High-latitude ionospheric transient events in a global context

G. I. Korotova, D. G. Sibeck, T. J. Rosenbush, C. T. Russell, and E. Friis-Christensen

Abstract. This paper presents a comprehensive global study of bow shock motion, magnetosheath dynamic pressure variations, daytime magnetospheric magnetic field perturbations, and cosmic noise absorption events attending a sequence of transient events observed in high-latitude global magnetograms on February 14, 1986. ISEE 2 spacecraft observations indicated that most of the transient ground magnetometer events were associated with abrupt inward and outward motions of the dawn bow shock during a prolonged period of strongly northward and orthogonal interplanetary magnetic field orientation. Geosynchronous GOES 5 and 6 magnetometer observations provide evidence for corresponding compressions and expansions, which propagated diskward through the prenoon magnetosphere. The magnetopause moved inward past the CCE spacecraft during some of the compressions. The compressions scattered magnetospheric particles and thereby produced quasi-periodic oscillations in the cosmic noise absorption recorded by high-latitude ground riometers. We infer that (unobserved) strong transient variations in the solar wind dynamic pressure produced the various phenomena and that the ground magnetometer signatures are best explained in terms of the pressure pulse model of Southwood and Kivelson [1990], in which a single sharp change in the solar wind dynamic pressure generates a pair of field-aligned currents.

Introduction

Transient symmetric and asymmetric bipolar variations in the north/south component of high-latitude daytime ground magnetograms are common [Tamao, 1964]. Events with durations less than 15 min occur about once per day (but sometimes much more frequently) and reach peak amplitudes prior to local noon in the vicinity of the cusp (A ~ 75°) [Sibeck and Korotova, 1996]. Most high-latitude events with large amplitudes coincide with abrupt step function and impulsive signatures in equatorial surface and geosynchronous magnetic field measurements [Matsumura, 1957; Sibeck, 1993]. Since the latter signatures have long been interpreted in terms of the magnetospheric response to abrupt changes in solar wind dynamic pressure [Chapman and Ferraro, 1933; Gosling et al., 1967], it seems quite likely that the high-latitude signatures are an integral part of that global response.

Tamao [1964] interpreted the differing equatorial and high-latitude responses in terms of the differing magnetohydrodynamic (MHD) waves that reach these two locations. Sudden changes in the solar wind dynamic pressure launch both fast and Alfven mode waves into the magnetosphere. Because Alfven mode waves do not travel perpendicular to magnetic field lines, the simpler equatorial signatures must be produced solely by fast mode waves. By contrast, the more complicated signatures observed at higher latitudes represent a composite response to both fast and Alfven mode waves.

Two recent theoretical treatments reach strikingly different conclusions regarding the relationship between impulsive events in high-latitude ground magnetograms and variations in the solar wind dynamic pressure. Southwood and Kivelson [1990] reported that a single abrupt variation in the solar wind dynamic pressure produces a pair of traveling convective vortices in the ionosphere and a bipolar variation in the north/south component of the magnetic field observed on the ground. By contrast, Glassemer and Fommer [1992] argued that a step function change in the solar wind dynamic pressure produces the observed signatures only when pressure and internal terms in the momentum equation have comparable magnitudes, and they concluded that an impulsive variation in the solar wind dynamic pressure is necessary to produce the bipolar signatures.

It should be simple to verify that impulsive events in high-latitude ground magnetograms correspond to variations in the solar wind dynamic pressure and to distinguish between these two models. In practice this process can be difficult. Although several detailed case studies demonstrated that some impulsive events can be related to abrupt changes in the solar wind dynamic pressure [e.g., Friis-Christensen et al., 1988; Sibeck et al., 1989a, Farrugia et al., 1989; Sibeck and Creutz, 1991; Korotova and Sibeck, 1994, 1995], statistical analyses of IMP 8 observations indicate that the vast majority of transient events are not ri

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namic pressure variations best explains the magnetospheric and ionospheric events or by criticizing the use of IMF 8 as a solar wind monitor. Possible alternative mechanisms include bursty merging on the magnetopause [Gloecker et al., 1984], the Kelvin–Helmholtz instability [McHenry et al., 1988], or impulsive penetration [Heikkila et al., 1991]. Each of the alternative mechanisms predicts a specific set of event occurrence patterns. Ionospheric events produced by the Kelvin–Helmholtz instability should occur during intervals of high solar wind velocities [Southwood, 1968], but they do not [McHenry et al., 1990; Sibeck and Korotova, 1994]. Events produced by bursty merging on the equatorial magnetopause should occur preferentially during intervals of southward interplanetary magnetic field (IMF) orientation [Rijnbeek et al., 1984], but they do not [Sibeck and Korotova, 1994]. If anything, the transient ionospheric events occur primarily during intervals of northward IMF orientation [Sibeck and Korotova, 1994], behavior that might be consistent with impulsive penetration [Ma et al., 1991] or might simply indicate that they are more difficult to identify when the IMF turns southward and the magnetosphere becomes more disturbed. Note that there are serious concerns about the efficacy of impulsive penetration [Owen and Cowley, 1991; Heikkila, 1992].

The speed and direction of event motion may help determine their origin. All the models predict that the majority of events will move antisunward, as observed [Sibeck, 1991; Hughes et al., 1995; Arnoldy et al., 1996]. However, the bursty merging and pressure variation models predict sunward-moving events in the vicinity of local noon under certain conditions. Insofar as the northern ionosphere is concerned, magnetic curvature forces pull newly merged magnetic field lines, and transient ionospheric events, dawnward when the IMF has a strong duskward component. The same curvature forces pull transient events in the northern ionosphere duskward during periods of strongly dawnward IMF orientation. As a result, sunward-moving events may occur in the early postnoon ionosphere during periods of duskward IMF orientation and in the late evening ionosphere during periods of dawnward IMF orientation [Korotova and Sibeck, 1995]. By contrast, the pressure variation model predicts sunward-moving events in the early postnoon ionosphere during (typical) periods of spiral IMF orientation and in the late evening ionosphere during periods of (unusual) orthogonal IMF orientation (Sibeck, 1991).

To date, efforts to distinguish between the two models on the basis of event velocity have been unsuccessful. Sibeck and Cowley [1991] discussed a case study in which event motion disagreed with expectations for the bursty merging model, and Sibeck [1991] reported a survey of events that indicated no tendency for the IMF orientation to control their motion. On the other hand, Kom et al. [1994] reported the results of a statistical survey indicating that event durations were longer at locations where magnetic curvature forces might be expected to combat pressure gradient forces but shorter when the IMF forces might be expected to act in concert. Korotova and Sibeck [1995] presented examples of sunward-moving events whose motion was consistent with both the pressure variation and bursty merging models.

For these reasons we are inclined to suppose that IMF 8 frequently lies too far out to ensure the observed features that strike the dayside magnetopause [e.g., Lenzsetz et al., 1989; Sibeck et al., 1989; Sibeck, 1992; Sibeck and Korotova, 1996] or too far from the bow shock to observe processes in the foreshock that substantially modify solar wind parameters before they reach the magnetosphere [e.g., Sibeck et al., 1989c; Fairfield et al., 1990; Lin et al., 1996]. If so, a monitor in the magnetosheath or the immediate vicinity of the bow shock may be essential.

Figure 1 shows the expected locations of the bow shock and magnetopause for a 6 eV solar wind dynamic pressure and a 0 eV component of the IMF. Whereas the...
location and shape of the magnetopause have been taken from the empirical study of Roelof and Sleight [1993] for the specified solar wind conditions, the shape of the bow shock is simply that of Fairfield [1971] scaled to a pres- sure thrice as great as that seen on average.

During the interval from 1300 to 2200 UT on February 14, 1986, ISSEE 2 moved through the equatorial dusk magnetopause from GSM $(x, y, z) = (-2.3, -20.5, 1.8)$ to $(0.7, -16.1, -2.5) R_E$ along a trajectory that basically par- alleled the nominal bow shock. With the assumption of a brief data gap from 1443 to 1507 UT, ISSEE 2 magnetom- eter observations [Russell and Elphic, 1978] were available for 12 s running averages every 4 s throughout this inter-
val. Following a prolonged data gap, IMP 8 plasma and magnetic field observations [King, 1962] become available after 1657 UT. From 1700 to 2200 UT, IMP 8 moved through the inner equatorial dusk magnetopause from GSM $(x, y, z) = (-28.6, 25.2, -6.2) R_E$ to $(30.3, 23.8, -3.2) R_E$.

The CCE satellite moved from a radial distance of 8.7 $R_E$ and a local time of 10.1 at 1300 UT (nominally just in-
side the magnetopause) through a radial distance of 6.1 $R_E$ and a local time of 12.2 at 1900 UT (very near GOES 6) to-ward perigee. We will present CCE magnetometer ob-
servations with a 6.4 s time resolution [Pfitzenmaier et al., 1983]. The GOES 5 (74°W) and 6 (100°W) satellites moved through geosynchronous orbit at local times UT $= 5$ and UT $= 7$, respectively. We will present GOES 5 and 6 magnetometer observations at 3 s time resolution [Grubb, 1975]. We use a database of digital global ground magne-
tometer measurements with 1 min time resolution from a global network of more than 50 stations at polar cap, au-
ral zone, and equatorial latitudes.

Observations

In this section we present and analyze the various satel-
line and ground observations sequentially from the solar wind to the ionosphere.

ISSEE 2 Bow Shock Observations

Figure 2 presents ISSEE 2 magnetometer observations in sp-
helical GSM coordinates from 1300 to 2200 UT. Here, longitude $\phi$ is upward, latitude $\phi$ is westward, and longitude $\phi$ is northward. Even in the absence of plasma obser-
ations it is a simple matter to identify numerous bow shock crossings during this interval on the basis of sharp changes in the magnetic field strength from $+$ve $B_z$ ranging from 8 to 15 nT in the solar wind to values rang-
ing from 20 to 50 nT in the magnetopause. In particular, we note bow shock crossings at 1429 (O), 1431 (O), 1531 (I), 1553 (O), 1558 (I), 1612 (O), 1623 (O), 1629 (O), 1649 (I), 1736 (O), 1755 (I), 2007 (O, 2038 (I), 2110 (O), 2112 (I), where $O$ indicates a crossing from the magnetopause to the solar wind and $I$ indicates a crossing from the solar wind to the magnetopause. As a result of the bow shock crossings, ISSEE 2 was in the solar wind during the intervals numbered 1 to 8 in Figure 2: 1429–1431, 1507–1531, 1533–1558, 1612–1623, 1629–1649, 1736–1755, 2007–2038, and 2110–2122 UT. In addition, ISSEE 2 made very brief partial exits from the magnetopause into the solar wind at 1917 and 1932 UT. These partial exits are labeled A and B in Figure 2. With the exception of two momentary southward turn-
ings at 1429 and 1435 UT, as well as several slightly more prolonged intervals from 1523 to 1526, 1534 to 1544, 1924 to 1930, and after 2138 UT, ISSEE 2 observed strongly northward interplanetary and magnetopause mag-
netic field orientations throughout the entire 9-hour-long interval from 1300 to 2200 UT. The IMF almost always assumed an unusual orthorhombic orientation with the longi-
tude either between 0° and 90° or between 90° and 180°.

Solar wind dynamic pressure variations provide one possible explanation for the multiple bow shock crossings on this day. Increases in the solar wind density and dy-
namic pressure move the bow shock inward, whereas de-
creases allow it to move outward [Volland and Asner, 1974]. If so, the solar wind dynamic pressure applied to the mag-
netopause was enhanced during each of the intervals 1–8, A, and B. Until this inference is corroborated by comple-
mentary observations (below), we need to exercise some caution. Changes in any one of several solar wind parame-
ters, including the Mach number, flow direction, or IMF orientation, might cause the bow shock to move [e.g., \textit{Lepping et al., 1996}]. Furthermore, if ISSEE 2 were located near the mean position of the bow shock, even negligible changes in solar wind pressure might cause the bow shock to sweep back and forth across the satellite. Finally, given ISSEE 2’s location so far off the Earth–Sun line, we cannot be sure that it observes solar wind features that strike the subauroral magnetopause.
Figure 3 presents IMP 8 magnetosheath magnetic field and plasma for the interval from 1337 to 2200 UT on February 14, 1986. As noted earlier, there was a prolonged data gap from the start of the interval to 1637 UT. Although it proves difficult to relate specific features in the IMP 8 and ISEE 2 magnetic field observations, probably due to draping of the magnetosheath magnetic fields, the IMP 8 observations do suffice to confirm that the duskside magnetosheath magnetic field orientation was steadily northward throughout the interval in which observations were available.

More important, the IMP 8 plasma observation shown in the bottom panel of Figure 3 indicate a series of strong dynamic pressure (envelope) variations in the magnetosheath, where $n$ is the density and $V$ is the velocity. Short bars mark the previously identified intervals when ISEE 2 was in the solar wind, and dots denote the two brief intervals, A and B, when ISEE 2 approached the bow shock. Comparison of the marked intervals and pressure trace indicates substantial increases in the magnetosheath dynamic pressure following intervals 5, 6, A, 7, and 8. There was a data gap in the plasma measurements following interval B. Since the magnetosheath dynamic pressure should be directly related to that in the solar wind, the IMP 8 observations suggest that large (but small) increases in the solar wind dynamic pressure caused the ISEE 2 bow shock crossings. The pressure increases that produce the bow shock motion can be observed at IMP 8 after ISEE 2 because they propagate anti-sunward with the solar wind.

CCE and GOES 5 and 6 Magnetospheric Magnetic Field Observations

The top panel of Figure 4 presents CCE observations of the northward component of the magnetospheric magnetic field in GSE coordinates. During the interval under study the CCE satellite observed a steadily increasing magnetic field strength as the satellite moved earthward from its 8.8 R$_E$ apogee near local noon. Numbered and lettered bars in Figure 3 indicate the previously identified intervals during which the bow shock was compressed toward or inward of the ISEE 2 satellite. Inspection of this panel reveals that the CCE observed no significant signature during brief interval 1, weak, variable, and sometimes southward magnetic fields during interval 2, a small increase in the magnetospheric magnetic field strength during interval 3, enhanced magnetic field strengths during interval 4, depleted variable magnetic field strengths during interval 5, a strong magnetic field increase during interval 6, and transient increases in the magnetospheric magnetic field strength during intervals A and B. The CCE was too deep within the magnetosheath to observe significant signatures in association with intervals 7 and 8. The CCE observations also suggest that a series of (unobserved) large-amplitude increases in the solar wind dynamic pressure compressed the magnetosphere, enhanced magnetospheric magnetic field strengths, and displaced the bow shock and magnetopause earthward. During compression intervals 3, 4, 6, A, and B the CCE observed enhanced magnetospheric magnetic field strengths. During in-
tervals 2 and 3 the CCE satellite crossed the magnetopause to observe weaker and more variable magnetic fields in the magnetosheath.

The GOES 5 and 6 magnetic field strength observations shown in the middle panel of Figure 4 confirm this interpretation. Like the CCE observations, they indicate magnetospheric magnetic field strength enhancements during intervals 3, 4, 6, A, and B. When the magnetopause moves inward past the CCE satellite during intervals 2 and 3, the GOES satellites remain within the magnetosphere and simply observe magnetospheric magnetic field strength increases within a compressed magnetopause. Note that unlike the CCE, GOES 5 and 6 remained in the outer magnetosphere during intervals 7 and 8 to observe magnetospheric field strength increases. Ranking the various events by their magnitudes, we see that events 2, 4, 5, 6, 7, and 8 produced more substantial compressions of the magnetosphere than did events 1, 3, A, and B.

Finally, the bottom panel in Figure 4 reproduces IMP 8 magnetosheath dynamic pressure observations. The similarity of the dynamic pressure traces to those for the geosynchronous magnetic field strengths at GOES 5 and 6 strongly suggests that pressure variations were the cause of the disturbances at geosynchronous orbit.

During the course of a separate study of observations on another day, Korotova and Seneck [1995] noted impulsive events moving sunward through geosynchronous orbit and the high-altitude dayside magnetopause at geosynchronous local times. They were unable to distinguish between two explanations. In the first, pressure features aligned with the orbi-thal IMF orientation initially struck the magnetopause prior to local noon and only later struck the magnetopause near local noon. In the second, antiparallel merging prior to local noon during an interval of dawnward IMF orientation generated events connected to the northern ionosphere that were pulled downward (sunward) by magnetic tension forces.

We wish to examine the GOES 5 and 6 observations on February 14, 1986, for evidence of sunward-moving features. We can determine the downstream component of the direction of motion of the transient magnetic field strength variations at GOES 5 and 6 by detrending and then cross correlating 20-min subintervals exhibiting significant magnetic field strength variations. As the survey shown in Figure 5 indicates, all of the cross correlations produced functions with pronounced peaks indicating lags from GOES 6 to 5 ranging from 3 to 60 s. Lags of this sense are expected when GOES 6 lies nearer local noon than does GOES 5, i.e., after 1800 UT, because the dawnward magnetosheath flow should sweep solar wind features past the magnetosphere.

However, similar lags were also observed prior to 1800 UT, when GOES 5 lies nearer local noon than did GOES 6. As shown in Figure 2, the IMF was strongly dawnward throughout this interval and frequently pointed duskward. The antiparallel merging model does not predict merging in the equatorial regions under these conditions. Although equatorial component merging is unlikely during intervals of strongly dawnward IMF orientation, if it did occur, tension in the newly merged magnetic field lines would produce dawnward (antisunward) moving events prior to local noon in the equatorial magnetosphere, and not the sunward-moving events observed.

As we described above, we already know that the various magnetospheric magnetic field strength variations correspond to bow shock motion at ISEE 2 and magnetosheath pressure variations at IMP 8. Given the orbi-thal IMF orientation observed by ISEE 2, we also expect magnetospheric features generated by solar wind pressure variations to move sunward through the prenoon magnetosphere as observed. Consequently, the solar wind and magnetospheric observations on February 14, 1986, support the hypothesis that solar wind pressure features can initially strike the magnetopause at locations away from the subsolar point.

Ground Magnetometer Observations

Given the evidence for bow shock and magnetopause crossings, magnetosheath dynamic pressure variations, and compressions of the dayside magnetosphere, it would indeed be a surprise if there were no corresponding features in ground magnetograms. We examined the traces from more than 50 observatories. Tables 1, 2, and 3 give the codes and geomagnetic coordinates for each of the stations used in this study. We begin by considering the global response and then focus upon the response areas in European and Greenland ground magnetograms.

Figure 6 presents 1-min averages of the X (north/south) component of the magnetfield from the global network of auroral and high-latitude stations. We can identify several impulsive events with widely varying amplitudes in these observations. The first, just after 1430 UT, was seen at stations ranging from DIF to SLC, with a peak amplitude at the latter station. At most stations (especially BRW, CBB, YKC, BLC) the event exhibited a "w" signature with negative, positive, and negative deflections of the X component of the magnetic field. The second, which occurs at 1800 UT, exhibits a bipolar positive-negative signature at PDB, FFC, BLC, and DIF, a monopolar negative signature at BRW, and a bipolar negative-positive signature at TIF. There is another global event, with much smaller amplitudes and generally negatively-positive bipolar signatures, at 1915 UT. Several stations (DIF, BLC, FCC, and PDB) observe a damped, long-period oscillation beginning at 2030 UT. And a large-amplitude transient event
begins at 2100 UT. This event exhibits a bipolar positive-negative signature at DIK and TIK, an "m" signature at BHRW, a "w" signature at MEC, and nearly monopolar positive signatures at BLC, FCC, and PDR. By inspecting signatures observed in Scandinavia and Greenland we can identify several further events with smaller amplitudes. Figure 7 presents the Scandinavian observations at geomagnetic latitudes ranging from 63° to 67°. At these locations the previously identified ground events at 1430, 1800, 1915, 2030, and 2125 UT all exhibit very clear signatures. However, the Scandinavian observations also indicate a "w" or monopolar positive event at 1645 UT, a weak bipolar positive-negative event in the MJO and PEL observations at 1700 UT, and a bipolar negative-positive event in the KIL and KAU observations at 1930 UT.

Inspection of the Greenland observations shown in Figure 8 indicates that the signatures for all these events, including those with small amplitudes, were quite widespread. The Greenland observations provide evidence for events at 1430, 1625, 1700, 1800, 1900, 1915, 1930, 2030, and 2125 UT. The wide latitudinal coverage of the Greenland data (geomagnetic latitudes ranging from 67° to 80°) allows us to demonstrate that the signatures seen in the ground magnetograms reverse with latitude, from bipolar positive-negative at TIL and SVS at 1430 UT and from bipolar positive-negative at NAQ, FHB, and GHB to bipolar negative-positive at TIL/SVS at 1800 UT. Asahi and Allen [1982] reported similar reversals in conjunction with other events, and Friis-Christensen et al. [1988] showed that they could be interpreted in terms of traveling correc- tion varicosities. Le et al. [1993] andRussell and Guestey [1995] presented statistical surveys that calibrated the re- sponse of subaural ground magnetometers to abrupt variations in the solar wind dynamic pressure. The events seen in Figures 6 through 8 typify those ob- served at high latitudes and considered by previous studies. Some are marked by bipolar signatures, others by monopolar or more complicated signatures. The nature of the signature observed often depends on the location of the observer, and some trigger widespread oscillations. It is sough to determine which fraction of the impulsive ground events could be identified with previously identi- fied compressions and expansions of the magnetopause. The lower panels in Figures 6 through 8 present GOES 6 geoelectronic magnetic field observations and indicate the previously identified intervals during which the mag- netopause was compressed, the bow shock moved inward, and pressure pulses were observed in the magnetosheath.

Event 1 was identified on the basis of transit toward bow shock motion. The abrupt compression of the magnetospheric field at 1430 UT. The ground obser- vations indicate a near-global impulsive event at this time. The fact that bipolar signatures in the Scandinavian and Greenland ground magnetograms were associated with a single sharp compression of the magnetopause argues for an interpretation of this transient event in terms of the
Table 3. Greenland Magnetometer Stations

<table>
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<th>Code</th>
<th>Station Name</th>
<th>Geographic Latitude</th>
<th>Geographic Longitude</th>
<th>Corrected Geomagnetic Latitude</th>
<th>Corrected Geomagnetic Longitude</th>
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<td>Artu</td>
<td>67.9</td>
<td>306.4</td>
<td>74.9</td>
<td>38.9</td>
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<tr>
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<td>Fieberbergh</td>
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<td>30.3</td>
<td>68.4</td>
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<td>Godtscheen</td>
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<td>306.5</td>
<td>76.1</td>
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<td>GHB</td>
<td>Godthul</td>
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<td>308.3</td>
<td>70.9</td>
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<td>Narsarsuaq</td>
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</table>

Theoretical model proposed by Southwood and Kivelson [1990], rather than that of Glatzmaier and Hepperle [1992].

Events 2 and 3 were identified during the interval 1500 to 1600 UT. We were unable to identify any corresponding isolated impulsive events in the ground magnetograms during the same interval. Instead we note large-amplitude fluctuations in the north/south components of the ground magnetograms with periods longer than the 5–15 min customarily associated with impulsive events. These fluctuations, most readily apparent in the Greenland and Scandinavian magnetograms, probably correspond to multiple north/south IMF turnings (see Figure 3). Sibeck and Korotova [1996] previously noted that impulsive events are more difficult to observe during intervals of southward IMF orientation, because the corresponding enhanced geomagnetic activity tends to obscure the events. GOES 3 and 6 observations indicate a sharp increase in the magnetospheric magnetic field strength during event 4 at 1625 UT and a sharp decrease in field strength at the end of event 5 at 1700 UT. Ground magnetograms in Greenland and Scandinavia record impulsive events at these times, but the events are not seen globally. There are other, smaller variations in the magnetospheric magnetic field strength during events 4 and 5 and other smaller variations in the ground magnetograms during the same interval.

A pronounced transient compression of the magnetosphere marks event 6. During the course of the event the magnetic field strength rises more gradually at 1730 UT than it falls at 1800 UT. Inspection of the ground magnetograms reveals a nearly global event at 1800 UT, again marked by nearly bi-polar magnetic field signatures in many locations, but little or no signature at 1730 UT (with the possible exception of stations in southern Greenland). Apparently, the duration, and not just the amplitude, of a magnetospheric compression determines the

Figure 6. The X (north/south) component of global ground magnetograms from 1300 to 2300 UT on February 14, 1986. See Table 1 for the locations of these stations. The lower panel shows GOES 6 geosynchronous magnetic field observations.

Figure 7. The X (north/south) component of Scandinavian ground magnetograms from 1300 to 2200 UT on February 14, 1986. See Table 2 for the locations of these stations. The lower panel shows GOES 6 geosynchronous magnetic field observations.
Figure 8. The X (north/south) component of Greenland ground magnetograms from 1300 to 2200 UT on February 14, 1986. See Table 3 for the locations of those stations.

The lower panel shows GOES 6 geosynchronous magnetic field observations.

strength of corresponding ground events, a point emphasized by Southwood and Kivelson (1990).

Geosynchronous observations indicate that events A and B exhibit relatively small amplitude, but sharp, magnetic field strength variations at 191 and 2300 UT. The amplitude of event A exceeds that of event B. The ground magnetometer observations indicate an impulsive event with near-global events at the time of event A. Any signature associated with event B appears to be limited to locations in southern Greenland and northern Scandinavia. A brief southward turning of the IMF at 1930 UT (Figure 2) controls the signatures at some of the ground stations, most notably BRW, MBC, and CBWE.

The magnetosphere is greatly compressed during the course of event B, but the compression and subsequent expansion are rather more gradual than those seen in the other events. On the ground, widespread oscillations begin at 2030 UT, shortly after the magnetospheric compression reaches its greatest amplitude.

Finally, event C is marked by an extraordinarily large and rapid compression of the magnetosphere at 2010 UT. Only a few minutes later the compression ends equally rapidly. Although global, the corresponding signatures in ground magnetograms are rather complex, ranging from strong negative deflections in Scandinavia and at BRW, to a bipolar positive/negative signature at DLR, and positive deflections over most of North America (BLC, FCC, and PD8). Our survey of impulsive events in ground magnetic observations on February 14, 1986, reveals that most are local, that ground events marked by simple bipolar north/south turnings correspond to steep function compressions or expansions of the magnetosphere, and that not only the amplitude but also the duration of the compression controls the strength of the signature observed on the ground.

Riometer Observations

Only a few papers have considered impulsive events in riometer observations, and there is no continuous concern about their origin [e.g., Suino et al., 1974; Storms et al., 1995]. In this paper we will consider the response of riometers in the polar cap to the transient events described above. Figure 9 presents the riometric noise absorption at two frequencies, 30 and 51.4 MHz, and two locations, McMurdo (LT = UT − 7) and South Pole (LT = UT − 3.5). The lower panel of the figure presents GOES 6 geosynchronous magnetic field observations and identifies the times of the EIDE 2 solar wind intervals, i.e., the time at which we have inferred enhanced solar wind dynamic pressures.

Both McMurdo and South Pole observed a gradual decrease in absorption following the 1436 UT sc. Despite their large separation the two ground stations observed rather similar, but unusual, quasi-periodic absorption intensity variations during the 3-hour period following 1500 UT. The modulation periods ranged from 20 to 40 min and increased with time. The amplitude of the modulation was greatest at McMurdo, which was located prior to local noon during this interval. At 1800 UT, following transient event 6, the instability modulation suddenly ceased at South Pole, and the absorption remained at a steady enhanced level for the next 3 hours. After the final magnetospheric compression at 2115 UT, the absorption suddenly increased, and some wave activity appeared again. There was no sudden cessation of wave activity at McMurdo, but rather some local disturbances during the period from 1840 to 2115 UT.

Because the nearly simultaneous quasi-periodic absorption enhancements covered a large area of the polar cap, we were forced to explain an exclusion of the cosmic

Figure 9. Riometer observations at McMurdo and South Pole at two frequencies from 1300 to 2200 UT on February 14, 1986. The lower panel shows GOES 6 geosynchronous magnetic field observations.
noise absorption modulations in terms of substorms. On the other hand, the period of the absorption intensity varia-
tions was rather similar to that for the bow shock crossings, magnetosheath pressure fluctuations, and magnetosheath magnetic field strength variations. It seems plaus-
able that compressions and expansions of the magneto-
sphere driven by quasi-periodic solar wind pressure varia-
tions reconfigure the magnetospheric magnetic field and modulate the access of solar protons into the polar cap. In addition to energetic electrons, solar protons are an addi-
tional source of ionization. Consequently, fluctuations in the flux of solar protons reaching the polar caps can pro-
duce nearly simultaneous modulations of the polar cap cosmic noise absorption at widely separated locations.

Conclusions

We presented a case study of simultaneous multipoint subaural and global ground magnetometer and riometer ob-
servations to study the magnetospheric response to a series of inferred solar wind magnetic pressure variations. We were able to infer increases in the solar wind dynamic pressure on the basis of systematic inward bow shock and magnetopause motion at the times of magnetospheric mag-
netic field strength increases and to infer decreases in the solar wind dynamic pressure on the basis of systematic outward bow shock and magnetopause motion at the times of magnetospheric magnetic field strength decreases. Lim-
ited plasma observations in the dusk magnetosheath sug-
gest that the bow shock motion and magnetospheric compressions were associated with bursty solar wind dy-
namic pressure variations. The simultaneous ISEE 2 bow shock, IMF 8 magnetosheath, and CCE magnetopause ob-
servations ruled out an interpretation of the events in terms of a process originating at the magnetopause. Because ISEE 2 and IMF 8 flank the magnetosphere and ob-
served consistent features, we could be confident that the IMF applied to the magnetosphere was almost always strongly northward and that there was little likelihood of magnetic ranging on the equatorial magnetopause.

We noted a sequence of impulsive events in high-lati-
tude ground magnetograms. Most of the events were glo-
bal, although the precise signature often depended upon latitude and local time. Events observed in ground magnetograms reached peak amplitudes in the range of geomagnetic latitudes from 70° to 75° but could be seen as far poleward as 85°. We established a close correspon-
dence between the ground events and compressions and expansions of the magnetosphere, magnetopause, and bow shock motion. The largest-amplitude ground events tended to be associated with sudden compressions and expansions of the magnetosphere (instead of occurring at the times of peak compressions or expansions). Although the amplitude of the compression or expansion of the magnetosphere is an important factor determining the amplitude of the ground event, so is the abruptness of the change, with larger-amplitude ground events tending to be associated with very abrupt compressions and expansions. The fact that events with lipolar north/south signatures in the ground magnetograms can be associated with step function compressions and expansions of the magnetosphere supports the model for ground events proposed by Smithwood and Kivelson [1990].

The compressional signatures observed at geosyno-
netic orbit moved inward through the prenoon magneto-
sphere. Although the time resolution and geographic spac-
ning of our magnetometer observations do not suffice to de-
termine the motion of the ground events, we suggest that the event motion was also sunward in the prenoon ionosphere. We interpreted this motion as evidence for solar wind pressure fluctuations aligned with the orthogonal IMF on this day, striking the prenoon magnetopause prior to reaching local noon. We noted evidence indicating that quasi-peri-
odic variations of the magnetospheric configuration modu-
lated the flux of solar protons arriving in the polar caps and thereby produced corresponding oscillations in the cos-
mic noise absorption.

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