIS image at 557.7 nm with all-sky photometer images at 557.7 and 630.0 nm near 1910, 1931, and 1935 UT. See caption for Plate 1. These images illustrate the establishment and decay of a Sun-aligned arc.

Plate 4. Particle and electric and magnetic field data from the Polar spacecraft. The increasing potential in Panel (d) indicates that the spacecraft was moving away from the negative potential minimum of the dusk cell toward the dawn cell. Panel (e) shows the electric field along the velocity vector. Negative (positive) values indicate antisunward (sunward) convection. From 1930-1935 UT the convection is weakly sunward. The energy spectrograms in Panel a-b depicts total electron fluxes and the electron anisotropy. Red colors indicate field aligned fluxes, while blue colors indicate a dominance of trapped fluxes. The electron fluxes at times 1730-1850 and 1930-1940 UT are consistent with a boundary plasma sheet origin.

Plate 5. Expansion of the inteval between 1920 and 1950 UT in Plate 4, where Polar is traversing the Sun-aligned arc. The four panels show the magnetic and electric fields, the electron skew and the electron energy spectrum.

Plate 6. (a) The simulated Northern Hemisphere potential pattern at t = 38 min. The last closed field line boundary is displayed by the blue and red dots. The blue (red) dots were determined from finding the boundary by tracing field lines from the Northern (Southern) Hemisphere polar cap. The box identifies the area shown in panels (b-i), which display changes in the nightside boundary with simulation time noted in the lower left of each panel. Panel (g) is highlighted as it will be investigated in detail in subsequent plates.

Plate 7. Panels (a-f) look down on the equatorial plane which is colored by the magnitude of B_Y. The blue (red) field lines connect to the Northern (Southern) Hemisphere ionospheres. The green field lines connect to the solar wind on both ends of the trace. The red dots indicate the initiation points of the field lines traces while the green dot indicates the location of the reversal front. The plane obscures all field lines below it. Simulation times are given in the lower right corner. Panels (g-l) are views from the Sun of the same traced field lines for each of the times in (a-f), respectively.

Plate 8. Field line traces from the root of the finger in the open-closed boundary. Plate 7a repeats Plate 5g with the black field lines representing the first open field lines next to the closed field lines at the root. In Plates 7b-f the open field lines are blue and the paired closed field lines are yellow. Attention is called to where the yellow and blue field lines diverge. This has been highlighted by the white dot. The orange dot indicates the location of the reversal front. Plates 7b and 7c depict YZ planes cutting through the reconnection location at $X = -60$ R_E, colored by the magnetic field magnitude and the energy density, respectively. Since the simulation has mirror symmetry about the X axis, the density enhancement at the bend in the plasma sheet, which is obscured by the field line traces, can be seen on the dawn side. Plates 7d-f show XY planes at $Z = 2R_E$, which approximately cut through the primary region of divergence. The planes are colored with B_Y, energy density and the magnitude of the magnetic field, respectively.

Plate 9. See captions for Plate 7. Plate 8 depicts the field line traces near the tip of the finger. In this case the primary region of divergence (solid arrows) is further down the magnetotail near $X = -83R_E$ and $Z = 6R_E$. There is a secondary site on the dusk flank noted by the dashed arrows. Note that some of the open field lines now trace to the dawn side of midnight, and some trace back to the reversal area.

Plate 10. See caption for Plate 7 and 8. Plate 9 depicts field line traces for the far side of the finger. The primary region of divergence is elongated in this case, ranging from X = -125 to -150 R_E and Z = 8 to 12 R_E. Note that the blue field lines exit on the dawn side of midnight. The divergence location follows the kink in the plasma sheet. There is a secondary region located on the dusk flank noted by the dashed arrow.