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# POLAR magnetic observations of the low-altitude magnetosphere during the January 1997 coronal mass ejection/magnetic cloud event

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**Abstract.** During the January 1997 coronal mass ejection/magnetic cloud event, the POLAR spacecraft experienced three successive perigee passes with dramatically different interplanetary magnetic field (IMF) and solar wind conditions on January 9, 10 and 11. The magnetic field observations during these three successive perigee passes are used to examine the response of the low-altitude polar and auroral magnetosphere to different IMF and solar wind conditions. We find that field-aligned currents are controlled mainly by the southward IMF component. They are greatly enhanced during strongly southward IMF conditions on January 10, but the solar wind dynamic pressure has little effect on their strength during the passage of the high-density solar wind filament on January 11. Thus, drag on the magnetosphere is principally due to reconnection at the magnetopause, with little due to viscous effects. Effects of the ring current and the magnetopause current can be identified in the magnetic field data in the low-altitude magnetosphere. During the magnetic storm of January 10, the ring current exhibits strong dawn-dusk asymmetry. It is much stronger in the dusk sector than in the dawn sector.

## Introduction

The Coronal Mass Ejection (CME)/Magnetic Cloud Event of January 6-11, 1997 was the first such event that has been followed from its generation on the sun to its effects on the magnetosphere and ionosphere in real time. On January 6, 1997 the SOHO spacecraft observed a halo coronal mass ejection [*Michels*, 1997; *Burlaga et al.*, 1998]. On the same day, ground-based H-alpha images of the sun revealed the disappearance of a central meridian filament, also signaling the possible ejection of material toward the Earth [See SHINE group preliminary report at http://umbra.nascom.nasa.gov/istp/SHINE_report.html, chaired by D. Webb]. This CME /Magnetic Cloud was seen at 1 AU by the WIND spacecraft on January 10-11 and the overview of the solar wind plasma and the interplanetary magnetic field was described in details by *Burlaga et al.* [1998]. Before and during the arrival of this magnetic cloud, the POLAR spacecraft experienced three successive perigee passes through the polar magnetosphere with dramatically different interplanetary magnetic field (IMF) and solar wind conditions. The magnetic field observations during these three successive perigee passes are used to examine the response of the low-altitude polar and auroral magnetosphere to different IMF and solar wind conditions. Because of the extreme conditions seen in the solar wind, these three passes clearly illustrate how the low-altitude magnetosphere reacts to the solar wind.

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Figure 1 shows the IMF and the solar wind conditions observed by the WIND spacecraft (courtesy of R. Lepping and K. Ogilvie), as well as the Dst Index (courtesy of NGDC) during the January 1997 event. In the bottom panel of Figure 1, we also show the Dst index with the effect of the magnetopause currents removed with a correction proportional to the square root of the solar wind dynamic pressure [*Burton et al.*, 1975; *Russell et al.*, 1994a, b]. This corrected Dst index (Dst*) contains mainly the ring current contribution [*Burton et al.*, 1975]. The shaded intervals labeled a, b and c are times when the POLAR spacecraft is near its perigee, passing through the low-altitude magnetosphere. During the perigee pass on January 9, before the magnetic cloud arrived at the Earth, the solar wind has a nominal

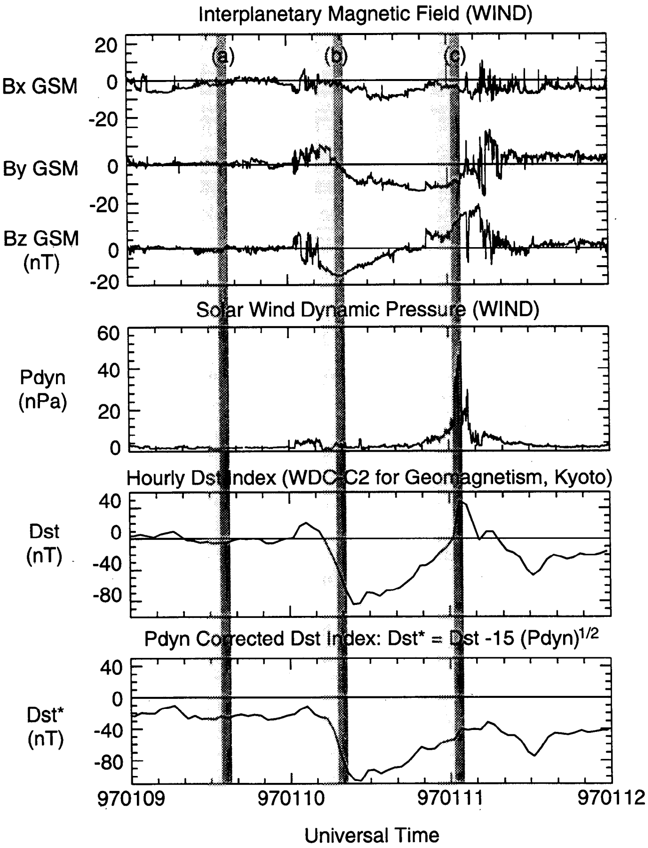

**Figure 1.** The interplanetary magnetic field by WIND (courtesy of R. Lepping), the solar wind conditions by WIND (courtesy of K. Ogilvie), the Dst index (courtesy of NGDC) and Dst index with the effect of the magnetopause current removed with a correction proportional to the square root of the solar wind dynamic pressure during January 1997 event.

dynamic pressure of ~ 1.6 nPa, and a small magnetic field of ~ 3 nT with an average Bz of ~ 0 nT. The corrected Dst index of -26 nT is that expected from a quiet-time ring current. The next perigee pass was on January 10, shortly after the magnetic cloud hit the Earth and the IMF had turned strongly southward (Bz ~ -15 nT) with a solar wind dynamic pressure ~ 3 nPa. When the magnetic cloud arrived at the Earth, the Dst index increased initially to ~ +20 nT in response to the sudden increase of the solar wind dynamic pressure and then decreased as the ring current built up. The corrected Dst index shows no increase at the time of the SSC indicating that no significant change in the ring current or the tail current occurred until the IMF turned southward. At the time of the subsequent perigee pass, the Dst index was ~ -50 nT and the corrected Dst index due to the ring current was ~ -80 nT. The third perigee pass on January 11 occurred after the IMF had rotated northward and during the period of an extremely high-density solar wind filament observed by WIND. The magnitude of the IMF is very high at this time with a strongly northward component (Bz ~ +15 nT) and a large negative By component (By ~ -10 nT). The solar wind dynamic pressure is also extremely high (~ 40 nPa on average), and is responsible for a large positive Dst index, ~ +50 nT, overpowering the pre-existing ring current depression. The corrected Dst value shown in the bottom panel of Figure 1 shows that the ring current continued its slow decay through this period, and the high solar wind dynamic pressure produced no obvious effects on the ring current.

## POLAR Orbit

The POLAR spacecraft is in a highly inclined, elliptical orbit around the Earth. Its apogee is about 9 $R_E$ in the northern high-latitude magnetosphere. Its perigee is about 1.8 $R_E$ in the southern high-latitude magnetosphere. With time, the plane of the orbit "precesses" with respect to the Earth-sun line due to the motion of the Earth around the sun within approximately a one-year period. During the January 10-11, 1997 magnetic cloud event, the POLAR orbit is nearly on the dawn-dusk meridian. Figure 2 shows the POLAR orbit in solar magnetic coordinates (SM) in which the SM Z-axis is along the magnetic dipole direction and the SM X-Z plane contains the solar direction. The top panels are the orbit projections on the SM XY plane (view from the magnetic north), and the bottom panels are the orbit projections on the SM YZ plane (view from the sun) for the three intervals of interest on January 9, 10 and 11. During these perigee passes, the POLAR spacecraft crosses the equational plane from north to south and moves from dawn to dusk over the southern polar cap.

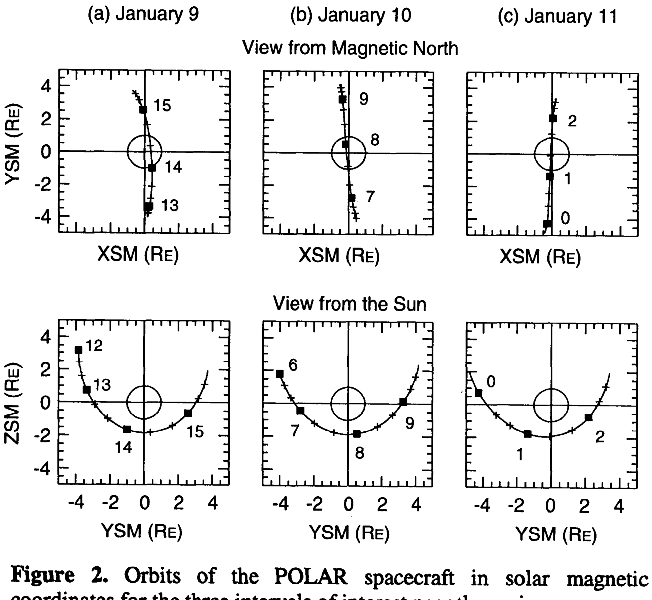

**Figure 2.** Orbits of the POLAR spacecraft in solar magnetic coordinates for the three intervals of interest near the perigee passes on January 9, 10, and 11 respectively. The top panels are the orbit projections on the SM XY plane (view from the magnetic north). The bottom panels are the orbit projections on the SM YZ plane (view from the sun).

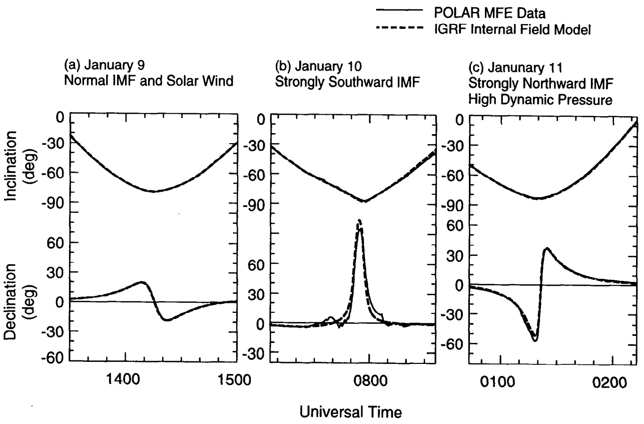

**Figure 3.** The magnetic field inclination and declination angles during the three perigee passes, (a) January 9, (b) January 10, and (c) January 11. The solid traces are from POLAR MFE data and the dashed traces are from IGRF internal field model.

## POLAR Magnetic Field Observations

In this study we use the magnetic field data [*Russell et al.*, 1995] for the three perigee passes to examine how the low-altitude magnetosphere responds to the different solar wind and IMF conditions. We are interested in deviations of the magnetic field from the Earth's internal magnetic field configuration. Herein, we use the 1995 International Geomagnetic Reference Field at the epoch of date (IGRF 95 model) as the baseline for the data and display the residual field after subtracting the model field from the data. The residuals of the magnetic field are contributed by the various external current systems, mainly the ring current, the magnetopause current, the region 1 and 2 field-aligned currents, and the magnetotail current.

First we compare the observed magnetic field inclination and declination angles with those calculated from the IGRF 95 model. The inclination is defined as the angle between the observed magnetic field and the local horizontal plane consistent with its definition in ground-based studies. The declination is the angle of the field projection in the local horizontal plane as measured from the local dipole magnetic meridian. Figure 3 shows the magnetic field inclination and declination angles during the three perigee passes. The observed inclination angle agrees with the model prediction very well throughout all three perigee passes. The observed and calculated declination angle agrees best throughout the perigee pass under normal IMF and solar wind conditions (January 9); and they agree fairly well for strongly northward IMF and high dynamic pressure (January 11). The largest deflection of declination angle occurs for strongly southward IMF (January 10). Since the magnetic field is largely perpendicular to the local horizontal plane near the perigee, the deflection in declination angle indicates that the deflection in the magnetic field is mainly in the local horizontal plane, or in the direction transverse to the local magnetic field. Thus the deflection is caused by the field-aligned current, and the southward IMF Bz plays the dominant role in determining the strength of the field-aligned current.

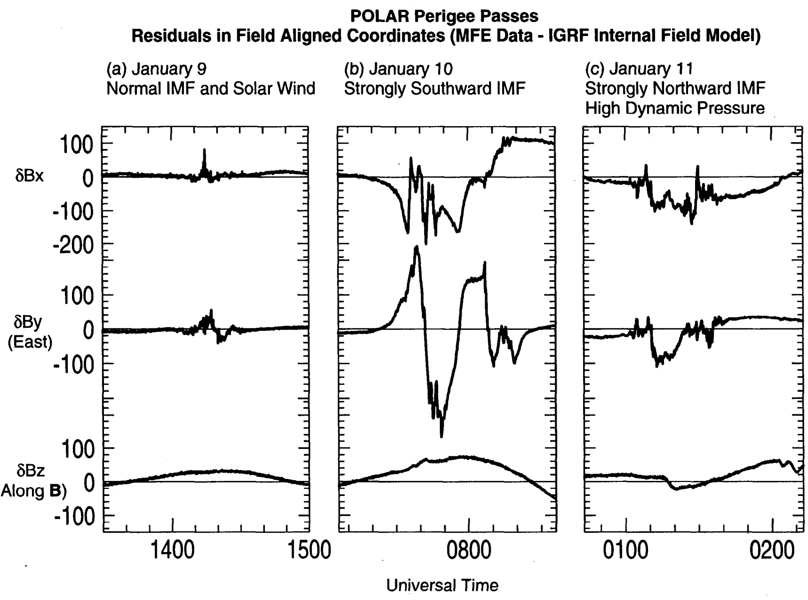

**Figure 4.** The magnetic field residuals (MFE data - IGRF model) in field-aligned coordinates (FAC) for the three perigee passes, (a) January 9, (b) January 10, and (c) January 11. In FAC, Z is along the local model field, Y is perpendicular to the model field and eastward, and X is perpendicular to the model field and completes the right-handed system.

Figure 4 shows the magnetic field residuals in field-aligned coordinates (FAC), where Z is along the local model magnetic field, Y is perpendicular to the model field and eastward, and X is perpendicular to the model field and completes the right-handed system. In the FAC coordinate system, the magnetic signature of the field-aligned current appears in the residuals of the FAC X and FAC Y components, and the residual of the FAC Z component is basically the residual of the magnetic-field strength. Comparing the three panels of Figure 4, the field-aligned currents as shown in residuals in FAC X and FAC Y components are much stronger under strongly southward IMF conditions (January 10). Based on the net change in FAC By component, the field-aligned current ranges from about 40 mA/m on January 9 to over 300 mA/m in the region 1 dawn sector on January 10, and returning to about 80 mA/m on January 11. In Figure 5, the magnetic field vector residuals are plotted along the track of POLAR ionospheric footprints for January 9, 10 and 11 perigee passes. On January 10 (Figure 5b), the sunward residual vectors in the dawn and dusk sectors are separated by the antisunward vectors in the polar cap. This is the signature that one would observe when passing through unbalanced Region 1/Region 2 field-aligned current sheets in the dawn and dusk sector. The Region 1 current flows into the ionosphere in the dawn sector and out of the ionosphere in the dusk sector. The Region 1 current in the higher latitudes is stronger than the lower latitude Region 2 current, which is consistent with previous results [*Iijima and Potemra*, 1978].

The third pass, on January 11, illustrates that an increase of solar wind dynamic pressure does not enhance the field-aligned currents under northward IMF conditions. The time corresponding to the leading edge of the high density solar wind filament is ~ 0115 UT, as indicated by a sudden decrease in the residual of the magnetic field strength caused by the sudden increase in magnetopause current (bottom panel of Figure 4c). The similarity of the magnetic perturbations on the dawn and dusk sides of the polar cap indicates that there is no enhancement in FAC Bx and By residuals associated with the passage of the high-density solar wind filament.

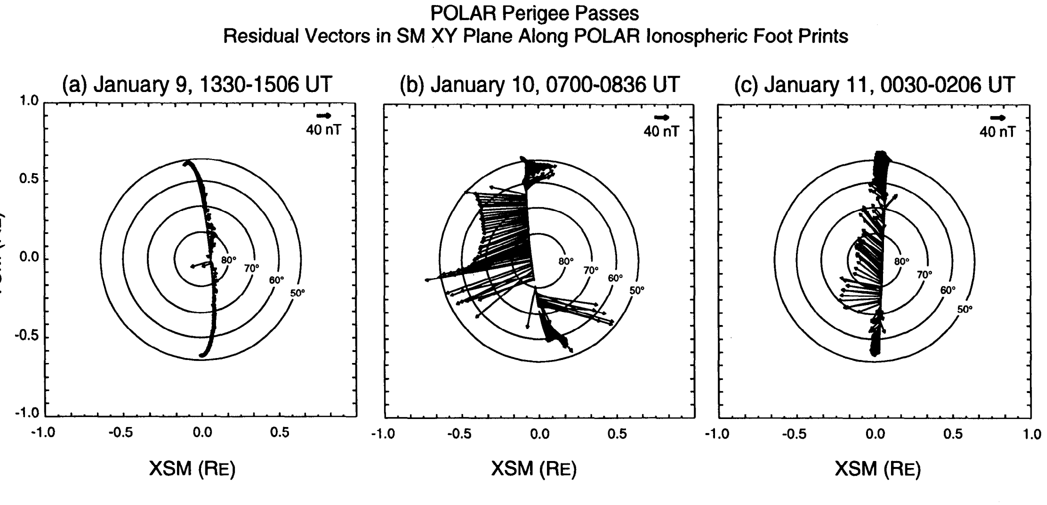

**Figure 5.** The magnetic field vector residuals along the track of POLAR ionospheric footprints for the three perigee passes, (a) January 9, (b) January 10, and (c) January 11.

Effects of the ring current as well as the magnetopause current can also be identified in the residuals of the magnetic field in Figure 4. Over the polar cap, the magnetic field perturbation due to the ring current is nearly parallel to the Earth's field, i.e., it increases the magnetic field strength. On the other hand, the perturbation field due to the magnetopause current over the polar cap decreases the magnetic field strength since it is antiparallel to the Earth's field. The bottom panels of Figure 4 show the residual of the magnetic field strength during the perigee pass. Under quiet conditions (January 9), the observed magnetic field strength is greater than Earth's internal field strength due to the quiet time ring current (Dst ~ -10 nT, Dst* ~ 30 nT). On January 10, the perigee pass occurs during the period of strongly southward IMF Bz and the strong ring current buildup in the magnetic storm (Dst ~ -50 nT, Dst* ~ -80 nT). The field strength is greater than the model field strength and the residual is about twice that of January 9. On January 11, we see a sudden decrease in the residual of the field strength at ~ 0115 UT, corresponding to the leading edge of the high-density solar wind filament. The compression of the magnetosphere by the large-density solar wind filament produces a strong magnetopause current almost instantaneously, which overcomes the ring current effect and causes a positive Dst index (Dst ~ +40 nT). Its effect near the polar cap appears to be to decrease the field strength, as evidenced by the negative residual in field strength after ~ 0115 UT. The negative residual lasts about 20 minutes, and gradually goes back to positive since there is still a strong ring current (Dst* ~ -40 nT) during this period.

During the injection phase of the January 10 magnetic storm, a strong dawn-dusk asymmetry of the ring current is also shown in the magnetic field data, as evident by the residual of the FAC Bx component in Figure 4 as the spacecraft moves from the dawn towards the dusk sector. Near the equator, the magnetic field associated with the ring current is southward inside the ring current. It appears to be a positive FAC $\delta Bx$ component in the region inside and below the equator. This ring current signature can be seen only when POLAR is in the dusk sector on January 10. The ring current also reduces the total magnetic field strength causing a negative $\delta Bt$ that is maximized at the equator. The residual of the magnetic field strength is asymmetric and is much stronger near the dusk equator, ~ -130 nT, than the dawn equator, ~ -30 nT (not shown).

## Discussion

The polar magnetosphere is an excellent recorder of the various stresses applied to the magnetosphere. During the January storm it showed clearly the stresses applied by the reconnection and carried to the ionosphere via field-aligned currents, it showed the distortion associated with the partial ring current and it showed a lack of unusual stress when the strong density pulse passed the magnetosphere. If we assume that the region 1 currents observed on January 10 were uniformly downward across the dawnside and uniformly upward in the afternoon, then about 3 MAmperes were coupling the ionosphere to the reconnection at the magnetopause associated with a 15 nT southward IMF.

## Summary

The magnetic field observations during three successive POLAR perigee passes have been used to examine the response of the low-altitude magnetosphere to different IMF and solar wind conditions. We find that field-aligned currents are controlled mainly by the southward IMF component. They are greatly enhanced during strongly southward IMF conditions on January 10, but the solar wind dynamic pressure has little effect on their strength during the passage of the high-density solar wind filament on January 11. Thus, drag on the magnetosphere is principally due to reconnection at the magnetopause, with little due to viscous effects. It is also supported by the observation that the region 1 current, that connects the magnetopause to the ionosphere and is driven by the magnetic reconnection, is much stronger than the region 2 current on January 10.

Effects of the ring current and the magnetopause current can be identified in the magnetic-field data in the low-altitude magnetosphere. Over the polar cap, the ring current causes an increase in the magnetic-field strength, whereas the magnetopause current decreases the magnetic-field strength. The residual of the field strength is correlated with the solar wind dynamic pressure and the Dst index. During the magnetic storm of January 10, the ring current exhibits strong dawn-dusk asymmetry. It is much stronger in the dusk sector than in the dawn sector.

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