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Large electric field at the nightside plasmapause observed by the Polar spacecraft

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[1] We report an example of large electric field with a peak amplitude of ~60 mV/m observed at the plasmapause by the Polar spacecraft on April 25, 1998. This electric field pointed radially outward and predominantly perpendicular to the ambient magnetic field. As comparing the plasmapause crossings in the previous and following Polar passes, we found that the large electric field is associated with forming a sharp plasmapause structure. Comparing with previous observations of subauroral electric fields in the ionosphere and magnetosphere, we suggest that the large electric field observed at Polar is associated with the subauroral ion drift phenomenon. In addition, we observed a negative-then-positive magnetic field perturbation at the plasmapause. That is, the magnetic field is reduced outside the plasmapause and enhanced inside the plasmapause. The field perturbation is dominant in the meridional plane. We suggest that the magnetic field perturbation is due to the dawnward plasmapause current ($\mathbf{J}_{pp}$), which is associated with the balance of forces ($\nabla P \sim \mathbf{J}_{pp} \times \mathbf{B}$) at the plasmapause, perpendicular to the background magnetic field.

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1. Introduction

[2] Large poleward electric fields have been observed in the premidnight sector of the subauroral ionosphere [*Smidy et al.*, 1977; *Karlsson et al.*, 1998]. These electric fields drive intense sunward plasma flows exceeding 1000 m/s in the ionosphere, called polarization jets [*Galperin et al.*, 1973] or subauroral ion drifts (SAID) [*Spiro et al.*, 1979; *Anderson et al.*, 1993]. The plasma drift and electric field signatures have a narrow (~1°–2°) latitudinal extent and coincide in the latitude range of the ionospheric projection of the plasmapause [*Smidy et al.*, 1977]. The models of SAID have been summarized well by *Anderson et al.* [2001].

[3] *Yeh et al.* [1991] observed sunward plasma drift in broader regions, equatorward of the evening auroral convection cell during a strong magnetic storm. *Foster and Vo* [2002] observed a similar phenomenon, called subauroral polarization streams (SAPS). The features of SAPS are generally broader and less intense than SAID. Recently, the term SAPS has been agreed to encompass the observations of subauroral plasma flows and electric fields [*Foster and Burke*, 2002]. Thus, SAID can be considered as a subset of SAPS.

[4] The occurrence probability of SAID increases with an increase in *AE* index, indicating a dependence on substorm activity [*Spiro et al.*, 1979]. *Anderson et al.* [1993] and *Karlsson et al.* [1998] reported that SAID occur during the substorm recovery phase, implying a significant time delay between substorm onset and SAID formation. However, *Nishimura et al.* [2008] reported that SAID-associated electric field occurs nearly simultaneously with the onset of substorms. Thus, it is still not completely understood how substorms affect the occurrence of SAID.

[5] SAID-associated electric fields in the magnetosphere have been reported by *Maynard et al.* [1980] and *Okada et al.* [1993]. Those electric fields have a peak amplitude in the rage from ~20 mV/m to ~125 mV/m and were observed at magnetic latitudes higher than 32° and L = ~2–4. There were few observations of SAID-associated electric field near the magnetic equator except for several events detected by Cluster and CRRES near the plasmapause [*Puhl-Quinn et al.*, 2007; *Mishin and Puhl-Quinn*, 2007; *Nishimura et al.*, 2008].

[6] In our study we present Polar observation of large electric field on April 25, 1998. The electric field has a peak amplitude of ~60 mV/m and was observed when the Polar spacecraft passed the plasmapause. We show that our event is similar to SAID-associated electric fields reported from previous studies. In addition, we observed a negative-then-positive magnetic field perturbation at the plasmapause. We suggest that the magnetic field perturbation is associated with the dawnward plasmapause current.

2. Observations

[7] Figure 1 shows an interval, 0355–0425 UT on April 25, 1998, when the Polar satellite passed inbound near the mid-

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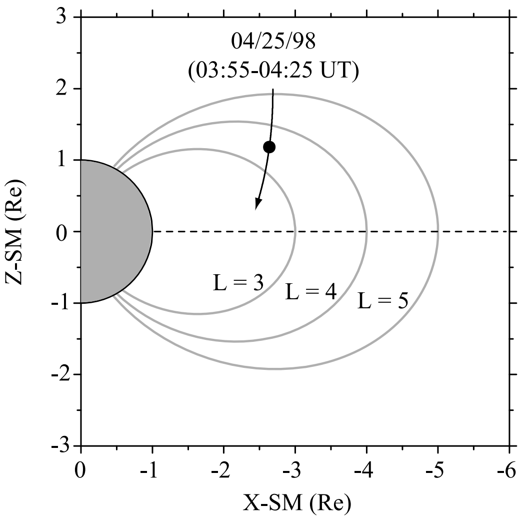

Figure 1. Orbit of the Polar spacecraft for the interval of 0355–0425 UT on 25 April 1998. The orbit is projected onto the solar magnetic *x-z* plane.

night plasmapause (~23 MLT). The orbit of the satellite for this interval is plotted in the SM (solar magnetic) *xz* plane along with the dipole field lines indicating the *L* shells from 3 to 5. The plasmapause crossing, which is confirmed in Figure 3 shown below, is marked by the solid circle.

[8] Figure 2a shows the auroral electrojet *AL* index for 0100–0500 UT on 25 April 1998. There is a sudden increase in *AL* intensity around 0220 UT. We have examined Los Alamos National Laboratory geostationary particle data provided on the World Wide Web (http://leadbelly.lanl.gov) and found that there was particle injection around 0210 UT. This implies that the *AL* change clearly indicates a substorm activity. During the interval from ~0330 to ~0450 UT, the *AL* intensity gradually decreases. The vertical dashed lines at 0411:30 UT on April 25, 1998 in Figures 2a–2d indicate the peak time of the strongly enhanced electric field event described in this study. The electric field event was observed in the recovery phase of the substorm. Since the geomagnetic index *Kp* was 4 as shown in Figure 2b, the event was not associated with an extreme geomagnetic activity. Figure 2c illustrates the interplanetary magnetic field (IMF) B_z in GSM coordinates, observed at the ACE spacecraft. During the three days ACE moved from GSE $(x, y, z) \sim (231.9, -38.7, -9.6)$ to $(230.7, -36.8, -12.5)$ R_E. The IMF data were time shifted to the bow shock nose at the Space Physics Data Facility of NASA Goddard Space Flight Center (http://omniweb.gsfc.nasa.gov). The data have been provided in 5-min time resolution. ACE observed fluctuating IMF B_z variations for the 3-day interval. Although there were several intervals of northward IMF, the average IMF B_z is shifted to southward after 24 April (day 114) 1998. These IMF conditions enhanced magnetospheric convection and caused the moderate magnetic storm on 24 April 1998. Figure 2d shows that our event was observed during a recovery phase of the moderate magnetic storm. The two solid vertical lines in Figures 2b, 2c, and 2d indicate inbound plasmapause crossings observed in the previous and following Polar passes. The former occurred around 1012 UT on April 24 and the later occurred around 2151 UT on April 25, respectively. Each of the crossings is separated by one orbit period of about 18 hours.

[9] The plasmapause crossings were identified from the spacecraft potential (SP) data as shown in Figure 3. The location of the plasmapause crossing is indicated in the panel of the SP data. The horizontal bar indicates the interval when Polar entered the plasmasphere. Figure 3b shows that the spacecraft potential sharply changed from −4.5 V to −1.3 V around 0411:30 UT, corresponding to density change from ~5 cm^{-3} to 200 cm^{-3} [*Scudder et al.*, 2000], within 30 s. This indicates that Polar crossed the plasmapause around 0411:30 UT and that the plasmapause is spatially sharp. During this plasmapause crossing, a large electric field with a peak amplitude of ~60 mV/m was observed in the GSM-z component. This event is discussed below. In Figure 3a, the spacecraft potential smoothly changes from −4 V to −1.3 V during the interval of 1005–1013 UT. It is likely that the plasmapause boundary is spatially smooth under the assumption that the plasmapause location remains steady during the crossing. Polar observed ~4-mV/m peak of electric field, which is much smaller than that observed at the sharp plas-

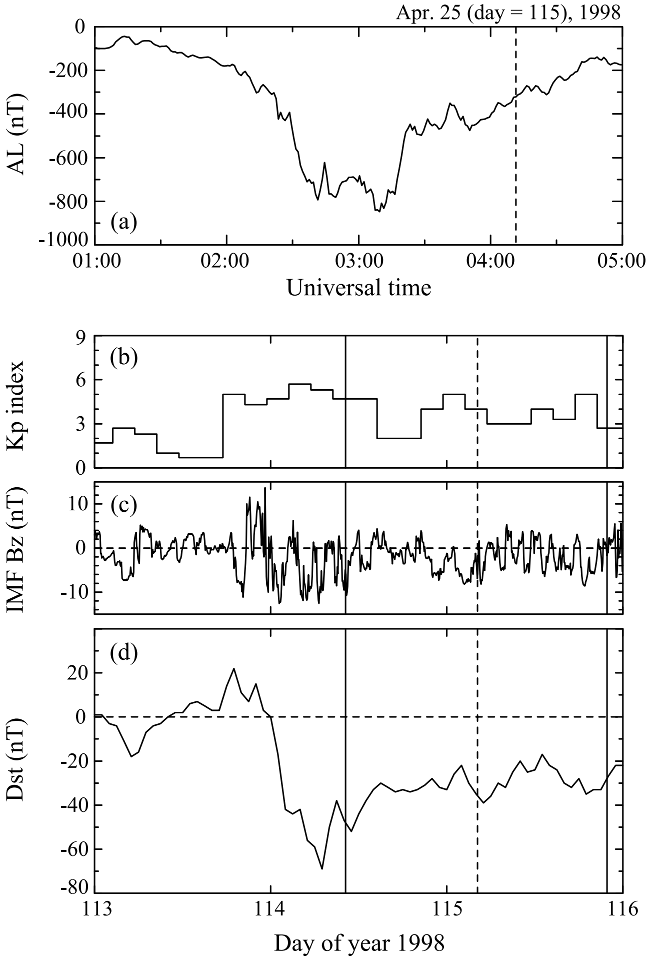

Figure 2. (a) *AL* index, (b) *Kp* index, (c) IMF B_z, and (d) *Dst* index. In each panel, the vertical dashed line indicates the peak time of the strongly enhanced electric field observed by Polar at the plasmapause. The vertical lines in Figures 2b, 2c, and 2d indicate the plasmapause crossings in the previous and following Polar passes.

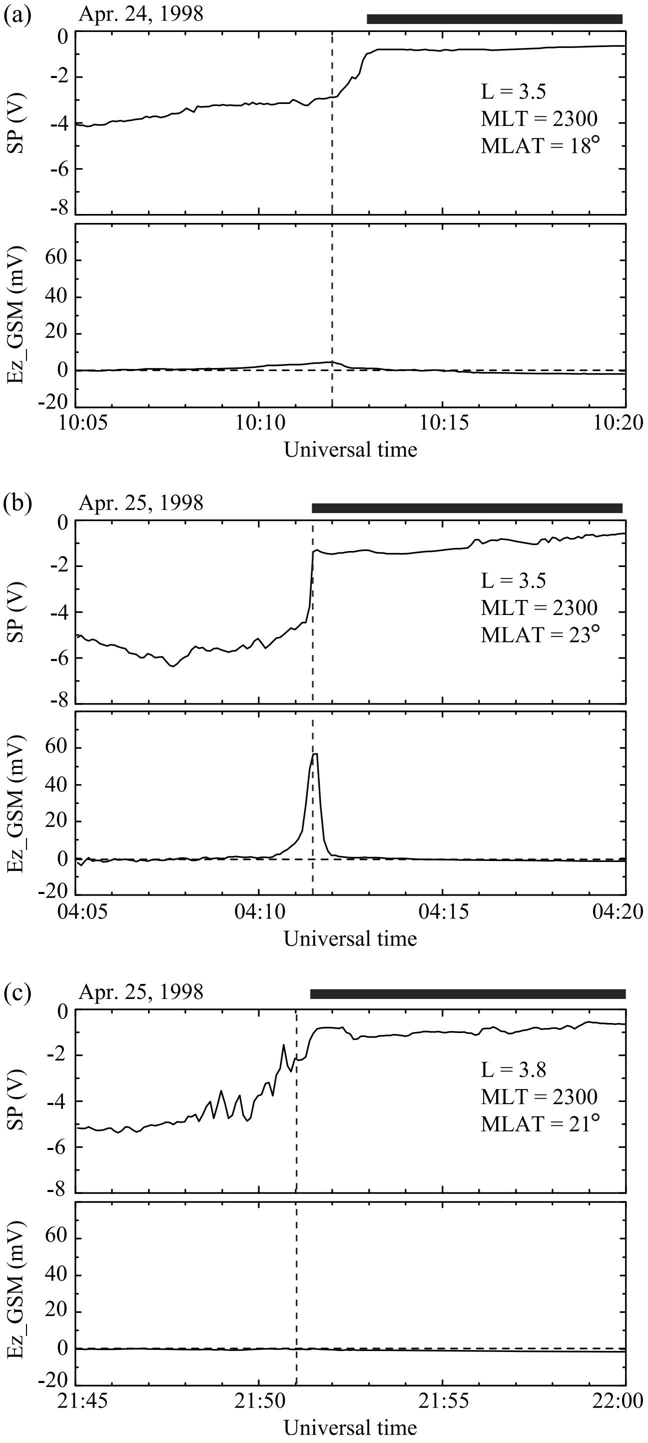

Figure 3. The spacecraft potential and electric field data for the plasmapause crossings (a) around 1012 UT on April 24 1998, (b) around 0411 UT on April 25 1998, and (c) around 2150 UT on April 25 1998. The horizontal bars indicate the intervals when Polar entered the plasmasphere.

mapause. Figure 3c shows that Polar made an oscillatory crossing of the plasmapause. Although we cannot determine whether the oscillatory crossing is due to a spatial or temporal effect, the plasmapause structure is much more complicated than that shown in Figure 3b. During the plasmapause crossing in Figure 3c, Polar did not observe an enhanced electric field. Thus, we suggest that the large electric field does not last during the entire recovery phase of the moderate storm but only when the plasmapause is well-formed with a sharp boundary.

[10] The intimate relationship between the amplitude of the electric field and the plasmapause density gradient leads to the investigation of what determines a steep density gradient at the plasmapause. Since the plasmapause is formed by the influences of both the solar-wind-driven convection electric field and the electric field associated with the Earth's rotation, the size and shape of the plasmasphere depend considerably on the level of magnetospheric activity and IMF conditions. We compare the IMF and geomagnetic conditions, shown in Figure 2, during the interval corresponding to each plasmapause crossing. The IMF B_z was northward for a couple of hours around the last plasmapause crossing. This condition is quite different from those during the previous two crossings and this can probably be the reason why no electric field enhancement was observed during the last crossing.

[11] For the first and second plasmapause crossings, we do not find any significant differences in IMF and geomagnetic conditions. The plasmasphere experiences erosion during southward IMF intervals [e.g., *Goldstein et al.*, 2004]. During the erosion the plasmapause is very dynamic. Thus, we need a global view of the plasmasphere. Although we have gained considerable insight into the relationship between the sharpness of the plasmapause and the appearance of the large electric field, it is difficult to explain the cause of the plasmapause density gradient from observations on a single Polar pass. We remain the relationship for future study.

[12] An overview of the Polar data showing the large electric field during an inbound pass from the plasma sheet into the plasmasphere on April 25, 1998 is shown in Figures 4a–4d. Figure 4a displays the electron density (N_{sp}) inferred from the spacecraft potential [*Scudder et al.*, 2000]. During the inbound pass, Polar encountered a sudden N_{sp} increase region from ~5 cm^{-3} to 200 cm^{-3} at ~0411:30 UT. Such an increase in density is due to a spacecraft crossing of the plasmapause. That is, the spacecraft was in the plasma sheet from the beginning of the plot (0408 UT) to ~0411:30 UT and in the plasmasphere from ~0411:30 to the end of the plot (0416 UT). It should be noted that N_{sp} in Figure 4a is obtained from an electron density fitting curve produced from an analysis of Hydra, Electric Field Instrument (EFI), and Plasma Wave Instrument (PWI) for May 29, 1996 [see *Scudder et al.*, 2000, Figure 4]. The high densities at very low potentials, corresponding to the density in the plasmasphere, were derived from UHR points provided by PWI. Because the model fit is not obtained from statistical data set, the curve has an uncertainty and may not be universal. However, the inbound plasmapause crossing characterized by a density increase from below 10 cm^{-3} to above 100 cm^{-3} shown in Figure 4a is not unusual as comparing with plasmapause crossings in MLT = ~2200–2300 reported from previous studies [e.g., *Takahashi et al.*, 1999; *Takahashi et al.*, 2001].

[13] Figure 4b shows the energy spectra of electrons and ions from Hydra measurements in the energy range from 12 eV to 18 keV [*Scudder et al.*, 1995]. The plasmapause location identified from N_{sp} coincides with the inner edge of the electron plasma sheet. That is, the entry into the plasmasphere is most clearly indicated by the order of

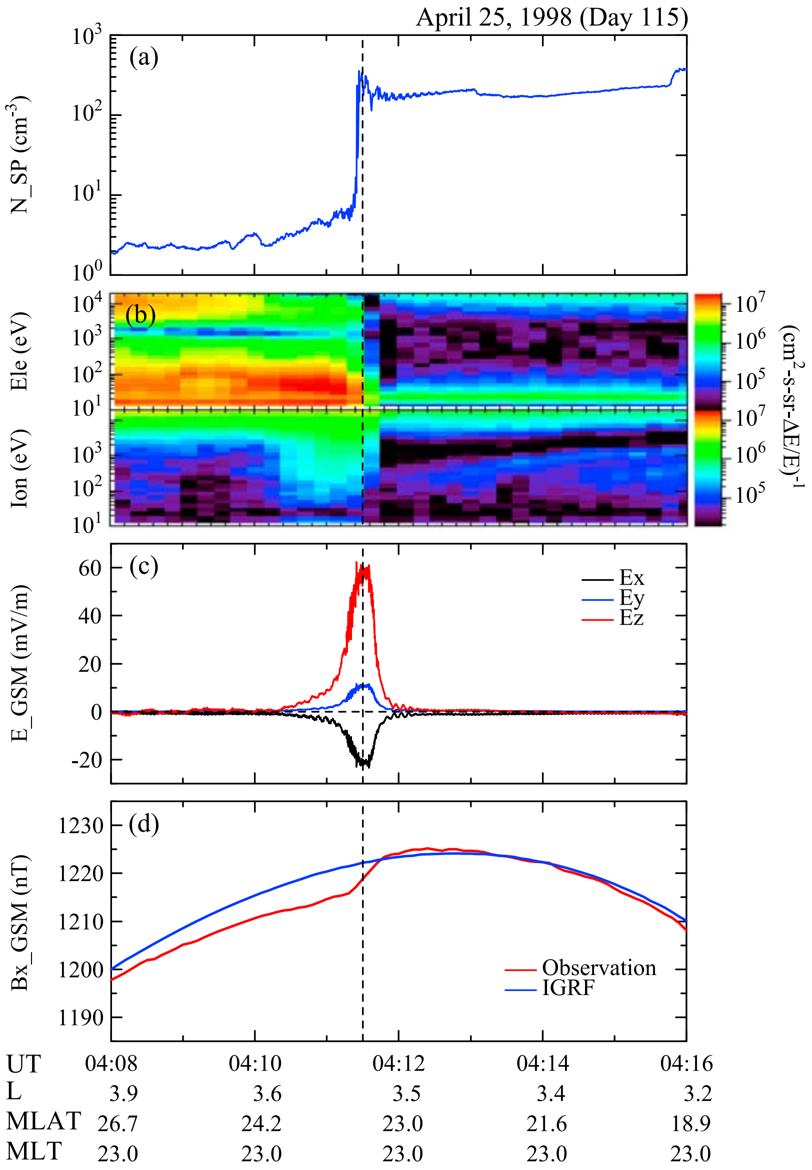

Figure 4. (a) Plasma density estimated from the Polar spacecraft potential data. (b) Energy-time spectrograms of electrons and ions. (c) Electric fields in GSM coordinates. (d) Comparison of observed magnetic field B_x (red) and model B_x determined from IGRF1995 (blue). The vertical dashed line in each panel indicates the plasmapause.

magnitude decreases in the electron fluxes from ~10 eV to ~10 keV. An enhanced ion flux in the plasma sheet was observed at an energy range of ~2–18 keV.

[14] Figure 4c shows the electric fields in GSM coordinates. For the event presented in this study, the electric field measurement on the spacecraft spin axis and the assumption that $\mathbf{E} \cdot \mathbf{B} = 0$ are not useful, so that the third component of the electric field is obtained by assuming that the component along the spin axis was zero. Since the three-dimensional electric field shown in Figure 4c is made from the two-dimensional spin-plane field and spacecraft was near the midnight, that is, the spin plane is close to the magnetic meridian, Polar observed a large electric field in a magnetic meridian plane. We note that the E_y component in Figure 4c could have a large uncertainty if the electric field has a large component along the spin axis. However, our assumption is not seriously wrong as long as our event is associated with SAID because SAID-associated electric field is radially outward and meridional in the magnetosphere as discussed below [*Okada et al.*, 1993; *Puhl-Quinn et al.*, 2007; *Mishin and Puhl-Quinn*, 2007].

[15] During the passage of the plasmapause, Polar encountered strongly enhanced electric field showing a spike signature. This electric field disappears as Polar moved into the plasmasphere, implying that the event is strongly localized near the plasmapause. Note that the third component of the electric field is obtained by assuming that the component along the spin axis is zero. The enhanced electric field occurred in all three components with negative E_x, positive E_y, and positive E_z perturbations. The electric field is dominant in E_z with a peak value of ~60 mV/m. As shown in Figure 1a, the E_z component is approximately perpendicular

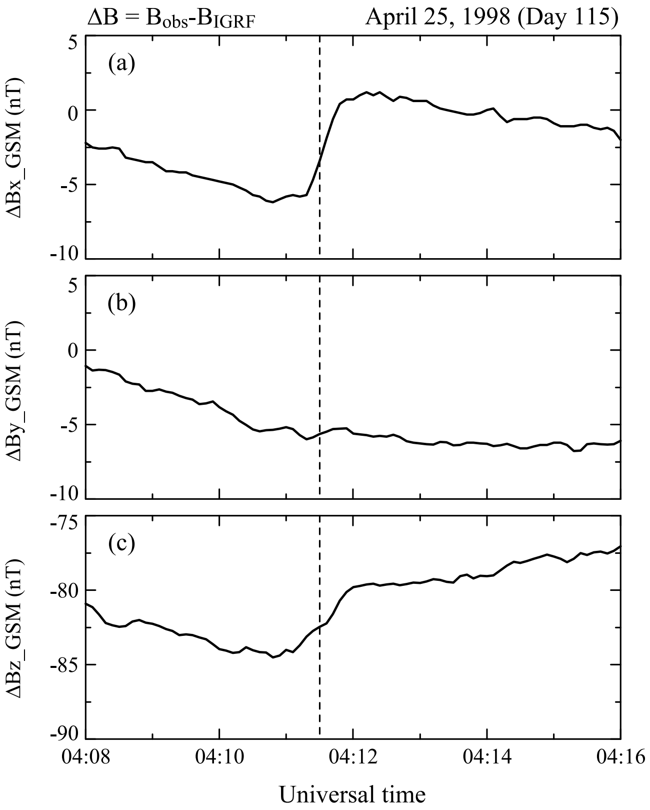

Figure 5. The difference between the observed and model magnetic fields (a) in B_x, (b) in B_y, and (c) in B_z. The vertical dashed line in each panel indicates the plasmapause.

to the dipole magnetic field. Thus, the electric field is outward and perpendicular to the ambient magnetic field.

[16] Figure 4d shows the magnetic field component B_x observed by Polar and the model B_x determined by the IGRF1995 magnetic field model. We note that the B_x component is dominant at the position of Polar. In the plasma sheet, the model field is larger than the observations. The observed B_x increases near the plasmapause, and the observations inside the plasmasphere follow the model field.

[17] In order to examine magnetic field variations on both sides of the plasmapause, the differences between the observed and model magnetic field components are plotted in Figure 5. An interesting feature is that there is a negative-then-positive perturbation in ΔB_x. That is, the magnetic field is reduced outside the plasmapause and enhanced inside the plasmapause. A similar field perturbation is also shown in ΔB_z. However, the negative-then-positive perturbation does not appear in ΔB_y.

3. Discussion and Conclusions

[18] We have reported the observation of a large amplitude electric field with a peak amplitude of ~60 mV/m at the plasmapause. This event was observed when Polar was located at a radial distance of 2.96 R_E, $L \sim 3.5$, the magnetic latitude of ~23°, and the magnetic local time of ~23 hours. The electric field is mostly radial, pointing outward, and accompanied by the background magnetic field baseline change (i.e., negative perturbation outside the plasmapause and positive perturbation inside the plasmapause). The magnetic field perturbations are dominant in the meridional plane.

[19] We suggest that the magnetic field perturbation shown in Figure 5 may be due to the dawnward plasmapause current ($\mathbf{J}_{pp}$) perpendicular to the background magnetic field. Assuming that the plasmapause is not moving in the earth-fixed frame and a thin current sheet at the plasmapasue, current density can be calculated using $\mu_0 J_{pp} = \Delta B_x/\Delta Z$, $\Delta B_x = B_{in}$-B_{out} at the plasmapause from the observed values ($\Delta B_x = 6.5$ nT), a scale length between a negative peak and a positive peak ($\Delta Z = \sim 270$ km), which is determined by the spacecraft motion during about 1-min interval. Then, $\mathbf{J}_{pp}$ at the plasmapause is about 0.02 μA/m^2. This current density is one order of magnitude larger than field-aligned currents (FAC) associated with SAID events near the magnetic equator [*Puhl-Quinn et al.*, 2007] and also one order larger than the ring current density and eastward current density during the recovery phase of a magnetic storm [*Lui et al.*, 1987].

[20] We can estimate the tailward $\mathbf{J}_{pp} \times \mathbf{B}$ force of 2.6×10^{-14} Pa/m with the observed magnetic field intensity of ~1300 nT. If we use the density of 200 cm^{-3} and temperature of 10 eV in the plasmasphere, the density of 5 cm^{-3} and temperature of 10 keV in the plasmasheet, and the scale length of 270 km, the pressure gradient is 2.8×10^{-14} Pa/m. Although our calculation of current density from the magnetic field perturbation is a very rough estimate, the estimated $\mathbf{J}_{pp} \times \mathbf{B}$ force agrees with the estimated pressure gradient. Thus, $\mathbf{J}_{pp} \times \mathbf{B}$ is balanced by the pressure gradient at the plasmapause.

[21] The intense electric field reported in our study is similar to radially-outward electric fields, which are associated with SAID, observed by Akebono [*Okada et al.*, 1993] at magnetic latitudes higher than ~32° (i.e., off the magnetic equator) and by Cluster [*Puhl-Quinn et al.*, 2007] at magnetic latitudes less than |14°| (i.e., near the magnetic equator) in the magnetosphere. Akebono observations reported that the large electric field events were dominant in the GSE-Z component with peak amplitudes of ~30–125 mV/m when the spacecraft was from 1900 to 2000 in MLT. Unlike our event, Akebono observed the large electric fields just outside the plasmapause when the location of the plasmapause was identified. Cluster observed SAID electric fields at the time of the plasmapause crossings. They were detected at ~22 MLT, and their amplitudes were in the range of ~15–25 mV/m.

[22] SAID-associated large poleward electric fields in the ionosphere were reported by *Smidy et al.* [1977]. They were observed in the premidnight sector near 60° invariant latitude and occurred near the ionospheric projection of the plasmapause. We note that the electric field polarities ($-E_x$ and $+E_y$) in our study are the same as those in *Smidy et al.* [1977] when they are mapped into the ionosphere, implying a strong westward drift velocity.

[23] Our event was observed during the substorm recovery phase. This is consistent with previous statistical studies of SAID [*Anderson et al.*, 1993] or SAID-associated electric fields [*Karlsson et al.*, 1998]. If the electric field of 60 mV/m observed at Polar in the magnetosphere (a radial distance of ~3 R_E) maps to the ionosphere, the electric field in the ionosphere is larger than that in the magnetosphere by a factor of about 7.5 (i.e., ~450 mV/m) [*Mozer*, 1970]. Such a large poleward electric field over 400 mV/m has been reported by

Karlsson et al. [1998]. It was observed near the vernal equinox, during a geomagnetic condition of Kp = 5-, and with a half width of the poleward electric field of about 0.3°. Our event was observed under similar geomagnetic and seasonal conditions to the strongest subauroral poleward electric field from *Karlsson et al.* [1998].

[24] Assuming that plasmapause motion is steady during our electric field event (i.e., during 2 min), a scale length of the event is about 650 km, which is comparable to Cluster observations [*Puhl-Quinn et al.*, 2007]. This corresponds to a ~0.5° band of latitude near 57° invariant latitude. This latitudinal scale is comparable to the strongest event from *Karlsson et al.* [1998].

[25] Our large electric field event was observed with a negative-then-positive magnetic field perturbation. We suggest that the magnetic field perturbation is associated with the dawnward plasmapasue current ($\mathbf{J}_{pp}$). Usually, the SAID-associated electric field is related to the region 2 field aligned current (FAC) and partial ring current [e.g., *Anderson et al.*, 2001]. Thus if our large electric field is associated with SAID, it is expected to be collocated with the region 2 downward FAC or westward partial ring current. However, our event is collocated with eastward plasmapause current. There are at least two possibilities suggested by our observations. One is that the usual explanation of the formation of SAID does not apply in our case. The other is that $\mathbf{J}_{pp}$ is not directly related to the large electric field. It must be noted that the present study is based on only one event observed on a single Polar pass. Obviously, it is very difficult to determine which possibility is appropriate to explain the relationship between the large electric field and the negative-then-positive magnetic field perturbation with our present data and we cannot generalize the quantitative argument. In the near future we will attempt to do a statistical survey of the large electric field and magnetic field perturbation events at the plasmapause.

[26] In conclusion we have shown that a large enhanced electric field with a peak amplitude of ~60 mV/m was observed at time of the plasmapause crossing by Polar. This crossing occurred for a short time interval less than one minute. This means that the plasmapause is spatially sharp. This big electric field was not observed in the previous and following plasmapause crossings, which have a smooth or complicated plasmapause structure. Thus, we suggest that the big electric field is associated with forming a sharp plasmapause structure. Our electric field event may be associated with SAID. While this finding was not unexpected in the magnetosphere, our event is one of few spacecraft observations of SAID-associated electric field in the magnetosphere. We also observed a negative-then-positive magnetic field perturbation at the plasmapause. This may not be due to the field-aligned current associated with SAID but due to dawnward plasmapause current.

[27] **Acknowledgments.** The geomagnetic indices (*Kp*, *AL*, and *Dst*) were provided at WDC for Geomagnetism, Kyoto. The Polar magnetic field data and plasma data were provided at http://cdaweb.gsfc.nasa.gov/cdaweb/. The Polar spacecraft potential and electric field data were provided at http://polarefi.ssl.berkeley.edu/. This work was supported by WCU program through NRF funded by MEST of Korea (R31-10016). This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0007393).

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