Field-aligned currents in the polar cap during saturation of the polar cap potential

R.E. Lopez\textsuperscript{a,1,*}, S. Hernandez\textsuperscript{a}, K. Hallman\textsuperscript{a}, R. Valenzuela\textsuperscript{a}, J. Seiler\textsuperscript{a}, P.C. Anderson\textsuperscript{b}, M.R. Hairston\textsuperscript{b}

\textsuperscript{a}Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA
\textsuperscript{b}W.B. Hanson Center for Space Physics, University of Texas at Dallas, Richardson, TX 75083, USA

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Abstract

During periods of very strong southward magnetic field in the solar wind the polar cap potential becomes saturated. Recent investigations of the saturation of the polar cap potential suggest that the Region 1 current system plays a major role in balancing the solar wind pressure, leading to the saturation effect. To do this, the Region 1 current must flow on open field lines, closing outside Earth magnetosphere, where it can exert a $J \times B$ force on the solar wind. In this paper we present observations from DMSP F13 of the low-altitude distribution of field-aligned currents with Region 1 polarity relative to the boundary between open and closed field lines. The observations show that during a period of strongly southward solar wind magnetic field, a substantial amount of field-aligned current was flowing on field lines that had merged with the interplanetary magnetic field. On the other hand, during a period of nominal southward solar wind magnetic field, much less field-aligned current with Region 1 polarity was found in the open field line region. These observations support the view that Region 1 field-aligned currents can play a role in the force balance between the magnetosphere and the solar wind during periods of strongly southward IMF.

Keywords: Polar cap potential; Saturation; Field-aligned currents

1. Introduction

The issue of coupling between the solar wind and the Earth magnetosphere is of central importance to magnetospheric physics. The transfer of energy from the solar wind to the magnetosphere is primarily controlled by the orientation of the interplanetary magnetic field (IMF), though under certain conditions the solar wind density can play an important role in regulating the coupling (Lopez et al., 2004). When the IMF is directed southward, antiparallel to the Earth field, merging of the fields on the dayside imposes an electric field onto the ionosphere and magnetosphere, driving convection. The key parameter in convection is the potential drop across the ionosphere imposed by dayside merging. This process also transfers magnetic flux from the dayside to the nightside (Wiltberger et al., 2003), which is eventually returned to the dayside by...
nightside reconnection during storms and substorms, as originally proposed by (Dungey (1961)).

The relationship between the polar cap potential and the solar wind driver was originally considered to be a linear relationship increase the strength of the solar wind driver and the ionospheric potential will increase proportionately (Reiff and Luhmann, 1986; Boyle et al., 1997). However, more recent work has established that during southward IMF when the solar wind electric field, $V_{Bz}$, is very large, the polar cap potential saturates and becomes insensitive to further increases in $V_{Bz}$. This phenomenon has been observed in studies using ionospheric potential determined from the assimilated mapping of ionospheric electrodynamics (AMIE) (Russell et al., 2001; Liemohn et al., 2002), DMSP drift meter measurements (Hastie et al., 2003), and high-latitude radar observations of ionospheric flow (Shepherd et al., 2002). Moreover, even global MHD models (Raeder et al., 2001; Siscoe et al., 2002a, b; Merkin et al., 2003, 2005; Hernandez, 2007) show evidence of the saturation of the polar cap potential, indicating that the cause must be some large-scale response of the magnetosphere that is represented reasonably well by global MHD models that do not contain features such as a storm-time ring current in the inner magnetosphere.

In particular, it has been proposed that when the polar cap potential is saturated, the Region 1 current is the dominant current system exerting a

Fig. 1. Solar wind data for February 17, 1998.
$J \times B$ force on the solar wind, as opposed to ordinary times when the Chapman–Ferraro current is the primary source of force balance (Siscoe et al., 2002a, b). In order for this to happen a portion of the Region 1 current must flow out into the solar wind (Siscoe, 2006; Hernandez, 2007), and thus one would expect to find Region 1 current flowing on open field lines. In this paper we will provide evidence that when the solar wind electric field is large enough that one would expect the polar cap potential to be saturated, substantial Region 1 current is indeed observed in the open field line region of the polar cap.

2. DMSP observations during large solar wind $VBz$

To look for evidence of Region 1 current flowing along open field lines into the solar wind during periods corresponding to polar cap saturation we will use observations from the low-altitude DMSP spacecraft. It is necessary to consider only steady-state configurations so that the DMSP data reflect spatial, not temporal, variations. Thus we need a period with fairly steady solar wind velocity and magnetic field with sufficient electric field that might suggest polar cap saturation, and we also want steady dynamic pressure so that magnetospheric boundaries do not move. We want a DMSP pass through the polar cap that is likely to encounter Region 1 current that would be flowing out to the dayside. And we also need to restrict ourselves to relatively small solar wind $B_z$ to focus on the effect of $B_z$, and also not to skew the field-aligned current (FAC) pattern too much toward the dawn or dusk. As one might expect, there are few events that meet all of the criteria enumerated here.

On February 17, 1998 there was a period of southward IMF that produced a magnetic storm.

![Fig. 2. DMSP F13 spectrogram and magnetometer data from February 17, 1998 showing a crossing through the southern polar cap. The boundaries of the region of open field lines as determined from particle precipitation data are marked by vertical lines crossing all panels, and approximate extents for the Regions 1 and 2 currents are indicated on the magnetometer panel.](image-url)
The ACE solar wind data in Fig. 1 show that from 1510 to 1540 UT the solar wind was steady and there was a strong southward \( B_z \) with little \( B_y \). Given the propagation speed of the solar wind, this period of solar wind would have encountered the magnetosphere about 1 h later, from 1610 to 1640 UT. The solar wind electric field (\( VB_z \) was around 3.6 mV/m) was strong enough that the polar cap potential should have exhibited the effects of saturation both in simulation results (Siscoe et al., 2002b; Hernandez, 2007) and in reality, since observations indicate that saturation effects become noticeable when \( VB_z \) is greater than 3 mV/m (Russell et al., 2001).

DMSP 13 is a sun-synchronous polar-orbiting satellite with an altitude of 835 km, a period of 101.5 min, and an orbital plane approximately along the 1800–0600 local time meridian. The spacecraft carries a variety of instrumentation; of interest to this study are the precipitating particle and magnetometer data. Observations made by DMSP F13 of particle precipitation (electrons and ions from 30 eV to 30 keV) and one component of the magnetic field are presented in Fig. 2. The particle data are in spectrogram format; both ions and electrons are plotted. The spectrogram shows a clear polar cap filled with soft electron precipitation. Vertical lines have been placed on the figure to mark the boundaries of the open field line region; this is discussed in more detail below. In the upper right portion of the figure a polar plot shows the satellite trajectory in latitude and local time. It is important to note that this pass was in the southern hemisphere, and that the satellite trajectory was restricted to the daylight hours. Such a pass will maximize the encounter with dayside, low-altitude Region 1 currents.

The \( B_z \) magnetic field component is the component that is perpendicular to the spacecraft trajectory and to the vertical direction. Given the fairly steady solar wind conditions, we assume that all of the magnetic variations observed by DMSP are due to the passage of the satellite through spatial structures. Thus variations in \( B_z \) correspond to the

![Fig. 3. DMSP F13 spectrogram and magnetometer data from February 17, 1998 showing entry into the polar cap at 16:26:28 UT, marked by the vertical line.](image-url)
passage of DMSP through currents flowing vertically, which are generally (though not exclusively) currents flowing along the field line. Recalling that this is a southern hemisphere pass, a positive change in $B_z$ as one moves from left to right on the figure corresponds to a downward FAC and a negative change corresponds to an upward FAC.

Two large magnetic perturbations are evident, each with a region of upward and downward FAC, on either flank. These structures are the low-altitude signatures of the Regions 1 and 2 current systems, and we have indicated their approximate spatial extent on the figure. The well developed Region 2 current system on the dayside flanks is indicative of the strong magnetospheric convection being driven by the magnetic cloud on this day. The entry and exit points from the polar cap as determined from the particle precipitation data are indicated by the vertical lines. Both the dawn entry and the dusk exit show that a considerable fraction of the total current with Region 1 polarity was flowing on open field lines. Specifically, on the dawn flank the current with Region 1 polarity produces a total magnetic perturbation of about 650 nT, and about 275 nT, or 42%, of this perturbation is found on open field lines. On the dusk flank, 37% of the Region 1 magnetic perturbation is found on open field lines. On subsequent passes, during the period of sustained strongly southward IMF, the DMSP magnetometer data continued to show that a significant fraction of Region 1 current was located on open field lines. Those currents must flow into the magnetosheath and would be able to exert a large force on the solar wind, contributing to the overall force balance (Siscoe et al., 2002a, b; Hernandez, 2007).

Fig. 3 presents an expanded view of the dawnside entry of DMSP F13 into the open field line region of the polar cap in the same format as Fig. 2. The polar cap boundary can be seen at 16:26:29 UT,
before which precipitating energetic electrons and ions were observed. In addition, the average electron energy was well above 500 eV, which has been identified as a robust indicator of closed field lines (Gussenhoven and Mullen, 1989). Therefore we have considerable confidence in the identification of the boundary between open and closed field lines.

Fig. 4 presents the duskside exit of DMSP F13 from the polar cap. A sharp boundary is very clear in both the ion and electron data, now at 16:36:27 UT. Poleward of that boundary one can see significant electron precipitation (particularly from 16:35:25 UT until 16:36:10 UT), is coincident with the upward FAC corresponding to the decreasing $B_z$ with decreasing latitude. Thus we identify these precipitating low energy electrons as the current carriers of the upward Region 1 FAC on open field lines.

One additional point should be noted. The variations in $B_z$, while due largely to FACs, are not due exclusively to FACs since the field line direction is not exactly vertical. In fact, separate from the clear overlap of the Region 1 current into the open field line region, one can see other variations on the order of 100 nT in the center of the polar cap. These may or may not be due to FACs, but those kinds of variations are clearly distinct from the variations that we associate with Regions 1 and 2 currents.
3. DMSP observations during moderate solar wind VBz

Fig. 5 presents solar wind data from ACE on February 16, 2002. The IMF was fairly steady for hours, moderately southward with little By. In contrast to the event presented above, VBz ranged from about 1 to 1.5 mV/m, and so one would not expect the polar cap potential to be saturated. From the speed of the solar wind we expect that 67 min after passing ACE, the solar wind would have arrived at Earth. While density data are not available, there is no indication from dayside mid latitude magnetometers (not shown) that there were big variations in solar wind dynamic pressure during the period of interest. Therefore this case represents an example of steady, moderate solar wind electric field driving the magnetosphere.

Fig. 6 shows the particle precipitation and magnetometer data for the entire pass in the same format as before. Again, this is a southern hemisphere pass and we use the criteria of the average electron energy (Gussenhoven and Mullen, 1989) along with inspection of the ion data to determine the boundary between open and closed field lines. We have determined that DMSP F13 entered the polar cap at 14:22:29 UT and that it exited at 14:29:07 UT. As before, this pass was on the dayside, so that any observed FAC on open field lines would also likely flow out to the dayside magnetosheath.

On the dawn side, the perturbation on open field lines was approximately 115 nT out of a total of about 350 nT in the Region 1 current. On the dusk flank it is clear that there was no Region 1 current located on open field lines. The duskside Bz perturbation started as soon as DMSP entered the...
closed field line region, and the precipitation boundary marking the boundary between open and closed field lines was very sharp. The center of the polar cap showed a steady decrease in $B_z$, however, we think that this perturbation does not represent a large-scale FAC extending across the polar cap. Such features are regularly seen in the DMSP data (Lopez et al., 1991), and they may be due to instrumental effects, or currents that are not field-aligned. In any case, the auroral zone $B_z$ perturbations routinely identified with FACs, which generally have large slopes, are quite distinct by comparison.

Compared to Fig. 2, the magnitudes of the magnetic perturbations in the auroral zone were significantly smaller, as one might expect given the much more moderate IMF. In fact, it is difficult to identify any distinct Region 2 current at the local times crossed by DMSP. Also, in contrast to Fig. 2, it appears that a much smaller amount of Region 1 current (as determined from the perturbation in $B_z$) was located on open field lines. Thus in this case, as compared to the first polar cap crossing we presented, significantly less Region 1 FAC was flowing out into the magnetosheath. Moreover, because of the weaker magnetic field in the solar wind and in the magnetosheath, the corresponding $J \times B$ force on the solar wind would have been much weaker than the $J \times B$ force that was exerted on the solar wind on February 17, 1998.

4. Conclusions

During periods of strong magnetospheric driving by the solar wind, as represented by large values of $VB_z$, when the IMF is southward, the polar cap potential saturates. Recent studies (Siscoe et al., 2002a, b; Hernandez, 2007) indicate that the Region 1 current system plays a key role in producing the saturation effect by usurping the role of the Chapman–Ferraro current as the primary agent of force balance with the solar wind. In order to do this, substantial amounts of Region 1 current must flow out into the magnetosheath on open field lines. We have presented observations from DMSP F13 indicating that during a period when one would expect polar cap potential saturation, a large amount of FAC corresponding to Region 1 does flow on open field lines. By contrast, during an extended period of moderate southward IMF that was too small to produce the saturation effect, there was much less Region 1 FAC flowing on open field lines, and it would have produced a much weaker $J \times B$ force on the solar wind given the lower IMF strength. These observations support the proposition (Siscoe et al., 2002a, b; Hernandez, 2007) that for large $VB_z$, Region 1 currents flowing on open field lines can exert dynamically significant forces on the solar wind.

Acknowledgments

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