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Initial POLAR MFE observation of substorm signatures in the polar magnetosphere

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Abstract. This paper studies substorm influences in the polar magnetosphere using data from the POLAR magnetic field experiment (MFE). The POLAR spacecraft remains in the high altitude polar magnetosphere for extended periods around apogee. There it can stay at nearly constant altitude through all phases of a substorm, which was not possible on previous missions. We report such an event on March 28, 1996. Ground magnetometers monitored substorm activity, while the POLAR spacecraft, directly over the pole at $(-0.8,-0.6,8.5)\,R_E$ in GSM coordinates, observed a corresponding perturbation in the total magnetic field strength. The total magnetic field first increased, then recovered toward quiet levels, consistent with erosion of magnetic flux from the dayside magnetosphere, followed by transport of that flux to the magnetotail, and eventual onset of tail reconnection and the return of that magnetic flux to the dayside magnetosphere.

1. Introduction

The time sequence of the magnetic field strength, *BT*, in the magnetotail lobe at a distance of about 15 R_E and beyond during substorms is well known. In the tail lobe over a wide range of distances from the Earth, *BT* increases during the growth phase or loading phase, then recovers toward the pre-growth phase value during the expansion phase or unloading phase [e.g., *Fairfield and Ness*, 1970; *Camidge and Rostoker*, 1970; *Russell and McPherron*, 1973; *Nishida and Nagayama*, 1975]. On the other hand, the time sequence of *BT* in the polar magnetosphere, the magnetic field lines of which are connected to those in the tail, has not been examined until now due to the unavailability of data in this region.

The ISTP spacecraft POLAR with its long dwell-time in the high altitude polar magnetosphere enables for the first time a detailed study of the time sequence of the magnetic field strength during substorms. In this paper we examine the influence of a substorm on the polar magnetosphere and present initial results, observed on March 28, 1996, when POLAR was directly above the polar cap and close to halfway between the surface of the Earth and the expected position of the magnetopause.

2. Data

The top panel of Figure 1 shows the interplanetary magnetic field (IMF), in GSM coordinate system, observed with the INTERBALL-1 spacecraft during an interval 0000–0800 UT on March 28, 1996. The Russian INTERBALL-1 satellite was launched on August 3, 1995. The magnetic field experiment onboard INTERBALL-1 is described by, e.g., *Klimov et al.* [1997]. The position of the satellite at 0300 UT on March 28, 1996 was $(X,Y,Z)=(14.4,21.6,2.3)\,(R_E)$ in GSE coordinates and the satellite was moving toward the Earth. We roughly estimate the propagation time lag from INTERBALL-1 to the Earth to be ~3 min, by simply dividing the spacecraft $X_{\rm GSE}$ position by 440 km/s, which is the average solar wind speed observed by IMP 8 around $(-3,30,19)\,(R_E)$ in GSM. The figure shows a southward turning of the IMF around 0242 UT. IMF B_Z reached a minimum value ~ -5 nT at 0301 UT, remained at that level ($B_Z < -4$ nT) until ~0413 UT, and then started to recover toward zero. The same variation was seen by IMP 8.

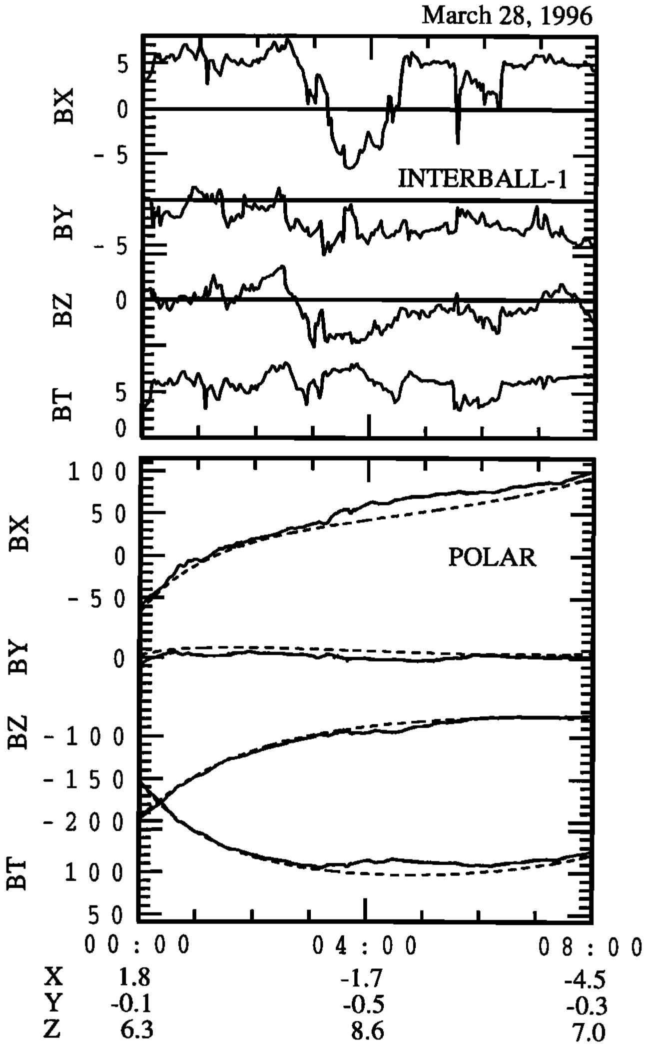

Figure 1. (top) Shows the magnetic field, in GSM coordinates, observed with the INTERBALL-1 spacecraft, during 0000–0800 UT, March 28, 1996. (bottom) Solid lines show the magnetic field, in GSM coordinates, observed with the POLAR spacecraft. Dotted lines show the model field by *Tsyganenko* [1995]. The attached text shows the position of POLAR in GSM coordinates.

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A southward IMF of the strength and duration shown in the top panel of Figure 1 could lead to substorm activity, and the top panel of Figure 2 supports that expectation. The panel shows X components of the ground magnetometer data from the CANOPUS network [e.g., *Rostoker et al.*, 1995], from the Geological Survey of Canada (GSC), and from the STEP Polar Network run by the University of Tokyo, for the same interval as that of Figure 1. Table 1 lists the stations and their locations in geomagnetic coordinates, assuming the geomagnetic north pole at 79.34° in geographic latitude and 288.51° in geographic longitude (based on IGRF 95). Among the listed stations, Poste-de-la-Baleine and Iqaluit are operated by the GSC, Schefferville is part of the STEP Polar Network, and the others are part of the CANOPUS network. The figure shows substorm activity during the interval 0300–0700 UT. More detailed discussion, including the explanation of the lines A-D in the figure, is given in the next section.

The bottom panel of Figure 1 shows data from the magnetic field experiment (MFE) on board the POLAR spacecraft [*Russell et al.*, 1995], in the GSM coordinate system (solid lines). Dotted lines show the model field, calculated as the summation of the IGRF95 and the Tsyganenko 1995 model [*Tsyganenko*, 1995]. The satellite was located at (−0.8,−0.6,8.5) (R_E) in GSM coordinate system at 0300 UT, and was outbound. The subsequent apogee passage took place around 0511 UT and the apogee position was (−2.7,−0.4,8.5). The figure shows that the observed total magnetic field strength BT deviated from the model value BT_{model}, during the interval from ~0300 UT to ~0700 UT. This interval is about the same as the substorm interval shown in Figure 2.

3. Behavior of the Polar Magnetosphere

The deviation of BT from the model, as shown in the bottom panel of Figure 1, cannot be mistaken as a spatial pattern, because the deviation took place when the spacecraft was near apogee: BT_{model} was fairly flat when the deviation was observed. In addition, preceding and following orbits without substorm activity do not show a similar deviation near apogee (not shown). We also note that the dynamic pressure observed by IMP 8 did not change much, and that the small change was not much correlated with the change in BT (not shown). The deviation in BT therefore must be associated with the concurrent substorm activity. Similar to the observations in the magnetotail lobe, BT first increased, and then recovered toward the quiet value, in the polar magnetosphere. Thus the same explanation could be applied to this polar phenomenon: magnetic flux tubes reconnected at the dayside magnetopause, under southward IMF, are carried downtail, expand the radius of the post-terminator magnetosphere and magnetotail, increasing the angle between the tail magnetopause and the solar wind flow, and increasing the pressure of the solar wind on the boundary.

The exact timing of the BT increase and decrease, in comparison with the ground signatures, is of interest, and we examine it using Figure 2. The middle panel of Figure 2 shows again the magnetic field observed by POLAR, but this time the difference between the observation and the model, $\delta\mathbf{B} \equiv \mathbf{B} - \mathbf{B}_{\mathrm{model}}$, is shown, and a new coordinate system is adopted, called the field-aligned (FA) coordinate system. Here, the Z_{FA} unit vector $\mathbf{k}_{\mathrm{FA}}$ is parallel to $\mathbf{B}_{\mathrm{model}}$, the Y_{FA} unit vector $\mathbf{j}_{\mathrm{FA}}$ is defined as $\mathbf{j}_{\mathrm{FA}} = \mathbf{k}_{\mathrm{FA}} \times \mathbf{r}$, where $\mathbf{r}$ is the position vector of the spacecraft, and the X_{FA} unit vector $\mathbf{i}_{\mathrm{FA}}$ satisfies $\mathbf{i}_{\mathrm{FA}} = \mathbf{j}_{\mathrm{FA}} \times \mathbf{k}_{\mathrm{FA}}$. Around 0400 UT, the model magnetic field was southward and sunward and the spacecraft was located near the GSM Z axis, (see the

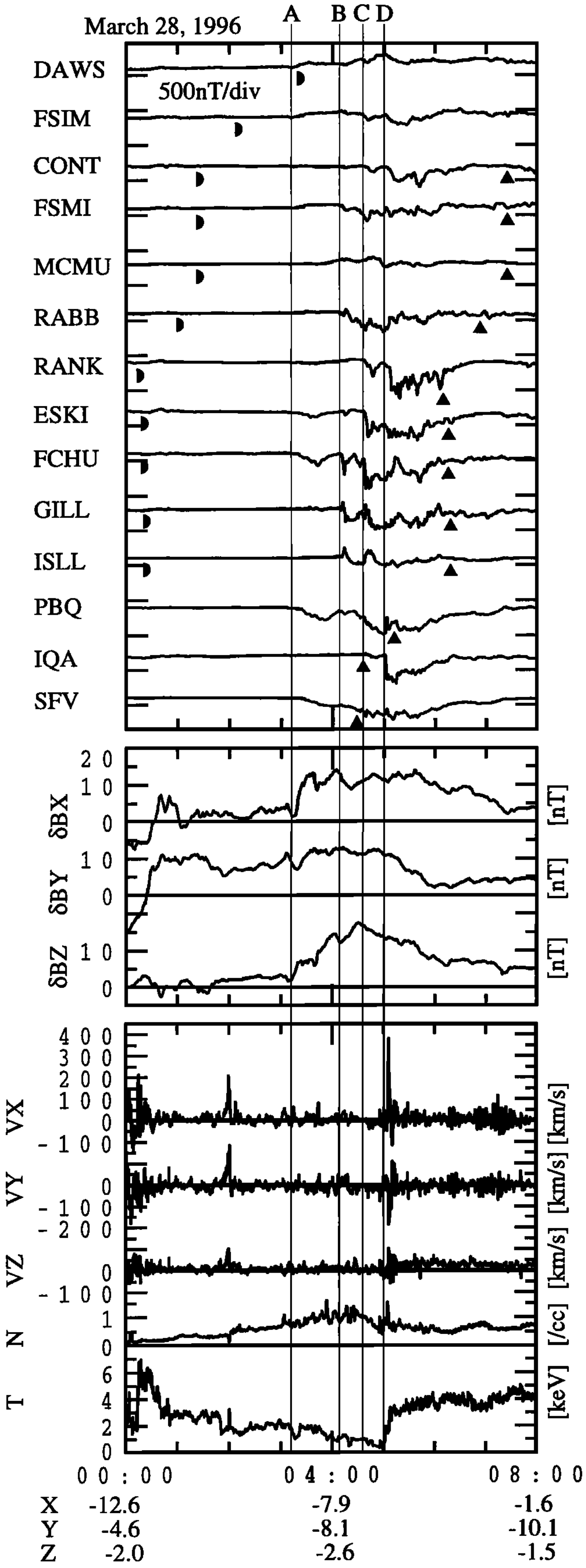

Figure 2. (top) Shows ground magnetometer X components data for the same interval as Figure 1. Superposed half-circles show the local dusk (1800 LT), and triangles show the local midnight (0000 LT). (middle) Shows the magnetic field observed at POLAR minus the model field, expressed in the "field-aligned coordinate system". See text for the definition of the coordinate system. (bottom) Shows the data from the GEOTAIL spacecraft: From top, the plasma ion velocity components in GSM coordinates, plasma ion density and temperature. Refer to the text for vertical lines A through D.

Table 1. Locations of ground magnetometer stations

Abbreviation	Station Name	Geomagnetic Latitude (deg.)	Geomagnetic Longitude (deg.)
DAWS	Dawson	66.13	269.63
FSIM	Fort Simpson	67.27	290.85
CONT	Contwoyto Lake	72.64	298.32
FSMI	Fort Smith	67.16	303.34
MCMU	Fort McMurray	64.06	306.60
RABB	Rabbit Lake	66.62	315.02
RANK	Rankin Inlet	72.42	327.81
ESKI	Eskimo Point	70.56	326.16
FCHU	Fort Churchill	68.25	327.47
GILL	Gillam	65.86	327.84
ISLL	Island Lake	63.37	328.82
PBQ	Poste-de-la-Baleine	65.85	351.28
IQA	Iqaluit	74.39	4.88
SFV	Schefferville	65.42	6.36

bottom panel of Figure 1), thus $\mathbf{j}_{\mathrm{FA}}$ is directed roughly dawnward, and $\mathbf{i}_{\mathrm{FA}}$ is directed roughly northward. We note $\delta B_{Z,\mathrm{FA}}$ (bottom curve) is almost the same as $BT - BT_{\mathrm{model}}$, because $\mathbf{B}$ is almost parallel to the Z_{FA} axis. For the sake of physical clarity, we will use the expression $BT - BT_{\mathrm{model}}$, or δBT, instead of $\delta B_{Z,\mathrm{FA}}$ throughout this paper.

$\delta B_{Y,\mathrm{FA}}$ (roughly dawnward) did not change much when δBT started changing around 0312 UT (line A superposed on the figure), but $\delta B_{X,\mathrm{FA}}$ (roughly northward, perpendicular to the ambient field) started increasing at that time. That is, the magnetic field vector became less tilted (ambient field was southward and sunward), consistent with decreased flaring of the lobe field. This deflection may be an effect of the pileup of the reconnected flux at the polar magnetopause northward of the satellite. That is, the piled-up flux would push the pre-existing polar magnetosphere tailward, and due to the finite conductivity of the ionosphere, the footprint of the field lines moved slower than the field lines in the polar magnetosphere, thus leading to less tilt.

4. Behavior of the Auroral Currents

Returning to the timing study, the line A superposed on Figure 2 marks the start of the increase in δBT. Many of the ground magnetometers data start to be perturbed; the perturbations are gradual until the time of line B, and thus they are consistent with the loading phase of the substorm. The difference field, δBT, at POLAR suggests that the flux pileup continued during this interval. We note there was a minimum around 0330–0337 UT in the data from FCHU and PBQ. (The Z component at FCHU also showed a general minimum, with twin (negative) peaks around 0330 and 0337 UT, (not shown).) However at ESKI and GILL, adjacent stations of FCHU in the same meridional chain, there was not much peak-like perturbation. This feature suggests that this minimum occurred only within a limited range of latitudes including FCHU and PBQ, possibly on a narrow auroral oval during the loading phase. We note the Z component of the magnetometer data showed a small positive perturbation at ESKI, a large negative perturbation at FCHU, and a small negative perturbation at GILL (not shown). This also suggests that the current was narrow, and was located between ESKI and GILL, and a little north of FCHU. LANL energetic electrons (>50 keV) at synchronous orbit (not shown) exhibit no flux enhancement at this time. The decrease in $\delta B_{X,\mathrm{FA}}$ and δBT at POLAR around 0339 UT might be related to the above weak ground activity, but the particle data obtained by POLAR suggest a different explanation as discussed in section 6.

Around 0408 UT (line B), FCHU and GILL recorded a sudden decrease in the X component. Lines C and D mark the following sudden decreases in the X component at several stations (around 0435 and 0500 UT), indicative of intensification of the westward electrojet. Whether they all correspond to substorm onsets is an important question, because they are not necessarily reflected in the magnetic field at POLAR. The difference field, δBT, at POLAR reached a maximum around 0430 UT, and the interval 0312–0430 UT (78 min) is comparable in length to the interval 0301–0413 UT (72 min) when the IMF was largely southward (see Figure 1). It is therefore likely that the interval 0312–0430 UT corresponds to the substorm loading phase. (We note that we estimated above the time lag from INTERBALL-1 to the Earth to have been ~3 min, while the observed lag appears to be 11–17 min. This difference may come in part from the response time of the magnetopause to a southward turning of the IMF.) However, the electrojet intensification at ~0408 UT (line B) preceded the 0430 UT field maximum at POLAR. We interpret this intensification at ~0408 UT as the first onset signature of multiple expansion onsets (lines B, C, and D); the interval 0408–0430 UT was in the initial unloading phase, but the pileup of the magnetic flux onto the polar magnetosphere continued, because the IMF was still southward. It is possible that the time variation of BT in the polar magnetosphere reflects the time variation of the energy input from the solar wind more directly than in the magnetotail proper where the effects of substorm onsets are also apparent. Another possible reason for the delay from the initial onset (line B) to the maximum δBT at POLAR would be the propagation time delay of the signal of the onset from the source region (in the near-Earth tail) to the polar magnetosphere. However, as stated in the next section, there is some difficulty with this explanation.

5. Behavior of the Plasmasheet

It is also interesting to compare the substorm signature in the polar magnetosphere with that in the magnetotail. The GEOTAIL spacecraft was located around (−6.4,−8.8,−2.4) (R_E) in GSM coordinates at 0500 UT. Figure 2 shows the data of POLAR and GEOTAIL in the same time frame. The bottom panel shows data from the low-energy plasma detector (LEP) on board GEOTAIL [*Mukai et al.*, 1994]. The GEOTAIL spacecraft was located within the plasmasheet throughout the interval of the figure: Before ~0500 UT, the ion density was rather high and the ions were not moving much (as shown in the ion bulk velocity data), which are features of the plasmasheet ions. The gradual temperature decrease from ~0300 UT to ~0500 UT can be explained in terms of the plasmasheet thinning during the loading phase of the substorm: Because of the thinning, the relative distance of the spacecraft from the center of the plasmasheet increased, which caused the decrease in temperature. The ion density gradually increased from ~0300 UT to ~0430 UT and then decreased until ~0500 UT. The decrease is consistent with the above-explained increase in the spacecraft distance from the center of the plasmasheet during the loading phase. The increase until ~0430 UT may have been caused by the compression of the plasma sheet during the loading phase, which overcame the effect of the relative motion of the spacecraft away from the plasmasheet center. Another possibility is the dawnward motion of the spacecraft: As a spatial structure of the plasmasheet, its density increases with decreasing distance from the flank magnetopause [e.g., *Lennartsson and Shelley*, 1986].

After ~0500 UT, the ion temperature jumped up, and there was a burst of earthward and dawnward ion flow with the duration of ~3 min. Thus, at first sight, GEOTAIL data appear to suggest that the substorm onset was ~0500 UT. There is a 52 min lag from 0408 UT, the initial onset time on the ground (line B). A possible way to explain this difference is the Y position of GEOTAIL. That is, because GEOTAIL was located at $Y = -8.8$, or at 3.6 hour MLT, dawnward propagation of substorm signal, from the onset region, might have taken several tens of minutes to reach the GEOTAIL position. *Nagai* [1982, Figure 12] reports that the east-west propagation speed of the substorm onset region, or so called the current wedge, is 3 ~ 7 [min/MLT hour]. We note in Figure 2 that the multiple onsets are more apparent at the 327° geomagnetic longitude chain than in any other longitudes, thus the onsets are likely to have happened in the premidnight sector, around 22 hour MLT. Then, the propagation time from 22 hour to 3.6 hour MLT is estimated to have been 17 ~ 40 min. The observed time lag (52 min) is larger than 40 min, but at least some of the lag may be explained in terms of the east-west propagation of the substorm heating of the plasmasheet. We note that GOES 8 satellite detected an initial onset of dipolarization at ~0427 UT and at ~23.5 hour MLT (not shown). That is, the onset at GOES 8, located between the ground magnetometer chain and GEOTAIL in longitude, happened after the event B and before the onset at GEOTAIL, which is consistent with the eastward propagation of the current wedge. We also note that LANL satellite 1990-095 detected an initial onset of energetic electrons (>50 keV) at ~0420 UT and at ~2 hour MLT (not shown). This is also consistent, and the earlier onset than at GOES 8 may be explained in terms of faster propagation of energetic particles than the current wedge.

Finally, in relation to the above, we note that POLAR was similarly distant from the expansion onset region (presumably in the near-Earth tail) to that of GEOTAIL. Thus the onset signal would have spent similar time to propagate to POLAR, but the time delay from the initial ground onset to the δBT maximum at POLAR (from ~0408 to ~0430 UT) was smaller than that at GEOTAIL (from ~0408 to ~0500 UT). Thus the delay for POLAR may not be explained in terms of the propagation of the onset signal.

6. Polar Energetic Particles

Finally we briefly mention the IMF B_X effect on the magnetic field and particle populations at the site of POLAR. The instrument called CEPPAD/IPS on board POLAR [*Blake et al.*, 1995] observes ions in the energy range from 12 to 1500 keV. From 0000 to 0800 UT on March 28, 1996, this instrument observed almost nothing, except for the interval from 0333 to 0357 UT when the instrument recorded $\lesssim$ 60 keV ions (not shown). These ions were rich in He^{++} and high-charge state (> +6) Oxygen (not shown). Thus they were of solar wind origin. This phenomenon is often observed by CEPPAD in northern polar magnetosphere when IMF $B_Z > 0$, or when $B_X < 0$, and most strongly when both are true [*Spence and Blake*, 1997]. We note that IMF B_X was negative during the interval from 0315 to 0420 UT (see Figure 1). Although IMF B_Z was negative throughout the interval, reconnection at the lobe magnetopause is possible due to the negative IMF B_X, which could explain the observed solar wind-origin particles. δBT at POLAR was generally increasing during this interval (see Figure 2), indicative of continuing dayside merging. However, there was a small dip in δBT around 0339 UT, which could be a diamagnetic effect caused by the particle population. We also note $\delta B_{X,\mathrm{FA}}$ transiently decreased at the same time, which indicates that the magnetic field tilt briefly recovered toward the pre-substorm value. Lobe reconnection at this time is consistent with this change in the magnetic field tilt angle.

7. Summary

The general substorm correspondence of the behavior of the magnetic field at (−0.8,−0.6,8.5) is clear. The magnetic field increases during the loading phase and decreases during the unloading phase. Good correspondence of the polar field variations and the ground onsets is seen. Activity at the GEOTAIL spacecraft to the dawnside of the near tail however is delayed, presumably due to the east-west propagation lag of the current wedge.

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