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RICE UNIVERSITY

POLAR CAP RESPONSE TO THE 18-21 OCTOBER 1995 MAGNETIC CLOUD EVENT

by

C. BENJAMIN BOYLE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE DOCTOR OF PHILOSOPHY

APPROVED, THESIS COMMITTEE

[Signatures]

Patricia H. Reiff
Professor and Chair
Space Physics and Astronomy Department
Thesis Advisor

Thomas W. Hill, Distinguished Faculty Fellow
Space Physics and Astronomy Department

F. Curtis Michel, Professor
Space Physics and Astronomy Department

Ronald L. Sass, Professor and Chair
Ecology and Evolutionary Biology Department

Houston, Texas
July, 1997
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C. Benjamin Boyle

ABSTRACT

A statistical study of ten years of solar wind particle and magnetic field observations, ionospheric convection measurements, and geomagnetic index data is combined with a case study of the interaction of the 18-21 October 1995 magnetic cloud event to illuminate several aspects of solar-terrestrial coupling. Models of polar cap responses to the solar wind are presented and compared to the observations from the case study. The sudden southward turning of the IMF during the event approximated a step function input to the coupled magnetosphere-ionosphere system. The resulting polar cap size, expansion rate, and polar cap potential are unusually large. This allows a straightforward analysis of effects which have traditionally been difficult to assess.

During the event, the polar cap expanded by up to 5°MLAT/hour, which is roughly the fastest rate of polar cap expansion observed by DMSP in a decade of continuous in-situ measurements. The rapid expansion is used to compare flow observations, estimates of the polar cap potential, and the induced emf which corresponds to the polar cap expansion by Faraday’s Law. The analysis also resolves earlier indications that the hypothesized saturation of the polar cap potential drop exists, and confirms the numerical and functional predictions of Hill et al [1976]. The implications for high time resolution models of the total polar cap potential are discussed.

The statistical analysis includes an expanded set of empirical proxies which relate commonly used magnetospheric parameters.
An analysis of the solar wind and ionospheric data also confirms the predictions of Hill [1985] regarding the rate of magnetic flux loss along the length of the magnetotail. In addition, while the ratio of open flux to polar cap potential is often approximated as a constant, the analysis reveals a functional dependence of the ratio which has implications for the length scale of the magnetotail.

The ionospheric data used came from six low altitude Defense Meteorological Satellites (DMSP), while WIND and the Interplanetary Monitoring Platform (IMP 8) solar wind monitoring satellites provided solar wind plasma and field data. The data set spans the period from 1987 through 1996.
ACKNOWLEDGMENTS

Although the list of people who have helped and encouraged me in this effort is almost precisely identical to the list of people I know, there are several who deserve particular thanks. First and foremost, I would like to thank my advisor Dr. P. Reiff for her patience and financial support. I would also like to thank Dr. R. Wolf, Dr. J. Weisheit, and Bryan Bales for being uncommonly helpful and patient throughout the period I have known them. Dr. T. Hill and Dr. F. Toffoletto also provided substantial guidance during the analysis of the most recent results.

The data used in this study was contributed by quite a few helpful researchers in solar-terrestrial interactions who are noted in the text. I would like to thank them for their help as well as for the data they provided. Drs. M. Hairston and F. Rich provided both the DMSP data and significant additional analysis which was essential to the research.
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Chapter 1

INTRODUCTION

The study of the interactions between the solar wind, magnetosphere, and ionosphere has been greatly advanced by the increasing availability of satellite data over the last three decades. Without measurements of the fields and particles in the solar wind, the magnetosphere, and the ionosphere, progress would be nearly impossible. During the last decade, the number of satellites taking measurements, as well as the quantity and quality of the measurements has substantially increased. The tremendous increases in the quantity, quality, and types of available data, coupled with improvements in computers, have helped accelerate our progress in understanding the near Earth space environment.

The study of solar terrestrial interactions has no shortage of open issues and unsolved questions, and I use a collection of data from a number of sources, spanning roughly a decade, to address several specific questions. The analysis combines the statistical analysis of several large data sets with the study of a particularly revealing event. The event is the arrival of a magnetic cloud at the Earth’s magnetopause on 18 October 1995. The cloud was a large (length scale ~ 1 AU) structure in the solar wind with the characteristics of a helical flux rope [Burlaga, 1988]. Although similar structures are often observed in the solar wind, the magnetic cloud in question was quite exceptional. The cloud had interacted with other features in the solar wind which caused the embedded magnetic field in the leading edge of the cloud to exhibit a very strong and abrupt gradient. The resulting magnetic field profile is one which is particularly well suited to exposing some aspects of the solar-terrestrial interaction. The slightly northward interplanetary magnetic field (IMF) prior to the arrival of the cloud had left the magnetosphere in a nominal or relatively weakly driven state. The abrupt southward turning of the IMF in the leading edge of the
cloud is a nearly ideal test case for studying the response of the magnetosphere and ionosphere to what we believe is the primary driver for the coupled system.

The response of the polar ionosphere to the magnetic cloud is analyzed and compared to predictions based on estimates of the steady-state functional relations between the solar wind and the polar cap. The response of the polar cap to the rapid and extreme changes in the IMF during the event may resolve the long running controversy on the existence of a saturation of the polar cap potential. The response to the southward turning is characterized by several distinct phases, which are summarized. The exceptionally rapid expansion of the polar cap provides a test case to illustrate the role of induced emf in the magnetospheric control of the ionosphere during dynamic events in the solar wind.

Additionally, the data set which was assembled to study the interactions allows the identification of simple relations which relate a variety of magnetospheric and ionospheric parameters. The analysis of the data includes a study of the relationship between the size of the polar cap and the polar cap potential. The size of the polar cap is related to the amount of open magnetic flux. The ratio of the open flux to the polar cap potential has implication for the convection time scale and the length of the magnetotail.

Several of the features and relations which are analyzed relate directly to theoretical predictions made in the 1980s. The results both confirm and extend the predictions with new information about the relationships between several geophysical parameters.

1.1 Coordinate Systems

Throughout this analysis, the locations of ionospheric phenomena are given using the geomagnetic coordinates magnetic latitude (MLAT) and magnetic local time (MLT). Ionospheric phenomena are much better organized in that coordinate system than in geographic or dip-angle coordinates.
Chapter 2
MAGNETOSPHERE

The sun emits a "wind" of magnetized plasma. The plasma consists largely of protons and electrons, although there are a significant number of alpha particles as well. The magnetic field in the plasma is one of the most important features of the solar wind from a space physics standpoint. By the time the solar wind reaches the Earth, the combination of gravitational and thermal gradients has accelerated it to supersonic (and superalfvenic) speeds.

When the magnetized plasma of solar wind reaches the Earth, the interaction with the Earth’s magnetic field causes the deflection of the solar wind around the Earth and the formation of a standing shock. The resulting separatrix between the volume of space where the Earth’s magnetic field dominates and the region where the solar wind field dominates defines the magnetopause. The magnetosphere (figure 1) extends sunward of the Earth to a point (typically 8-12 $R_E$) where the magnetic field pressure of the Earth roughly balances the pressure of the streaming solar wind. On the night side of the Earth, the interaction with the solar wind stretches the magnetosphere into a long tail. The length of the tail is not well known, although several current topics of space physics research are directly related to the length of the tail.

Study of the near-Earth space environment necessarily implies an emphasis on the physics of magnetized plasmas. Although this is a complicated subject, there are several useful ideas which can be applied throughout the majority of the magnetosphere. First, it is generally a reasonable approximation to assume the magnetospheric plasma is an ideal magnetohydrodynamic fluid (that the conductivity of the fluid is infinite). Another helpful tool is the concept of magnetic field lines. Field lines, of course, are traces along the magnetic field vectors; they are a convenient conceptual tool which help describe a field configuration. A related, and particularly useful, simplification is "frozen-in-flux," which
Figure 1. A cross section of the magnetosphere showing the principle features. The sun is to the left in this representation, and the polar cap is enclosed by the auroral oval [after National Research Council, 1981].
was developed by Hannes Afvén. Frozen in flux states that the particles in the plasma which are on a field line will remain on that field line. A more thorough discussion and derivation of frozen-in-flux as it applies to magnetospheric physics can be found in [Parks, 1991]. Together these two are invaluable in describing the overall configuration and behavior of the magnetosphere. In summary, the collisionless, low energy, low density particles of the plasma in the magnetosphere are free to move along field lines, but not across them. Bulk motion of the plasma also corresponds to movement of the field line(s).

The fact that the solar wind is magnetized, and moving with respect to the Earth, provides the basis for an interaction between the solar wind and the magnetosphere which is far more involved than simple pressure balance alone. Viewed from the rest frame of the dipole, there is an electric field due to the flow of the magnetized solar wind as described by the ideal MHD version of the Lorentz transform

$$\bar{E} + \bar{v} \times \bar{B} = 0$$  \hspace{1cm} (1)

where here v is measured in km/s, B is in nanoteslas, and E is in microvolts/meter. This assumes the electric field in the frame of the plasma is zero (i.e., perfect conductivity).

By several processes, the solar wind interacts with magnetic field lines from the earth and the plasma on those field lines. The solar wind electric field, impressed across the magnetopause, drives the complicated behavior of the plasma in the magnetosphere and also affects the polar ionosphere. Although many of the details of the interaction are still areas of active research, some portions of the coupling mechanism are fairly well understood.

The dominant coupling mechanism appears to be magnetic merging between the IMF field lines and the closed terrestrial field lines (figure 2 a). "Closed" refers to field lines which intersect the Earth's surface at two points, while "open" field lines are those which do not intersect with the Earth's surface twice. IMF magnetic field lines initially do not intersect with the Earth's surface, and are thus open. When an IMF line merges with a
Figure 2a. This view of the noon-midnight plane shows the sense of the magnetospheric and ionospheric convection processes (antisunward at high latitudes, sunward at low latitudes). Several distinct phenomena are associated with the high latitude ionosphere and the region of open magnetic field lines: the open closed boundary, the convection reversal boundary, and the aurora.
dipole field line it creates two field lines, each of which has one end which intersects the Earth's surface, while the other end extends off into the solar wind plasma. Since portions of IMF lines are then connected to portions of dipole lines, plasma is relatively free to flow along the newly merged field lines. Magnetic merging refers to a process whereby adjacent antiparallel magnetic field lines "merge" and release energy. The application of the theory of magnetic merging to the magnetosphere began with Dungey [1961] who first proposed the "open magnetosphere."

An alternate theory proposed by Axford and Hines [1961] described a "closed magnetosphere." The closed magnetosphere does not incorporate magnetic merging, and instead relies on the fluid properties of the plasmas for interactions which transfer energy and particles from the solar wind to the magnetosphere. These processes, which are not well understood even at this time, are generally referred to as "viscous processes."

During the subsequent 30 years, it became clear that both concepts contained useful ideas; the magnetosphere is now generally believed to interact with the solar wind via both viscous and merging processes. Statistical studies of a large number of observations indicate that magnetic merging accounts for the majority of the energy transfer, with viscous process apparently accounting for the remaining fraction [Boyle, et. al., 1997].

As field lines are opened (or otherwise receive energy from the streaming solar wind) they are carried antisunward by the solar wind as it continues to flow away from the Sun. Eventually, they reconnect to other open field lines in the magnetotail (figure 2 b) and the newly closed field lines then begin to move sunward. The movement of field lines antisunward when open, and the returning flow of closed field lines inside the magnetosphere, is referred to as magnetospheric convection. The rate of convection is indicative of the strength of the coupling between the solar wind and the magnetosphere. The movement of the magnetospheric field lines (caused by the solar wind) is equivalent to the presence of a magnetospheric electric field. The opening of field lines due to merging, and their resulting movement, can be viewed as an electric field and corresponding potential
across the dayside magnetopause. A similar process occurs in the corresponding nightside reconnection of field lines in the magnetotail. The difference between the dayside merging rate and the nightside reconnection rate is the rate of increase (or decrease) of open flux. This, of course, directly affects the polar ionosphere. Although the two rates would be equal under steady conditions, in general the two are not equal.
Chapter 3

IONOSPHERE

The low altitude portion of the field lines which are involved in the convection process move in large circulation patterns which are called ionospheric convection patterns. Although the convection pattern often comprises two large cells centered near the dawn and dusk edges of the polar cap, the convection pattern is not always so well defined [Heppner and Maynard, 1987]. The features of the polar cap, and the processes responsible for them, are a result of the interaction of many factors.

The center region of the polar ionosphere contains the low altitude portion of open field lines which pass through the polar ionosphere and extend out into the magnetosphere where they interact with the magnetosphere and the solar wind. The lower geomagnetic latitude polar regions generally are threaded by closed field lines which extend into the inner magnetosphere and then intersect the ionosphere again near the opposite pole. The magnetospheric electric field maps along the field lines to the polar ionosphere. There the polar cap electric field causes currents and the circulation of the ionospheric particles.

The line integral of the electric field across the polar cap gives a polar cap potential drop. The two cell convection pattern which prevails during southward IMF has potential extrema near 6 and 18 magnetic local time. While any line across the polar cap defines a potential difference, the total cross polar cap potential drop (henceforth simply referred to as the polar cap potential, or \( \Phi \)) is defined as the difference between the extrema at the centers of the dawn and dusk convection cells.

\( \Phi \) is a single scalar which, in highly idealized circumstances, is a very useful indicator of magnetospheric processes. Unfortunately, many of the areas of current research emphasize aspects of magnetosphere/ionosphere coupling which do not correspond to those idealized circumstances. One important area of research is the behavior of the coupled systems during times when the IMF is strongly northward. Under these
conditions, however, the ionospheric convection pattern is not a simple two celled pattern; it often exhibits many small convection cells. When there are not two primary convection cells, the definition of $\Phi$ becomes problematic. Another area, particularly relevant to this research, is the high time resolution time dependent behavior of the coupled ionosphere/magnetosphere system. In the steady state, the potential along a line across the dayside, center, and nightside portions of the polar cap would yield the same value. That value is clearly $\Phi$. Under dynamic conditions, such as a sudden southward turning of the IMF, these three hypothetical measurements would yield very different values in the frame of the moving boundary of the polar cap. The southward turning would cause an increase in the dayside merging rate, and move (at least) the front of the polar cap boundary to lower geomagnetic latitudes.

Throughout this study, references to measurements of the $\Phi$ refer to integrated electric fields deduced from in-situ ion drift measurements by satellites. It should be made clear that these derived measurements are interpreted as imperfect measurements of the idealized "true" polar cap potential, with the appropriate limitations attached to that concept. In a study of the quasi-steady-state functional relation between the IMF and $\Phi$ in Boyle et al. [1997] (henceforth referred to simply as EPCP), estimates of the asymptotic $\Phi$ were developed. These $\Phi_A$ are empirical models of the convection speed to which the system would eventually asymptote given steady IMF inputs. They are cited for comparison to the observed response of the ionosphere/magnetosphere system to extremely dynamic inputs.
Chapter 4

DATA

In this study a variety of data types are collected, processed, and coordinated in order to analyze specific aspects of the solar-terrestrial interaction. One way in which this study is unique is in the size and scope of the input data, much of which has only recently become available. The data span more than 10 years of observations of the solar wind and the corresponding magnetospheric and ionospheric responses.

The collection of disparate data types spanning a decade at relatively high resolution presented several problems. In addition to the difficulties in storing, manipulating, and analyzing a data set of this size with available computing technology, synchronization of the dissimilar data required a variety of techniques. Some of the data used in this analysis were both asynchronous and irregular.

4.1 Data from the Defense Meteorological Satellite Program

The primary event analysis records based on times of DMSP observations of ionospheric convection. This measurement time is somewhat approximate because DMSP takes a variable, non-negligible time to cross the polar cap and complete a set of convective flow measurements; thus any single measurement time is a convenient oversimplification. The time associated with each DMSP Φ observation is computed from the times of consecutive equatorial crossings.

DMSP observations of overall polar cap phenomena are limited in several respects. First, the convection speed of the ionosphere changes under the control of the solar wind on time scales smaller than the time it takes a DMSP satellite to cross the polar cap. Further, the polar cap size changes on time scales comparable to the time scale of the DMSP overflight of the polar region. This complicates not only measurements of the polar cap size, but also the determination of polar cap potential. There are also variations because
the ground tracks of the inertial DMSP orbits wobble considerably in geomagnetic coordinates as a function of time of day.
<table>
<thead>
<tr>
<th>data set</th>
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<td>( \Phi )</td>
<td>convection</td>
<td>DMSP IDM</td>
<td>1987-1996</td>
<td>20 minute</td>
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<td></td>
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<td>DMSP IDM</td>
<td>1987-1996</td>
<td>4/second/satellite</td>
<td>( &gt;10^9 )</td>
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<td>plasma density</td>
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<td>1987-1996</td>
<td>5 minute</td>
<td>400,000</td>
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<tr>
<td>IMF</td>
<td>B field vector</td>
<td>IMP-8 magnetometer</td>
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<td>5 minute</td>
<td>400,000</td>
</tr>
<tr>
<td>Solar wind</td>
<td>plasma density</td>
<td>WIND</td>
<td>18-22/10/1995</td>
<td>1.5 minute</td>
<td>3700</td>
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<tr>
<td>IMF</td>
<td>B field vector</td>
<td>WIND magnetometer</td>
<td>18-22/10/1995</td>
<td>1.5 minute</td>
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Table 1. Data type and availability
4.1.1 DMSP Ion Drift Meter Data

The potential and polar cap measurements used in this paper are derived from plasma flow measurements by Defense Meteorological Satellite Program (DMSP) satellites F8-F13. These satellites used circular (848 km altitude), polar (98.8° inclination), and approximately sun-synchronous orbits. Several of the DMSP satellites had orbits which were approximately dawn-dusk, while others had orbits which ran approximately noon to midnight. Although the orbits were roughly polar and sun-synchronous, the variations in orbit parameters and the Earth's tilted, offset dipole resulted in considerable variations in the orbit tracks in geomagnetic coordinates. Most high latitude ionospheric phenomena are best represented in geomagnetic coordinates, including polar cap convection and the resulting potential. Only passes which overflowed the dawn and dusk potential extrema measured the total polar cap potential. Thus, the determination of the total polar cap potential relies heavily on those passes, while the determination of the polar cap boundary uses passes whose ground track spanned all magnetic local times.

An extensive analysis of DMSP data resulted in a statistical description of the distribution of potential in magnetic local time as a function of IMF conditions [EPCP]. This description is used, as described in EPCP, to estimate the total $\Phi$ from passes which are slightly oblique (within 1.5 hours MLT of the true extrema). In the analysis of the magnetic cloud event, the corrected potential measurements (which are invariably higher than uncorrected measurements) were used exclusively. In the statistical analysis portion of the study, restrictions in the magnetic local time of the crossings were used to further decrease errors at the expense of decimation of the larger data set. For the cloud event the need for every recoverable observation warranted manual inspection and analysis of every point. In figure (3) the open circles are the uncorrected potentials, while the filled circles are MLT corrected. One example of possible problems with this method is shown by a point near day 291.5, where a small measured potential was greatly increased by the MLT correction. In the case of that point, rapid changes in IMF $B_\gamma$ caused the error. Because
of the negligible By component in the leading edge of the cloud, the MLT correction of those passes is relatively robust against this type of error even without manual inspection of each point.

The DMSP satellites included Ion Drift Meters (IDM) which measured the local plasma flow. The IDM reports drift vectors 6 times per second. This is recorded along with a number of related parameters, including the time of the measurement, the spacecraft position, and related housekeeping data. These measurements, spanning 10 years and 6 spacecraft, add up to more than 550GB of data. With currently available computers and data analysis techniques, a substantial reduction in the size of the data set was necessary to make a reasonable analysis feasible. The primary DMSP data products used here are magnitudes and locations of potentials calculated from the flow data by the following method.

Assuming ExB drifts, the measured cross track plasma flow data have been combined with a modeled local B field to determine the electric field along the spacecraft trajectory. The integrated electric field, with appropriate endpoints, gives the potential along the orbit track. The convection reversals in the flow data correspond to potential extrema. It is these extrema that I use in this analysis. The difference between the observed dawn and dusk extrema is generally less than the total polar cap potential drop, since the spacecraft generally observes only a portion of the convection pattern during each orbit. The calculation of potentials from the flow data was performed by the Air Force Geophysics Laboratory and the University of Texas at Dallas. For a more detailed summary of the flow measurements, see Rich and Hairston. [1994]. The software used to process the flow data is described in Heelis and Hairston [1990] and Hairston and Heelis [1993].
Figure 3. The open circles and closed circles represent uncorrected and MLT corrected observations of $\Phi$ by DMSP. The lines on the plot are empirical estimates of $\Phi$. 
Additionally, the high time resolution flow data were available (flow speeds are shown by the length of the vectors in figure 4). The 4 second averaged flow data were used in the manual determination of polar cap sizes, and in the determination of data filtering criteria [EPCP]. The data filtering and selection process is the most labor-intensive portion of a study using data sets as large as the ones collected by DMSP. Since only processed, condensed data products are compact enough for a practical analysis, considerable care must be taken in the data selection and interpretation. During the analysis, a large fraction of the DMSP passes were discarded.

Roughly half of the DMSP orbits produced "null" records: these are records where the automated DMSP IDM data processing software determined that the orbit was unusable. The majority of such cases (>50% of the orbits) were due to either inadequate data quality (e.g. excessive scatter in the flow measurements, generally due to low ion densities) or orbital geometry which caused the satellite to skim or completely miss the polar cap. In other cases, the observed convective flow pattern was too disorganized to permit calculation of a meaningful cross polar cap potential. For more information on the pass rejection algorithms in the DMSP data processing software, see the above-mentioned documentation of the IDM data processing and drift integration software.

In order to ensure that the data points which remained corresponded to the total polar cap potential (and thus the primary convection reversals), I also adopted the selection criteria used successfully by Nagai [1993]. These included rejecting passes which failed to reach higher than 80°MLAT and passes where the flow integration software calculated an offset correction of greater than 25% of the measured potential. The requirement on the highest magnetic latitude is to ensure that the orbit passed over enough of the convection pattern to get a good estimate of the condition of the polar cap. The offset correction criteria is to ensure that the data is not heavily biased by changes in the polar cap size, by changes in its convection during the satellite pass, or by the data processing software. This
Figure 4. A representative sample of the horizontal (cross track) ion drift data from DMSP used in the determination of polar cap electric fields.
rationale as applied to the DMSP data set is documented in greater detail in EPCP. The integration software further marks orbit records if any of several types of problem are detected by the convection-pattern determination routines. Passes marked as unusable (case >3) were discarded, although usable passes where the pattern could not be determined (case 0) were retained. Also, the data were filtered using several data quality flags generated by the flow integration software; only passes marked as highest quality by the telemetry processing software were retained.

DMSP data availability is also strongly affected by solar cycle. Near solar minimum, at DMSP altitudes the ion density frequently decreases to the point where instrument limitations prevent useful observations.

The DMSP data set was, necessarily, further reduced by requiring comeasurement of other relevant geophysical parameters. Those sections of the analysis which involved both DMSP and IMF data were, for example, reduced to that subset which contained clean data of both types simultaneously. In general, IMF data were available roughly 50% of the time, so the usable DMSP passes were further reduced by a factor of (approximately) two when fitted to IMF data. Fortunately, the other data types had much higher availability. The geomagnetic activity indices are available for almost the entire period for which there is DMSP data, with slight exceptions each described in the appropriate section below.

The end result of the necessary, cumulative data decimation was the selection of approximately 10,000 DMSP passes which were used for the majority of the analysis. Those portions of the analysis which did not require concurrent IMF data included a larger set of more than 20,000 integrated DMSP passes. While a data decimation of 90% may seem excessive at first, it is important to realize that the majority of the DMSP orbits simply did not cover the high latitude regions adequately enough to ensure reliable data for analysis. Instrumental limitations further reduced the data availability. Selection of passes which actually cross the high latitude region should not directly bias the functional relation observed between the solar wind and the changes in the polar cap. Also, while the number
of usable passes has been greatly reduced it is still considerably larger than the data sets used in previous analyses of similar polar cap phenomena. Further, the data selection used was based on factors such as orbital parameters of the spacecraft, not on solar wind, magnetospheric, or ionospheric data. Therefore the selection, although fairly draconic, should not introduce any significant biases into the analysis.

There are, however, two selection effects which are not part of this analysis, but may impact it slightly. The automated IDM integration software does not currently scale its data quality criteria with the observed level of convection. This may bias slightly against high polar cap potential observations. However, the increase in size and strength of the convection patterns during times when $\Phi$ is large may increase the chance of a pass observing the total potential drop. Neither of these, however, is due to the data selection criteria imposed in this study.

4.1.2 DMSP Based Auroral Boundary Index

DMSP data is also used to generated the Phillips Laboratory Auroral Boundary Index. The index is an estimate of the equatorward boundary of the precipitating auroral electrons near midnight local magnetic time as measured by the SSJ4 instrument on the DMSP spacecraft. The index is provided courtesy of the USAF Phillips Laboratory. The Auroral Boundary Index is often referred to as the midnight equatorward boundary index (MEB). The generation of the index is described in Gussenhoven, et. al. [1982]

4.2 Interplanetary Monitoring Platform (IMP) Data

The IMP 8 spacecraft (which is also referred to as IMP J) has been a reliable source of IMF and solar wind plasma data since 1973. Although the vehicle is well past its design lifetime, it continues to provide data which have been invaluable in advancing our understanding of the solar wind and its interaction with the magnetosphere. The spacecraft orbit spends a significant fraction of its time inside the magnetosphere or magnetosheath where it is unable to provide information about the solar wind (figure 5). This is the
Figure 5. The X-YGSM projection of the IMP-8 orbit. The satellite spends a significant portion of its time inside the magnetosphere or magnetosheath. A rough approximation to the outline of the magnetopause is shown overlaid on the orbit data. The vertical line at -10RE GSM indicates a cutoff point in the data selection process: measurements from times when the spacecraft was antisunward of this line were not used because of limitations in the propagation algorithms and the increased risk of mixing magnetosheath data with solar wind data.
primary limitation on IMF data availability, but it is compensated, to some extent, by the extremely long duration data set the satellite has provided.

Twenty-minute-averaged IMP 8 data were used for the majority of the analysis which relied upon IMF data. Although 5 minute averaged data were also gathered and processed, initial analysis revealed the noise present in the combined data sets did not warrant inclusion of the higher resolution IMF data. The preshock (i.e. well outside the magnetosphere) velocity, density, and IMF measurements were propagated from the IMP 8 spacecraft position to the estimated (via pressure balance if the data were available) location of the "subsonic point" at the sunward edge of the magnetopause.

4.2.1 Propagation of Solar Wind Data

Three simple propagation methods were tested and compared. Numerical simulation of the propagation of the solar wind is still a topic at the cutting edge of space physics. While progress has been made, particularly with the recent advances in affordable computational power, there is no ready-made solution appropriate for use in this problem. Detailed modeling of the solar wind flow requires data and techniques that are not presently available. Although numerical techniques are being developed, very extensive boundary and initial condition data (which are neither available nor likely to become available) would be required to implement a detailed simulation.

Because of the lack of suitable propagators, in many space physics data analysis efforts the propagation of the solar wind observations from the measurement point to the magnetosphere is crudely approximated by simply using the XGSM component of the solar wind velocity. The arrival time of a feature observed by a remote spacecraft is then computed by dividing the spacecraft’s XGSM distance by vXGSM. For a spacecraft in IMP 8’s orbit, the propagation delay for the features observed at IMP 8 to reach the magnetosphere may be as much as 8 minutes. Because this study initially used 5 minute averaged IMF, more accurate propagation delays were desirable. In this study, with the
help of Andrew Urquhart, I developed and tested another simple propagation approximation. A test of a similar propagator has recently been documented in Ridley et al. [1997], which indicated the new planar solution propagator performed better than the simple method.

Figure (6) shows a schematic diagram which illustrates the algorithm of the newer method. In the new propagator, the orientation of the IMF is used to adjust the anticipated arrival time of effects which correspond to an IMP observation. Since the observations (IMP 8 in this example) are often taken at positions well off the Earth-Sun line, the orientation of the magnetic field can strongly influence the arrival time of the associated volume of solar wind which actually impacts the magnetosphere. Simple examples are shown in figures (6 a,b) where the differing orientation of the IMF affects when the corresponding portion of the observed feature arrives at the magnetopause. The algorithm does assume that the features observed at the satellite have spatial scales comparable to the $Y_{GSM}$ component of the spacecraft position vector with respect to the Earth, and a roughly planar structure aligned with the magnetic field vector. The first two of these assumptions, however, is present in any attempt to use data from remote spacecraft to approximate the solar wind that actually arrives at the magnetopause.

The new propagation algorithm is equivalent to solving

$$\text{delay} = P \cdot (B \times N) / N^2$$

where $P$ is the spacecraft position vector with respect to the subsolar point of the magnetopause, $B$ is the IMF vector, $V$ is the solar wind velocity vector, and $N$ is a constructed vector (equal to $B \times V$) in the presumed plane of the measured feature. The coded implementation also compensates for changes in the position of the magnetopause as the pressure due to the solar wind changes [Wolf, 1996].

The practical implementation of the above geometric correction requires a method for simulating the behavior of the successive features in the solar wind. If the measured
Figure 6. The magnetic field orientation affects the estimation of the arrival time of features in the solar wind measured by satellites well outside the magnetosphere.
direction of the IMF changes, the calculated time of arrival of consecutive features can overlap. In the implementation used in this analysis, features which are "overtaken" by later observations are overwritten. A more sophisticated arbitration method should account for the particle and field densities in neighboring propagated measurements, but that is beyond the scope of this project. Also, for features with normal vectors closer to $Y_{\text{GSM}}$ or $Z_{\text{GSM}}$, the point of contact with the magnetopause should be calculated, rather than simply determining the time of arrival of the signature at the subsolar portion of the magnetopause.

Several tests of the two propagators were inconclusive. The solar wind data propagated by each of the two methods were compared in statistical analyses of the observed ionospheric convection. However, analysis using the new algorithm did not provide significant improvements over the simpler method. This may be due, in part, to the imperfect implementation of the algorithm. It may also simply have been a small correction compared to the other sources of error in the data; the propagation times from IMP-8 to the magnetosphere are fairly short. Future analysis using WIND data will allow much more conclusive testing and development of practical propagators than was possible with the IMP-8 observations. For the October 1995 cloud event the propagation is not an issue since the signature of the cloud’s arrival is unambiguous due to the magnetic field profile of the cloud.

4.3 Kp Data

The index Kp is a 3 hour averaged indicator of global magnetospheric activity. Although a 1 hour averaged Kp also exists, it is much less readily available. The index is generated by a complicated process [Mayaud, 1985] which incorporates magnetometer observations from mid latitude observatories. In geomagnetically active periods, the auroral zone expands southward. During these periods, Kp is affected by a combination of perturbations due to the enhanced auroral electrojet, changes in the ring currents, and increased field aligned currents. While Kp is not a particularly focused index, it is often
used as an indicator of magnetospheric activity. In recent years, however, other parameters, such as AE, $\Phi$, or Dst, are often used as a more specific and higher time resolution indicator of magnetospheric activity.

Although the index has a very high availability, there were a small number of Kp index values which appeared to be empty records. Out of many years of data, a few dozen data points were exactly zero when all other relevant geophysical parameters showed significant sustained magnetospheric activity. Interpreting these as null records, they were removed from the data set.

4.4 Dst Data

Dst is an activity index which is obtained from magnetometer stations which are near the equator but at high enough latitudes that the equatorial electrojet does not dominate the perturbations observed. The resulting hourly averaged value is a measure of field perturbations which correspond to the strength of the magnetospheric ring current [Kelly, 1989]. Large negative values indicate increases in the ring current, which occur on time scales of roughly 1 hour. Decreases in the ring current take somewhat longer. Dst is often used to characterize or analyze magnetospheric substorm phenomena.

As with Kp, a very small number of apparently empty records were eliminated from the otherwise complete and very extensive set of Dst values.

4.5 WIND Data

IMF and solar wind plasma data from the WIND spacecraft was used for analysis of the October, 1995 magnetic cloud event. WIND is a modern solar wind monitoring platform with a substantially more elongated orbit than IMP-8. During the October, 1995 event WIND was over 120 Earth radii from the Earth, located at roughly $-123R_E X_{GSE}$ by $120R_E Y_{GSE}$. While the propagation delays for observations from this spacecraft are considerably larger than those needed for IMP-8 observations, establishing high quality WIND data propagation methods is beyond the scope of this study.
Rather than undertake the project of developing and testing better propagators for WIND data, we use the simpler propagators described above. Errors in the analysis due to errors in the propagation are minimized by the exceptionally sharp features of the cloud and the ensuing ionospheric response. While propagation tools would be necessary for statistical analysis of WIND data, for a case study of the October 1995 event the signature of the arrival of the magnetic cloud at the magnetosphere is apparent.

4.6 Other Index Data

In addition to the Kp and Dst indices of magnetospheric activity, I included two solar activity indexes. The F10.7 index is a proxy for solar ultraviolet (UV) data, which has a significant impact on ionospheric conductivity. The solar UV is, after all, responsible for the creation of the ionosphere. Variations in the solar UV produce changes in the ionospheric conductivity. The ionospheric conductivity, in turn, is an important parameter which affects the magnetosphere via field aligned currents. The sunspot number was included because, ultimately, the sun is the source of all magnetospheric activity.
4.7 Fitting Methods and Fit Assessment

The fits used in this paper were generated using a combination of standard closed form linear least squares algorithm, an iterative implementation of the Marquardt [1963] algorithm, neural networks, and the Kaleidagraph(TM) commercial data analysis program. A detailed comparison of standard data fitting algorithms, including those used in this study, can be found in Press et al. [1991]. Press et al. also contains justification for the use of least squares methods as a maximum probability modeling technique, so that material is not repeated here.

The primary quality of fit parameters used were the correlation coefficient and reduced chi squared:

\[
\begin{align*}
\sigma_m^2 &= \frac{\sum (m_i - \langle m \rangle)^2}{n} \\
\sigma_p^2 &= \frac{\sum (p_i - \langle p \rangle)^2}{n} \\
\sigma_{mp}^2 &= \frac{\sum (m_i - \langle m \rangle)(p_i - \langle p \rangle)}{n} \\
r &= \frac{\sigma_{mp}^2}{\sqrt{\sigma_p^2 \sigma_m^2}} \\
\chi_r^2 &= \frac{\sum (p_i - m_i)^2}{(n - N)\sigma_m^2} \\
\text{err}_{\text{RMS}} &= \sqrt{\frac{\sum (m_i - p_i)^2}{n}}
\end{align*}
\]  

(3a-c)

(4a-c)

where \(n\) = number of observations, \(N\) = number of fitted parameters, \(m_i\)=\(i\)th measurement, \(p_i\)=\(i\)th estimate (prediction), and \(< >\) represents averaging. The root mean square (RMS) error is given by (4c). \(\chi_r^2\) is the reduced form of chi squared and differs from chi square only by the normalization shown above.

A variety of other quality checks were also used, including an analog to a covariance matrix [Dennis and Schnabel, 1983], reduced error functions, and the Q parameter [Press et al., 1991]. Elements of the pseudo covariance matrix were used to generate the cited uncertainties in the coefficients for some of the fits.

The data (post selection) were uniformly weighted based on analysis summarized in EPCP.
Chapter 5
Empirical Proxy Relationships

Despite the size and complexity of the combined solar wind/magnetosphere/ionosphere system, due to the strong coupling between various regions of the magnetosphere, many of the commonly used geophysical parameters exhibit correlated behavior. Interestingly, two parameters which are directly related physically (e.g., IMF $B_Z$ and polar cap size) may not show behavior as strongly correlated as some indirectly coupled portions of the system (e.g., Kp and polar cap size). Further, because of limitations in the quality and availability of geophysical data, there is often a need for relations which approximate one type of observation or index in terms of a different observation or index. Although the relations could be either theoretical or empirical in origin, to be useful they must, at least, be calibrated by observations. In this section I summarize a number of empirical relations which relate commonly used magnetospheric parameters.

While approximations to each of the following relations using smaller data sets have been available for years, the large database of filtered and synchronized data created for this study allowed new estimates spanning decades of observations with a wide variety of geophysical parameters and time scales.

While these are generally not the definitive models of these parameters, they are useful both as practical proxies and as illustrations of the strong coupling between the common observables and indices. One example is in space environment modeling where it is desirable to run magnetospheric models even though not all of the preferred input data may available at all times. In such a case, the missing observation or index might be approximated via a proxy relation. Ideally, of course, the parameters themselves would correlate well but their availability should be uncorrelated.

As a specific example, direct measurements of polar cap convection are very useful but they are frequently unavailable or unusable due to practical considerations such as orbital
mechanics or instrument limitations. Fortunately, a reasonable estimate of the polar cap convection can be made using Kp (or vice versa). Although Kp and Φ are strongly correlated, their availability is almost totally uncorrelated. This makes estimates of Φ based on Kp an excellent choice to augment or replace the more precise and higher time resolution in-situ convection measurements.

It is worth clarifying the distinction between the following relations and more specialized empirical models such as those presented in other sections or in EPCP. These relations, by virtue of their simplicity and the lack of special restrictions on the data sets, are lower in fidelity but are more widely applicable than more specialized models derived for specific conditions or to answer more specialized questions. The models presented in EPCP represent the input/output relationship to which the system will asymptote. They are also explicitly only applicable to "southward-like" IMF conditions (i.e. for cases when the IMF B_{Z, GSM} has been consistently <+3nanoTesla). The following relations, on the other hand, simply quantify the fact that in the magnetosphere a host of coupling mechanisms ensure that, in general, one can estimate the value of most geophysical parameters in several ways. Of course, any of the following relationships can be trivially inverted if the inverse relation is desired.
5.1 Proxies Related to Polar Cap Potentials

While empirical models of polar cap potentials are discussed in greater depth in EPCP, it is often necessary to model Φ with less than ideal input parameters. Φ is an important parameter, in part, because it is related to so many other useful magnetospheric quantities. Although the combined time history of the solar wind and the IMF is generally the most ideal input for estimating Φ, it is possible to express Φ in terms of many other geophysical variables (and vice versa). The classic example, variations of which have been in use for several decades, is

$$Φ(B_Z) = 52.8(±0.78) - 3.45(±0.056)B_Z$$

where $B_Z$ is the hourly averaged IMF Z GSM component for the hour immediately preceding the period of the estimate in nanotesla. This estimate is similar to a large number of published estimates which used far smaller data sets to approximate the above relation. This estimate makes no assumptions about the history of the IMF prior to the time of the estimate. The low correlation in these is due to a combination of the time dependent response of the Φ and to the inclusion of northward IMF cases. For approximately southward only ($B_Z < -3$ nanoteslas), the correlation improves to ~0.61. For comparison, the form used in EPCP which includes both "viscous" and "merging" terms

$$Φ = 10^{-4}v_B^2 + 11.79 B_{\text{sin}}^3(0.5 \text{ invcos}(B_Z/B))$$

has a correlate and RMS error with respect to observed Φ ($r=0.87, 12kV$) for steady IMF conditions.

As mentioned above, Φ can also be approximated fairly well by using the global magnetospheric activity index Kp, despite the fact that Kp is a very low time resolution index.

$$Φ(K_p) = 10.2(±0.5) + 15.5(±0.15)K_p$$

$r=0.73$
As noted in EPCP, in the limit of very steady IMF the correlation improves to \( r = 0.84 \).

Although the physical relation between \( Kp \) and \( \Phi \) is less direct than that between other indices and \( \Phi \), particularly the auroral indices, \( Kp (\Phi) \) can be used to approximate \( \Phi (Kp) \) with a root mean square error of roughly 14kV (1). As noted in chapter 6, the time scale for polar cap convection, and thus the response time of \( \Phi \), span a range of scales. Since \( \Phi \) may take several hours to reach its equilibrium value for a given input, the three-hour averaging used to compute \( Kp \) is less of a disadvantage than might be expected from traditional assumptions regarding convection time scales.

A relationship between \( \Phi \) and the shorter-time index \( Dst \) is also evident upon analysis of the last decade of data

\[
\Phi(Dst) = 33.7(\pm 0.488) - 0.634(\pm 0.0127)Dst \quad \text{r=0.58} \]  

(8)

\( Dst \) has three times the temporal resolution of \( Kp \), and it therefore measures related phenomena which occur on the same time scales closer to the expected time scales of changes in \( \Phi \). However, \( Dst \) is not a significantly better input than \( Kp \) for estimating \( \Phi \). This is due largely to the fact that the phenomena measured by \( Dst \), ground level mid-latitude magnetic field perturbations, correspond to changes in the magnetospheric ring current. The ring current is not directly coupled to magnetospheric convection on time scales of less than 1 hour, which more than offsets the higher resolution of \( Dst \) in estimating \( \Phi \). Further, as noted in chapter 6, the polar cap response times span a wide range of time scales.

Both the size of the polar cap and \( \Phi \) are indicative of the strength of the coupling between the IMF and the magnetosphere. Therefore it is somewhat natural to express one in terms of the other, although, in fact, the relationship is fairly complicated. While the relation between polar cap size and \( \Phi \) is discussed in more detail in later chapters, it is possible to approximately relate the \( \Phi \) and the polar cap size.
\[ \Phi(\text{MEB}) = 526(\pm 4) - 7.61(\pm 0.0004) \text{MEB} \quad r = 0.775 \quad (9) \]

where MEB is in °MLAT. Similarly, if the MEB index is unavailable, the polar cap width based simply on the automatic determination of the magnetic latitude of the observed convection reversals can be used as well.

\[ \Phi(\text{width}) = -32.8(\pm 1.15) + 3.06(\pm 0.0404) \text{width} \quad r = 0.65 \quad (10) \]

where the width in °MLAT is the sum of the distances from the magnetic pole of the dawn and dusk extrema. The width of the polar cap, based on in situ convection data, is often much more useful than the location of either reversal by itself by similar means. The combination of the measurements reduces the contributions of errors and minimizes the effect of the IMF By induced shift of the convection features. The correlation between the magnetic latitudes of the dawn or dusk reversals by themselves with \( \Phi \) is poor but significant

\[ \Phi(\text{dawn cr}) = 265 - 2.79 \text{dawn cr} \quad r = 0.36 \quad (11) \]

\[ \Phi(\text{dusk cr}) = 279 - 3 \text{dusk cr} \quad r = 0.48 \quad (12) \]

where the locations of the dawn and dusk convection reversals are in °MLAT. The locations of the convection reversals change with the size of the polar cap, the dawn-dusk shift induced by IMF BY and other factors. The combined variances from each of these dependencies, as well as measurement errors, are the cause of the poor correlation in (11) and (12).

\( \Phi \) does not form usable interchange relations with the Y GSM shift of the polar cap, the sunspot number, or F10.7.

A more detailed study of the dependence of \( \Phi \) on specific physical processes and observables under steady conditions can be found in EPCP. The time dependent behavior of \( \Phi \) is discussed in chapter 6.
5.2 Proxy Relationships for Sunspot and Solar UV Indices

Although both the sunspot number (also known as the Wolf number) and the solar ultraviolet flux affect high latitude conductivity, the effects are sufficiently subtle that neither observable was useful for this study. While the effects of UV on ionospheric conductivity are substantial, and the role of ionospheric conductivity in solar-terrestrial coupling is significant, other factors listed here dominated the interactions to the extent that neither solar index was useful for this study. However, the sunspot number and the F10.7 index are highly correlated to each other (figure 7), and could reasonably be used interchangeably via the following empirical relation

\[ F_{10.7}(\text{sunspot number}) = 65.5(\pm)0.875(\pm)\text{sunspot number} \quad r = 0.95 \quad (13) \]

5.3 Proxy Relationships for Polar Cap Size

The nature of the merging-driven coupling between the solar wind and the magnetosphere means the size of the polar cap is inherently related to many other magnetospheric quantities of interest. In addition to the relation noted earlier between \( \Phi \) and the polar cap size (presented here in reversed form for convenience) there are several other functional relationships with statistics robust enough to be significant. Taking the MEB index as an indicator of polar cap radius one can approximate

\[ \text{MEB}(\Phi) = 66.4(\pm0.0408) - 0.0788(\pm0.00066)\Phi \quad r = 0.774 \quad (14) \]

\[ \text{MEB}(K_p) = 64.5(\pm0.047) - 1.85(\pm0.0117)K_p \quad r = 0.852 \quad (15) \]

\[ \text{MEB}(D_{st}) = 64.5(\pm0.0458) + 0.0804(\pm0.00119)D_{st} \quad r = 0.705 \quad (16) \]

\[ \text{MEB}(\text{IMF } B_Z_{GSM}) = 62.2(\pm0.0316)0.246(\pm0.0059)B_Z \quad r = 0.391 \quad (17) \]

\[ \text{MEB}(\text{dawn}_\text{cr}) = 39.4(\pm0.568) + 0.299(\pm0.0074)\text{dawn}_\text{cr} \quad r = 0.382 \quad (18) \]

\[ \text{MEB}(\text{dusk}_\text{cr}) = 36.5(\pm0.418) + 0.34(\pm0.0055)\text{dusk}_\text{cr} \quad r = 0.546 \quad (19) \]
Figure 7. The 10.7cm RF flux index, a proxy for solar ultraviolet output, is extremely highly correlated with the sunspot number.
where $\Phi$ is in kV, Dst and $B_Z$ are in nanotesla, the dawn and dusk convection reversal locations are in $^\circ$MLAT, and $\Phi/A$, the ratio of $\Phi$ to the polar cap area, is in kV/$^\circ$MLAT$^2$. This ratio is discussed further in section 3 of chapter 6. MEB, as noted in chapter 4, is a precipitation data based index which describes the location of the equatorward edge of auroral features near 24 MLT. Although the MEB index is distinct from the open/closed boundary, and from the convection reversal boundary, it is another indicator of the size of the polar cap. In general, the best simple relation exists between $Kp$ and the radius of the polar cap, although $\Phi$ and the radius are also nearly interchangeable for most purposes.

Using the automatic DMSP convection reversal detection, rather than the MEB index, yields

$$\text{width}(\Phi) = 21.3(\pm 0.07)+0.121(\pm 0.001)\Phi \quad r=0.60 \quad (20)$$

$$\text{width}(Kp) = 20.8(\pm 0.1)+2.65(\pm 0.035)Kp \quad r=0.61 \quad (21)$$

$$\text{width}(\text{Dst}) = 25.1(\pm 0.12)-0.104(\pm 0.0035)\text{Dst} \quad r=0.45 \quad (22)$$

$$\text{width}(\text{IMF } B_Z_{\text{GSM}}) = 27.9(\pm 0.06)-0.62(\pm 0.01)B_Z \quad r=0.474 \quad (23)$$

where width is the distance in magnetic latitude between the dawn and dusk convection reversals, and the units are the same as in previous sections. Figures (8 a-c) show the dependence of the polar cap size as determined by convection measurements (shown with "+") symbols) and as determined by MEB (shown with "x"s) on $\Phi$, $Kp$, and IMF $B_Z$. Although IMF $B_Z$ controls the amount of open flux, and thus the radius of the polar cap and its associated structures, the plots indicate a closer correspondence between $r$ (determined by either method) and either $\Phi$ or $Kp$ than between $r$ and $B_Z$. The plots also indicate the relationship between $\text{Dst}$ and $r$ is less obvious than those of the other variables with $r$. Since the aim of the figures is to display the functional dependence of polar cap size, it should be noted that there are simple differences between the two measures; in
Figure 8a, b. Observed polar cap radii using convection reversal data (labeled $r_{NADIA}$) and MEB. Although the IMF $B_z$ component controls solar-terrestrial coupling and the resulting parameters (e.g. $\Phi$, polar cap size), some of the "dependent" variables correlate much better to each other than to the controlling IMF $B_z$ for very simple models.
Figure 8c, d. The width in $^\circ$MLAT between the dawn and dusk convection reversals.
Figure 8c. The width in °MLAT from dawn to dusk convection reversals is not a strong function of Dist.
addition to the width (dawn to dusk) being double the radius, the MEB index is, on average, larger by $-13.8^\circ$MLAT due to the nightside shift mentioned earlier. Manual determination of the convection reversals are also possible, albeit labor intensive, but the manually determined radii are not a significant improvement over the other two methods even during very dynamic events. In some special cases, such as the extremely dynamic period of 18-21 October, 1995, particular observations may be of such importance that manual processing is still warranted to ensure that especially critical data points are correct.

5.4 Proxy Relations for Activity Indices

While relations between the Dst and Kp activity indices and other observables are provided in the preceding sections, the two indices are statistically related to each other as follows

\[
\text{Dst}(\text{Kp}) = 1.79(\pm 0.0212) - 0.0325(\pm 0.00055) \text{Kp} \quad r = 0.645 \quad (24)
\]

\[
\text{Dst}(\text{Kp}) = -4.44(\pm 1.06) - 2.32(\pm 0.73) \text{Kp} - 1.64(\pm 0.111) \text{Kp}^2 \quad r = 0.662 \quad (25)
\]

Conceptually the two indices are quite different, and they are traditionally used exclusively of one another. Physically, as mentioned earlier, changes in the Dst index correspond to changes in the ring current, and the index is computed hourly. Therefore Dst is generally viewed as an index which provides information about (and on the time scale of) substorm activity. Kp, however, is much lower resolution in every sense; it is often associated with magnetospheric substorm as well as storm activity. Although a cross index relation may seem unnatural, the two indices are, in fact, strongly correlated.

Despite the fact that both Kp and Dst are largely driven by the IMF, and that southward IMF is the primary stimulus for magnetospheric activity, neither Kp nor Dst respond directly enough to the IMF for a simple model. When compared to hourly averaged IMF $B_Z\ G_S M$, for example, variations in Kp or Dst correlate with the changes in the IMF at a
barely significant $r \approx 0.35$. More sophisticated models of the indices using time histories of the IMF are possible, but a simple proxy relation cannot be determined.
Chapter 6
POLAR CAP PHENOMENA

As described in Chapter 3, the high latitude ionosphere includes a central region of open magnetic field lines called the polar cap approximately surrounded by regions of field-aligned currents, and aurora. Because it is a direct result of, and the site of, the interaction between the magnetosphere and the ionosphere it is of considerable interest to magnetosphere/ionosphere coupling studies.

6.1 Indicators of the Polar Cap Boundary

The points along the DMSP orbit at which the extrema are measured are the points at which the observed cross-track ion convection changes direction. Near dawn and dusk the flow reverses at the convection boundary. Closer to noon and midnight, however, the flow does not change as clearly, and detection of the convection reversal boundary there is more difficult. This analysis does not rely on passes near noon or midnight, however. These convection reversals are one type of indicator of the boundary of the polar cap, although there are several other observables which also relate to the polar cap boundary. Direct observation of precipitating particles reveals features which can be interpreted as indicators of the footprint of the boundary between open and closed field lines. This is often used as an indicator of the location of the edge of the polar cap. Conceptually it may well be the least ambiguous indicator of the polar cap boundary, however the precipitating particle observations data set was neither available nor practical for use in this study. An index derived from this type of data, however, was included in the study. The visible (as well as in other spectral ranges) aurora also occur near the edges of the polar cap, and observations of the auroral oval are also often used as indicators of polar cap boundaries. With the launch of the POLAR spacecraft, large quantities of high quality, wide field of view images of the aurora viewed from space will soon become available for research use.
In this study I primarily used, instead, measurements which correspond to a third feature of the polar cap, the convection reversal boundary. By incorporating the Phillips Laboratory Auroral Boundary Index (also called MEB) the analysis includes two of the three major types of polar cap boundary information.

In general, each of these three features (any of which might arguably mark the edge of the polar cap) is located near, but generally not coincident with, the other physical boundary features. The convection reversal is generally slightly poleward (in magnetic latitude) of the boundaries implied by both precipitating particle data and auroral images. While the precipitating particle data provides a sensitive and detailed indicator of the characteristics of the plasma on field lines which cross the observation point, it is difficult to automate the detection of the polar cap boundary from the data. The auroral boundary index is the most extensive, readily available, and convenient form of precipitating particle data. While automated detection of edges from the images of the aurora is becoming possible, the relation between the auroral display and the open/closed boundary (or even the convection reversal boundary) is not simple or entirely understood for all conditions. The automatic processing of in-situ convection measurements, however, has already been successfully implemented, and a substantial experience and software base exists for handling the huge volume of data. Also, the convection data is readily available in several forms, including the both the locations of the convection reversals as well as the actual ion drift measurements.

The drawback to use of convection measurements is that although automated detection of the convection reversal (CR) is a fairly mature technique, the CR is phenomenologically distinct from the open/closed boundary (OCB). In simple models of an open magnetosphere the sunward flow is on closed field lines, and the antisunward flow is on open field lines (figure 2). Thus, in a simple model, the open/closed boundary and the convection reversal boundary are the same. In reality, however, the two are distinct; the CR boundary (CRB) can be up to 3-5°MLAT from the OCB under extreme conditions [Lu
et al., 1994]. Even under these conditions, the behavior of the two boundaries are similar; both expand and contract due to the same stimulus of merging due to southward IMF. The difference between the two is due to departures from the simple open two-cell model. Near dawn and dusk the difference is largely due to $B_y$ induced effects. During the early portion of the 18 October 1995 event $B_y$ is negligible. Under these conditions, the dawn-dusk portions of the OCB and of the CRB should not differ significantly. Near midnight, the ionospheric flow continues past the OCB as discussed in Ding [1995]. For further information on the differences between the two boundaries, see Lu et al. [1994].

Although the manual processing employs a substantial experiential base acquired from a large number of observations, there are practical difficulties which limit the usefulness of manual processing. In addition to the labor-intensive aspect of manual inspection, it is not clear that the manually determined radii are more useful than the automatically determined radii or the MEB index. While the manual estimates varied in response to features in the observed flow which are apparently averaged or filtered out of the MEB index, MEB is more useful for two reasons. One is that ~181,000 MEB records have been compiled. This data set is amenable to statistical analysis with minimal additional effort, and the set approximately spans the periods during which either DMSP or IMF data are available. Another difference is that not all of the features in the flow data appear to correspond to overall behavior of the coupled ionosphere-magnetosphere system. The manual determination of the location of the convection reversals may incorporate features the existence of which are not reflected in the behavior of the relevant geophysical parameters. The differences between the estimates by each method are probably due to a sum of instrumental errors, features whose temporal or spatial scale is below a critical threshold, and inevitable human errors.

Several points regarding MEB are worth noting. First, the index is intended to represent the location of the most equatorward auroral feature in the midnight sector rather than the OCB itself. Second, the polar cap (by any of the three measures described above)
is shifted to the nightside of the polar ionosphere. Thus the magnetic latitude of nightside
features have an offset compared to measurements based on the width of the polar cap.
Additionally, the auroral feature which MEB models is generally significantly equatorward
of both the CRB and the OCB. Despite this, as the amount of open flux increases, the
features described by MEB would be expected move equatorward as the polar cap expands.
Analysis is presented which shows that MEB and the convection based estimates of radii
change identically (to within the uncertainty of the statistics) with IMF Bz. Therefore I take
changes in parameter either as reasonable indicators of the expansion of the polar cap.
6.2 Response of the Polar Cap to a Southward Step in the Interplanetary Magnetic Field

The magnetic cloud event of 18-21 October, 1995 provides an excellent test case for study of the time dependence of the polar cap boundary. The sudden strongly-southward turning of the IMF in the leading edge of the cloud followed a period of very minimal activity. Before the arrival of the cloud, the IMF had been very slightly northward. From previous studies, it is known that the (relatively) well understood behavior of the ionosphere under southward IMF persists continues for small northward IMF. Under these conditions the solar wind/magnetosphere coupling is relatively weak, and the magnetosphere/ ionosphere system is weakly driven: convection slows, geomagnetic activity becomes minimal. When the IMF becomes strongly northward, of course, the behavior of the ionosphere changes significantly. The October 1995 cloud, however, subjected a previously quiet magnetosphere to an extremely strong input. The response of the system to the sudden input is fairly revealing.

As noted earlier, there is a very direct connection between the \( \Phi \) and the amount of open flux. The amount of open flux is equal to the integral of the magnetic field over the area of the polar cap. Although there are slight distortions to the shape of the auroral oval with IMF \( B_y \) here I neglect this small correction. The \( B_Y \) driven distortions may be more significant near noon in MLT, but the analysis does not rely on data from this region. While it is possible to make empirical models of the polar cap size using the IMF, or using any of several indices, here I use only actual measurements of the polar cap size as indicated by DMSP observations of convection flow boundaries or the particle precipitation based MEB index (which also uses DMSP data). For observing changes in the polar cap size either should be quite suitable, particularly for periods with relatively small IMF \( B_Y \) such as the leading edge of the magnetic cloud of 18-21 October 1995. Figure 9 shows the sharp step in the IMF \( B_z \) with negligible \( B_Y \) during the event, and also the solar wind velocity data.
Figure 9 a-c. The IMF and solar wind velocity profiles observed during the 18-21 October 1995 magnetic cloud event show a strong, abrupt southward step in the IMF BZ GSM component.
Figure 9d. The solar wind velocity profile of the magnetic cloud event. The profile includes a large increase in flow speed during the event.
Under steady IMF conditions, the dayside merging rate and the nightside reconnection rate are, at least in a time-averaged sense, equal. The $\Phi$ and the polar cap size remain approximately constant under these conditions, although there is still considerable scatter in observations of both $\Phi$ and cap size under even steady conditions. Under dynamic conditions, as the solar wind/IMF input to the magnetospheric system changes, both $\Phi$ and the size of the polar cap change. Since both are driven by the opening of magnetic field lines at the dayside magnetopause, it is reasonable to expect that the two vary roughly in parallel. Under the most dynamic conditions, it has long been believed that at times the dayside merging rate may substantially exceed the nightside reconnection rate. When this happens, the polar cap expands as the amount of open flux is increased. As the polar cap expands, the polar cap boundary moves to lower latitudes. There are also many other consequences of the increased merging rate which are beyond the scope of this study. If the increased coupling is sustained it generally leads to a global increase in magnetospheric activity, including increased auroral activity, geomagnetic substorms and storms, and changes in the field and plasma structures throughout the magnetosphere. The immediate consequence, however, of increased merging is the expansion of the polar cap as previously closed field lines become open ones.

For the period in which the cloud impacted the magnetosphere, the polar cap radius was determined by several methods for comparison (figure 10). The first method is the automatic determination of the location of the convection reversals by the NADIA DMSP IDM data processing software. Second, the detailed uncorrected high time resolution (4 second averaged) ion drift meter data were plotted and examined manually to determine the location of the convection reversals. Finally, the MEB index also provides an estimate of the polar cap radius, although it is intended to represent the location of the most equatorward auroral feature in the midnight sector.

During the October, 1995 cloud, the sudden southward turning of the IMF caused an immediate and rapid (up to 5°/hour) expansion of the polar cap (figure 11 a-c). This initial
Figure 10. Even during the very dynamic period of 18-21 October, 1995, the magnetic latitude of the smoothed location of the convection reversal boundary (here represented by \( r_{\text{smooth}} \)) and the equatorward-most edge of the nightside aurora (MEB) change in a similar manner.
Figure 11a. The rate of expansion (contraction) of the polar cap during the event and the corresponding IMF $B_Z$ GSM component.
Figure 1b. An expanded view focusing on the response during the purely southward IMF portion of the event.
Figure 11c. A view of the MEB data for the critical portion of the event and the processing done to determine the expansion rate.
expansion rate was five times faster than is typically observed (the long-term RMS rate of expansion/contraction of the polar cap is roughly 0.8°/hour) (figure 12). The expansion began close enough to the calculated arrival time of the leading edge of the cloud that the two times are simultaneous to within the uncertainties of estimating the cloud arrival time. Although there are difficulties in calculating an arrival time for the cloud from the WIND observations, the analysis relies largely on relative time differences rather than the absolute time of arrival of the cloud at the magnetosphere. Further, the most interesting aspects of the interaction occur on time scales which are large (several hours) compared to the total propagation time, and also larger than the probable errors in estimating the arrival time.

During the initial expansion both the radius and $\Phi$ changed very rapidly (up to 5°MLAT/hr and 0.4kV/second respectively). Further, the second derivative of the polar cap size was positive; the rate of expansion of the polar cap was accelerating. $Dr/dt$ rose during the first hour until it reached a value of 4-5°MLAT. Although there were several observations which indicated an expansion rate of 5°MLAT/hour, it is possible the rate increased rapidly to ~4°MLAT/hour and that the rate of expansion peaked at that level. Shortly afterwards, however, the rate of rise of both the polar cap radius and the $\Phi$ dropped by a factor of 10. The change occurred, despite the still constant -20nT $B_Z$, when the polar cap radius exceeded 20°MLAT (or possibly as much as 30°MLAT according to inspection of the high resolution flow data) and $\Phi$ passed 168kV (figure 13). This occurred roughly 2.5 hours after the apparent (and estimated) arrival of the cloud. Both the radius and the potential continued to rise after that point, indicating that the system still had not yet reached its asymptotic value. This is further borne out by the fact that, despite the initial rapid rise, once the potential exceeded ~160kV, it only slowly approached the asymptotic steady-state value $\Phi_A$ (figures 14 a-c). It is interesting, although not necessarily significant, that the actual rise rate of $\Phi$ during the first phase of the polar cap response corresponds quite well to an estimate using $\Phi_A$ with 15 minute time-averaged,
Figure 12. This histogram shows the number of occurrences of various polar cap expansion (contraction) rates observed by DMSP during the years 1987-1997.
Figure 13a. The polar cap potential and size during interaction of the magnetic cloud with the magnetosphere.
Figure 13b. An expanded view of figure 13a indicating a rapid initial rise in $\Phi$ and $r$, followed by slower increases in $\Phi$. 
Figure 13c. The early portions of the polar cap response to the magnetic cloud used in the analysis.
Figure 14a. A comparison of the observed potential (MLT corrected) with the steady state model showing the overall pattern and the magnitude of the differences.
Figure 14b. An expanded version of figure 14a showing the periods of interest.
Figure 14c. The highest available resolution comparison of the observed and steady-state potentials during the initial portion of the event.
propagated cloud data. During the second phase of the response, when $\Phi$ was greater than 160kV, the observed $\Phi$ rose slowly towards $\Phi_A$.

When the polar cap reached this transition, the expansion rate slowed dramatically, despite the steady southward IMF and the continued rise of the $\Phi$. This occurred roughly 3 hours after the apparent impact of the southward step at the leading edge of the cloud upon the magnetosphere. Somewhat later, what had been a steadily southward IMF rotated to a clock angle of 45° from southward, and the polar cap began to shrink. Table 2 summarizes the observed phases of the response. Because of the near-perfect step input, the table summarizes the polar cap’s response to southward IMF in an unusually unsullied fashion. It is likely that for a less strongly southward IMF step the overall pattern of the response would be similar, albeit scaled accordingly. Analysis of the ionospheric response to a similar, but less extreme magnetic cloud which occurred in January 1997 would definitively answer the question of scaling. Isolation of a comparable step from southward to small $B_Z$ or northward IMF would also be very useful, but one does not exist in the currently available data base.

The radius of the polar cap (as approximated by the CRB in this case) is shown overlaid upon the IMF $B_Z$ for this event in figure (15). The two measurements track each other much more closely than might be expected from statistical attempts to model $r$ using the IMF $B_Z$. One possible (and probable) explanation is that during expansion and contraction the relation between the two changes. Data from a comparable (to this cloud) northward step from steadily southward IMF would greatly clarify this issue. The figures also illustrate the removal of two unusable radius measurements from the data set.
Figures 15a, b. The size of the polar cap (here determined by convection reversals) and the IMF $B_z$. The strong IMF control of the radius is non uniform: during the early portions of the southward step and during a northward period (day 293) the radius does track the IMF $B_z$ as well as during other portions of the event.
<table>
<thead>
<tr>
<th>delay</th>
<th>conditions</th>
<th>parameter</th>
<th>trend</th>
<th>value</th>
<th>summary</th>
</tr>
</thead>
</table>
| 0     | Bz=-20nT  
By=0nT  | MEB       | expanding slowly | 28°        | accelerating expansion  |
|       |                  | Φ         | increasing rapidly | 79kV      |                          |
|       |                  | dr/dt     | increasing       | 0-5°/hr    |                          |
|       |                  | d2r/dt    | constant         | 4°/hr²     |                          |
| 50 min.| Bz=-20nT  
By=0nT  | MEB       | expanding rapidly | 35°        | maximal expansion        |
|       |                  | Φ         | increasing slowly | 168kV     |                          |
|       |                  | dr/dt     | constant         | 4-5°/hr    |                          |
|       |                  | d2r/dt    | ~zero            | 0°/hr²     |                          |
| 160 min. | Bz=-20nT  
By=0nT  | MEB       | constant         | 37°        | constant size            |
|       |                  | Φ         | increasing slowly | est. 180kV |                          |
|       |                  | dr/dt     | decaying to zero | -0°/hr     |                          |
|       |                  | d2r/dt    | small negative   | <0°/hr²    |                          |
|       | Bz=-10nT  
By=-10nT | MEB       | shrinking slowly | 35°        |                          |
|       |                  | Φ         | increasing       | est. 200kV |                          |
|       |                  | dr/dt     | constant         | <0°/hr     |                          |
|       |                  | d2r/dt    | -                | -          |                          |

Table 2: Response of the Polar Cap to a Southward Step in IMF. The observed time delay after the initial arrival of the cloud is indicated for the start of each phase of the polar cap response to the southward step in IMF. No time delay is indicated for the fourth phase, since it is a response to a change in the IMF which is not part of the response to the step. MEB is shown here, but the different measures of cap size behave very similarly during the event, as shown in figure 10.

Due to the irregular timing and significant variance of DMSP based estimates of the radius of polar cap, the radius data were smoothed, as indicated in the figures. The variations of the unsmoothed data about the smoothed average follows trends which are common in DMSP data analysis. One such trend is a tendency for an oscillation between values observed in the northern and southern hemisphere. As mentioned in section 4.1.1 these patterns are well understood, and the smoothed results are probably a reasonable indicator of the true behavior of the polar cap during this period. As noted above, three observations indicated a peak expansion rate of >5°MLAT/hour, but these observations were imbedded in a longer sequence which indicated a peak expansion 20% lower (e.g. 4°MLAT/hour). Although there are >30 periods between 1987 and 1997 during which the smoothed expansion/contraction rate exceeded 4°MLAT/hour, none exceeded
5°MLAT/hour. Of these dynamic events, this event is the least ambiguous because of the clean southward step in the input IMF. Given the available information, it is probable that the actual value is 4-5°MLAT/hour, but another comparable event would be necessary to clarify the distinction.

Because the expansion rate dr/dt changes as a function of time and the state of the polar cap even when the IMF inputs to the system are almost ideally simple (as in this case), there is no convenient way to statistically model the dependence of dr/dt on IMF from the available set of data. A large number of unusually clear cases, similar to the October 1995 cloud but with differing IMF values, would be needed to directly model the functional dependence of the expansion rate on IMF values with any confidence and accuracy from the DMSP observations. A promising alternative is to use DMSP flow data to calibrate sophisticated simulations of the polar cap, and then query the simulation regarding specific behavior [Richmond, 1992]. As these simulations are further improved, it may be possible to extract the functional information from the calibrated models without waiting decades for a larger collection of exceedingly rare events such as the October 1995 event. Another promising possibility involves the expected availability of a very large number of images of the aurora from the POLAR spacecraft.
6.3 The Ratio of Open Flux to the Polar Cap Potential

Several modern magnetic field models [Toffoletto and Hill, 1989, 1993; Ding, 1995] assume the ratio of the $\Phi$ to the area of the polar cap is constant. Using DMSP convection data it is possible to observationally test this assumption. The ratio is related to the convection time scale. More directly, the ratio of the amount of open flux in the polar cap ($\phi$) to the polar cap potential $\Phi$ gives the convection time scale explicitly [Hill, 1985].

Both the ratio $\phi$/area and the ratio $\phi$/\Phi are determined using the DMSP data from 1987-1996 and compared to concurrent values of $\Phi$, IMF $B_z$, Kp, and Dst. The differences between $\Phi$/area and $\phi$/\Phi are simply the inversion and the integration of the flux as a function of area. Figure 16 simultaneously shows the relation between width and open flux as well as the span of both included in this data set. $\Phi$/area has units of kV/(°MLAT$^2$) and $\phi$/\Phi has units of seconds. Both are considered, simply because while $\phi$/\Phi is conceptually more closely related to physical quantities of interest, $\Phi$/area is easier to model based on the data. This is largely attributable to the larger variances of $\Phi$ than the other quantities. The amount of open flux is calculated for the available data set and it is also compared to $\Phi$, IMF $B_z$, Kp, and Dst.

Additionally, by using the solar wind velocity data to determine the progress of the distant portion of the open field line which is in the solar wind, I calculate the distance which the solar wind portion of an open line travels during the ionospheric convection from the dayside to the nightside. This provides an estimate of the rate of flux loss across the magnetopause, or, equivalently, the length scale of the magnetotail [Hill, 1985]. I also plotted $\Phi$ in relation to the area of the polar cap, the amount of open flux, the convection time scale, and the length scale of the magnetotail estimated from these calculations.

Based on the observations, the ratio $\Phi$/Area is not even approximately constant in value; the variance of the ratio is comparable to the RMS value of the ratio. The observed distribution of the ratio is shown in figure 17. The ratio varies strongly with any major
Figures 16 a, b. The range, relation, and distribution of the polar cap size parameterized by open flux and width.
Figure 17. A histogram of the ratio of $\Phi$ to the size of the polar cap.
Figures 18 a, b. The ratio of $\Phi$ to the area of the polar cap versus Kp and Dst. The ratio is reasonably well described by a linear fit to Kp.
Figures 18 c, d. Comparison of use of geomagnetic colatitude with geomagnetic latitude.
Figures 18 e, f. Despite the fact that both $\Phi$ and $r$ are controlled by $B_z$, $B_z$ is not the best choice for modeling the ratio using simple linear methods, as noted in the text.
activity indicator: Φ, Kp, Dst, IMF BZ, or even the size of the polar cap itself (figures 18 a-f). It is worth noting in passing that some forms, such as Φ/colatitude² are cleaner functions of Φ than others (Φ/MLAT²) which are physically (if not numerically) very similar. Closer examination reveals that although the ratio Φ/Φ is nearly linear with magnetospheric activity (or the strength of the coupling between the IMF and the magnetosphere) there is a higher order dependence. The ratio initially increases with any of these parameters (except IMF BZ), but the rate of increase falls off slightly during the most active times. The ratio’s dependence on IMF BZ appears, at least in some respects, to mimic the “double sided” behavior common to magnetospheric parameters. As the Z component of the IMF turns northward, magnetospheric activity decreases dramatically. When the IMF is strongly northward, however, many indicators of activity, such as Φ, increase again with increasingly northward IMF. The symmetric behavior of the ratio with BZ also reflects this tendency.

\[
\Phi(\Phi/\varsigma^2) = 5.99(\pm 0.07) + 4.92 \times 10^3 (\pm 6) \Phi/\varsigma^2 \quad r = 0.99 \quad (26)
\]

\[
\text{MEB}(\Phi/\varsigma^2) = 66.2(\pm 0.04) - 402(\pm 3) \Phi/\varsigma^2 \quad r = 0.80 \quad (27)
\]

\[
K_p(\Phi/\varsigma^2) = 1.04(\pm 0.02) + 1.74(\pm 1.6) \Phi/\varsigma^2 \quad r = 0.75 \quad (28)
\]

\[
\text{Dst}(\Phi/\varsigma^2) = -0.84(\pm 0.6) - 2.74 \times 10^3 (\pm 52) \Phi/\varsigma^2 \quad r = 0.61 \quad (29)
\]

\[
B_Z(\Phi/\varsigma^2) = 4.10(\pm 0.08) - 422(\pm 6.5) \Phi/\varsigma^2 \quad r = 0.55 \quad (30)
\]

\[
R_{CRB}(\Phi/\varsigma^2) = 10.7(\pm 0.04) + 340(\pm 3.75) \Phi/\varsigma^2 \quad r = 0.68 \quad (31)
\]

where \(\varsigma\) is the geomagnetic colatitude in degrees, and \(\varsigma^2\) is therefore an area proxy. \(R_{CRB}\) refers to the radius of the polar cap convection reversal boundary in \(^{o}\)MLAT.
One might argue that these correlations are as high as they are because they are nearly auto correlates, but the argument is specious. It is true that $\Phi$ correlates perfectly with itself, and correlates well with the size of the polar cap and the other parameters. That it varies in the same sense as the product of itself and another of these correlated parameters is hardly surprising. However, the different observables are physically related rather than simply statistically redundant copies of the same information. The particularly high correlation above is simply because the ratio is a function of the level of magnetospheric activity, as further indicated by the polynomial fit which incorporates the rolloff during active periods. Figures (18 a-f) show the observed relations described above. As with several other examples throughout the analysis, despite the fact that IMF $B_Z$ controls many of the interactions (directly or otherwise), the quantities of interest are not well organized by $B_Z$. The changes in the ratio with polar cap size are also shown, but the plots show excessive scatter overlaid upon fairly simple trends (figures 19 a, b).

The conversion from area to open magnetic flux is simple, and the results are easier to interpret as meaningful magnetospheric quantities (figure 20 a, b). Again, although $B_Z$ controls both the amount of open flux and $\Phi$, the variables it controls exhibit behavior more strongly correlated to each other than to $B_Z$. Similar plots (to those above) for $\phi/\Phi$ are also included (figures 21 c-d), although the $y$ axis is relabeled as convection time to reflect the units and the meaning of the ratio more clearly than was possible with the approximations above. While the convection time scale is not well correlated to the polar cap size, it shows a power law dependence on $\Phi$. The convection time is not simply the result of the flow speed ($\Phi$), but instead reflects the relationship between the flow speed and the amount of open flux across the parameter regime from lightly driven to strongly driven. If the cap size were more constant, the power would be closer to -1 rather than (roughly) -0.55. The length scale of the magnetotail, determined by the method described above, is shown as well. The calculation of the length scale is described above, and the result (figures 22 a-b) are discussed in chapter 7. The tail length is, again, roughly a power law dependence on
Figures 19 a, b. The relation between the ratios considered so far and the size of the polar cap are significant but not optimal for simple linear modeling purposes.
Figure 20a. The observed relationship between the polar cap potential and the amount of open magnetic flux is approximately linear.
Figure 20 b. The observed relationship between the Z component of the IMF and the amount of open flux, which is naturally very similar to comparable plots of \( \Phi \) versus \( B_z \). Although it is not amenable to a simple linear least squares fit, the same methods used to model \( \Phi(\text{IMF}) \) should allow an accurate description of \( \Phi(\text{IMF}) \) as well.
Figures 21 a, b. The estimated convection time scale, using the arguments of Hill [1985], versus polar cap size and polar cap potential. A power law dependence is apparent in figure b.
Figures 22 a, b. Using the measured solar wind speed, the time scales yield length scales of the magnetotail, again following Hill [1985]. A somewhat less compact power law dependence is still clearly represented in the data. The power is approximately -0.55.
\( \Phi \), with a mean length scale of approximately 1200 \( R_E \). Figure 22c uses very restrictive magnetic local time selection in an attempt to minimize errors due to MLT dependence of \( \Phi \) in the measurement and analysis, at the cost of further reducing the data set. Figures (23 a, b) illustrate the typical symmetric dependence on IMF \( B_Z \).
Figures 23 a, b. IMF $B_z$ versus the time and length scales.
6.4 Polar Cap Potential, the Polar Cap Boundary, and Faraday's Law

One unfortunate consequence of the practical difficulties in measuring high latitude ionospheric phenomena is that, although the observations may generally conform to a trend, there is considerable scatter in observations even under ideal conditions. A consequence of the plethora of processes which can occur in large scale, heterogeneous, magnetized plasma systems is that for any observation there are typically several plausible explanations. This makes it difficult to distinguish between measurement errors and any number of possible mechanisms for any particular observation. Thus, the study of solar terrestrial coupling has acquired a suite of often cited, but seldom (if ever) definitively identified processes. One such process is the induced EMF during polar cap expansions. It has also never been conclusively and quantitatively studied in sufficient detail to empirically verify its role in the dynamic response of the polar cap.

When the polar cap expands or contracts, generally due to changes in the dayside or nightside merging rates, there is a change in the amount of enclosed magnetic flux. The polar cap boundary moves equatorward (or poleward) as the amount of open flux increases (decreases). The open flux is given by

$$\phi = \frac{1}{2} \bar{B} \cdot d\bar{A}$$  \hspace{1cm} (32)

where $f$ has units of Tesla meters squared, $B$ has units of Teslas, and the area of the polar cap has units of meters squared. For this section of the analysis, a dipole representation of the geomagnetic field was used

$$B = \frac{3.5 \times 10^{-5}}{R^3} (2 \cos \theta \hat{r} + \sin \theta \hat{\theta})$$ \hspace{1cm} (33)

where $B$ is in Teslas, $R$ and $R_E$ (the radius of the Earth) are in km.

Faraday's law

$$\nabla \times E = -\frac{dB}{dt}$$  \hspace{1cm} (34)
implies an induced electromotive force should occur when the amount of enclosed flux changes rapidly. The effective induced potential

$$\Phi = \oint E \cdot d\vec{l}$$

is equal to the line integral around the expanding segment of the polar cap in the rest frame of the moving boundary

$$\oint E \cdot d\vec{l} = \frac{d}{dt}(\oint B \cdot d\vec{A})$$

Given the existence of a fairly accurate estimate of the potential $\Phi_A$ which occurs across the polar cap for a given IMF input during steady conditions, it is reasonable to look for the mechanism for the shortfall in observed potentials (relative to $\Phi_A$). One possibility is that the sum of the observed $\Phi$ (not in the frame of the moving boundary) and the induced emf will approximately equal $\Phi_A$ during an event.

One way to definitively determine the importance of Faraday's Law in $\Phi$ observations is to directly observe the polar cap response during very dynamic periods. During the magnetic cloud of 18-21 October 1995, the polar cap was subjected to one of the most extreme changes in the input IMF observed in several decades of solar wind observations. The exceptionally rapid change in an very strong IMF followed by a prolonged period of stability produced an uncommonly ($>99^{th}$ percentile, see figure 13) rapid expansion of the polar cap. The fact that the event occurred during simultaneous availability of IMF data, solar wind plasma data, and concurrent in-situ measurements by two DMSP satellites provides an exceptional opportunity to compare the magnitude of the induced emf with the difference between the observed and asymptotic polar cap potentials. The characteristics of the event are also discussed further in earlier sections.

For the October 1995 event, figure (3) shows a comparison of observations and empirical estimates of $\Phi$. The observed (by DMSP) convection (shown by the dots in the
figure) fell below the prediction based on steady-state input/output relations between the IMF and $\Phi$ (shown by the solid lines). In cases such as this, the induced EMF might reasonably be suspected to account for a significant fraction of the difference. It is apparent that some form of time-dependent effect sets in during the response, and it is known that the polar cap expanded rapidly during this period.

Figure (24) shows the resultant induced emf from Faraday's Law (shown with triangles on the plot) corresponding to the observed expansion superimposed on a plot of the observed (shown with filled circles) and "expected" ($\Phi_A$) potentials (shown with a dash-dot line) during the event. During the initial response to the step, the observed $\Phi$ was far below $\Phi_A$, but $d\Phi/dt$ was quite small (but growing). During this phase, the induced emf was small compared to the difference between the ionospheric convection and $\Phi_A$. Later, however, the rapid expansion corresponded to an emf of $>100$ kV, which was roughly comparable to $\Phi$ (and to $\Phi_A-\Phi$) at that point. Beyond that point the emf dropped rapidly as the rate of expansion of the polar cap slowed while $\Phi$ continued to rise towards $\Phi_A$. In fact, the derivatives of both $\Phi$ and the expansion of the polar cap decrease by about a factor of 10 at the roughly same point during the event. There are apparently three distinct periods in the response to the southward step.

In the initial response both $\Phi$ and the induced emf corresponding to the movement of the polar cap boundary are small compared to $\Phi_A$. Later, there is a period during which an estimate of the emf is comparable to the difference between $\Phi_A$ (which may correspond to the dayside merging rate) and $\Phi$. Still later in the response, the emf decays away although $\Phi$ is still well below $\Phi_A$. Additionally, the change in behavior of both $\Phi$ and polar cap size (the reduction in the rates of increase of each of the quantities) occurs at roughly the same point in the event for both $r$ and $\Phi$.
Figure 24. A comparison of the observed potential, the steady state potential corresponding to the observed solar wind and IMF, and the emf calculated from the movement of the polar cap boundary. Several distinct phases of the step response are discussed in the text.
Chapter 7
DISCUSSION AND CONCLUSIONS

A number of simple proxy relationships are presented which use the unusually large data set assembled for this analysis to provide simple tools for operational use. The proxy relations are improvements (in the statistical sense of being drawn from a much larger data set than previous estimates) over previous comparable estimates, but they are not the highest fidelity models of any of the listed quantities. A variety of simple exchange relations were presented which may help compensate for problems in data availability and data quality for some uses of the most commonly used geophysical parameters.

The polar cap response to a sudden increase in the southward component in the IMF was observed during the initial phase of the ionospheric response to the magnetic cloud of 18 October 1995. The resulting polar cap potential was comparable to the largest observed in the last decade of nearly continuous in-situ convection measurements. The polar cap expanded at a similarly exceptional rate which peaked between 4 and 5°MLAT/hour. The response of the polar cap to this event allows clear insight into aspects of solar-terrestrial coupling which are otherwise very difficult to determine. Although several features visible in the data from the event have been previously discussed, the event contains clear, usable indications of effects which have not, until now, been adequately understood. Combination of analysis of this event with another comparable event, such as the more recent January 1997 cloud, would provide even more interesting details of the interaction.

The polar cap potential is, on average, about 55kV. During slightly northward IMF, $\Phi$ appears to asymptote to a value of 20-25kV, although the behavior of the polar cap changes dramatically for more northward IMF. During the period from 1987-1997, there have been several dozen periods when the polar cap potential was significantly higher (greater than 150kV).
The issue of saturation of \( \Phi \) has been a long standing controversy in solar terrestrial interactions. *Hill et al.* [1976] predicted the onset of saturation at roughly 150kV. Subsequent studies have found conflicting evidence: some supporting saturation, while others found no evidence of it. A comprehensive study of functional relations [ECP] between the IMF and \( \Phi \) in the steady state did not find clear evidence of a saturation, but did reveal hints as to the actual situation. In the steady state, the best fit description of \( \Phi(\text{IMF}) \) does not change as a function of the regime (versus \( \Phi \) or \( B_Z \), for example) [EPCP]. However, there are very few observations of \( \Phi \) greater than 150kV, and none above 250kV. The IMF during the last 10 years has periods which, using \( \Phi_A \), correspond to predictions of \( \Phi > 250 \text{kV} \). The fact that there are fewer observations at very high \( \Phi \), yet the best fit steady state form does not change with \( \Phi \), is explained by the response to of the polar cap to the October 1995 cloud. There are few observations of \( \Phi > 150 \text{kV} \) (and none above 250kV) not because \( \Phi \) cannot reach these values, but because the time dependent response of the polar cap (combined with the statistical characteristics of the IMF) means there are very few times when \( \Phi_A \) is large enough, long enough for \( \Phi \) to rise that high. The fact that the behavior of the system, as evidenced by the derivatives of both \( \Phi \) and the radius of the CRB, changes abruptly at \( \sim 160 \text{kV} \) appears to confirm the predictions of *Hill et al.* [1976].

The extremely strong southward IMF during the October 1995 cloud, with its sudden onset preceded by a period of relative quiescence, allows an unambiguous investigation of the role of emf corresponding to the expansion of the polar cap. Although the initial difference between the observed and estimated steady state potentials is large compared to the emf, there is a period in the ionospheric response where \( \Phi_A \sim \Phi + \text{emf} \). This may correspond to a situation where \( \Phi_A \) is a reasonable indicator of the dayside merging rate, and the observed \( \Phi \) is less by (at least) the appropriate emf. However, during the earliest phase of the polar cap response, it is clear another effect, not identified here, plays a larger role. Further, the finite rise of the observed \( \Phi \) indicates the coupling process is time-
averaging or throttling the affect of the input IMF. The observations allow an estimate of this rise rate, but further analysis and additional data would be necessary for a definitive investigation. Further, the characterization of the polar cap response may, eventually, allow an explicit reconciliation between steady state estimates and simulations and observations which observer lower potentials under nonsteady conditions.

The relationship between $\Phi$ and the amount of open flux (or, almost equivalently the size of the polar cap) was estimated by Hill [1985]. In that analysis, the ratio of the amount of open magnetic flux to the polar cap potential was related to the rate of flux loss along the magnetotail. This, in turn, implies a length scale for the tail. Although many of the polar ionospheric quantities respond similarly to the IMF, they do not respond identically, and the differences (particularly when parameterized by geophysical quantities) had not been quantitatively studied in adequate detail. Even in very modern magnetic field models, for example, the ratio is approximated as a constant [Toffoletto and Hill, 1993]. The ratio is, in fact, not even approximately a constant. It varies by more than its mean value with changes in related parameters. The ratio, and several related quantities, have been calculated and compared to related geophysical quantities. One significant result is that the length scale of the tail appears to obey a power law dependence on the polar cap potential. The length scale which results from these calculations is, perhaps, longer than may be expected. It is possible that in cases where the flux loss calculation implies an extremely long tail, that at some point far downstream other process may dominate and cause a shortening of the tail relative to these estimates.
REFERENCES


