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Initial POLAR MFE observation of substorm signatures in the polar magnetosphere

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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) RE 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 Re 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)(Re) 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 position by 440 km/s, which is the average solar wind speed observed by IMP 8 around (-3,30,19)(Re) in GSM. The figure shows a southward turning of the IMF around 0242 UT. IMF Bz reached a minimum value ~ -5 nT at 0301 UT, remained at that level (Bz < -4 nT) until ~0413 UT, and then started to recover toward zero. The same variation was seen by IMP 8.

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Figure 1. (top) Shows the magnetic field, in GSM coordinates, 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)(Re) 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 position by 440 km/s, which is the average solar wind speed observed by IMP 8 around (-3,30,19)(Re) in GSM. The figure shows a southward turning of the IMF around 0242 UT. IMF Bz reached a minimum value ~ -5 nT at 0301 UT, remained at that level (Bz < -4 nT) until ~0413 UT, and then started to recover toward zero. The same variation was seen by IMP 8.
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) (RE) 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 $B_T$ deviated from the model value $B_{T,mod}$, 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 $B_T$ 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: $B_{T,mod}$ 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 $B_T$ (not shown). The deviation in $B_T$ therefore must be associated with the concurrent substorm activity. Similar to the observations in the magnetotail lobe, $B_T$ 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 $B_T$ 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, $\delta B \equiv B - B_{model}$, is shown, and a new coordinate system is adopted, called the field-aligned (FA) coordinate system. Here, the $Z_{FA}$ unit vector $k_{FA}$ is parallel to $B_{model}$, the $Y_{FA}$ unit vector $i_{FA}$ is defined as $i_{FA} = k_{FA} \times r$, where $r$ is the position vector of the spacecraft, and the $X_{FA}$ unit vector $k_{FA}$ satisfies $k_{FA} = i_{FA} \times k_{FA}$. 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](image-url)
bottom panel of Figure 1), thus \( \mathbf{J}_\parallel \) is directed roughly dawnward, and \( \mathbf{i}_\parallel \) is directed roughly northward. We will use the expression \( \mathbf{B}_T - \mathbf{B}_\text{model} \), or \( 6\mathbf{B}_T \), instead of \( \mathbf{B}_T \) throughout this paper. However, as stated in the next section, there is some difficulty in explaining this intensity at \( \sim 0408 \) UT as the first onset signature of multiple expansion onset signatures (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 \( \mathbf{B}_T \) 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 \( 6\mathbf{B}_T \) 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 \((-6.4, -8.8, -2.4) \) (RE) 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 \( \sim 0500 \) 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 \( \sim 0300 \) UT to \( \sim 0500 \) 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 \( \sim 0300 \) UT to \( \sim 0430 \) UT and then decreased until \( \sim 0500 \) 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 \( \sim 0430 \) 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 \( \sim 0500 \) UT, the ion temperature jumped up, and there was a burst of earthward and dawnward ion flow with the duration of \( \sim 3 \) min. Thus, at first sight, GEOTAIL data appear to suggest that the substorm onset was \( \sim 0500 \) 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 \( 3 \sim 7 \) [min/MLT] hour. We note in Figure 2 that the multiple onsets are more apparent at the 327° geomagnetic latitude 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 \( \delta B \)T maximum at POLAR (from ~0408 to ~0340 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 \( >60 \) keV ions (not shown). These ions were rich in \( \text{He}^+ \) 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 \( B_x > 0 \), 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 \( B_y \) 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. \( \delta B \)T at POLAR was generally increasing during this interval (see Figure 2), indicative of continuing dawnside merging. However, there was a small dip in \( \delta B \)T around 0339 UT, which could be a diamagnetic effect caused by the particle population. We also note \( \delta B_y \), 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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References


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