Magnetosphere on May 11, 1999, the Day the Solar Wind Almost Disappeared: II. Magnetic Pulsations in Space and on the Ground

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Abstract. Simultaneous observations by Wind and IMP-8 in the upstream region on May 11, 1999, when the solar wind density was well below its usual values and the IMF was generally weakly northward, indicate there were upstream waves present in the foreshock, but wave power was an order of magnitude weaker than usual due to an extremely weak bow shock and tenuous solar wind plasma. Magnetic pulsations in the magnetosphere have been observed in the magnetic field data from Polar and at mid-latitude ground stations. By comparing May 11 with a control day under normal solar wind conditions and with a similar foreshock geometry, we find that the magnetosphere was much quieter than usual. The Pc 3-4 waves were nearly absent in the dayside magnetosphere both at Polar and as seen at mid-latitude ground stations even through the foreshock geometry was favorable for the generation of these waves. Since the solar wind speed was not unusual on this day, these observations suggest that it is the Mach number of the solar wind flow relative to the magnetosphere that controls the amplitude of Pc 3-4 waves in the magnetosphere.

Introduction

On May 10-12, 1999, a prolonged interval of extremely low solar wind density was observed by the WIND and ACE spacecraft. This is an important interval to study because it enables us to separate effects such as those of the dynamic pressure on the magnetosphere from those of the orientation of the interplanetary magnetic field (IMF). In an earlier letter [*Le et al.*, 2000] we reported how the Earth's magnetospheric current systems responded to the drop in solar wind dynamic pressure. The drop in density also changed the magnetosonic Mach number of the solar wind flow relative to the Earth and hence weakened the bow shock. This too could have noticeable effects on the magnetosphere. Herein we examine how magnetic pulsations in the magnetosphere were altered by the weakening and expansion of the radius of the bow shock using magnetic field data from the Polar spacecraft and from ground-based mid-latitude stations, as well as simultaneous records obtained in the foreshock and in the nearly undisturbed solar wind observed by Wind and IMP-8.

Pc 3-4 magnetic pulsations (10-100 mHz) in the dayside magnetosphere are believed to have a energy source from upstream waves in the Earth's foreshock region [*Troitskaya et al.*, 1971; *Greenstadt and Olson*, 1977; *Odera*, 1986; *Troitskaya*, 1994]. The upstream waves are generated by the interaction between the solar wind plasma and backstreaming ion beams in the foreshock region. Then they are carried downstream to the magnetopause along the solar wind streamlines through the magnetosheath. If the IMF cone angle is small ($< 45°$), the upstream waves fill the subsolar upstream region and the pressure fluctuations associated with the upstream waves can be carried to the magnetopause. The magnetopause responds to these pressure fluctuations and ultimately transfers the wave energy into the dayside magnetosphere and generates Pc 3-4 magnetic pulsations [*Wolfe et al.*, 1989]. Thus, Pc 3-4 pulsations can be potentially a very useful diagnosis of the state of the solar wind.

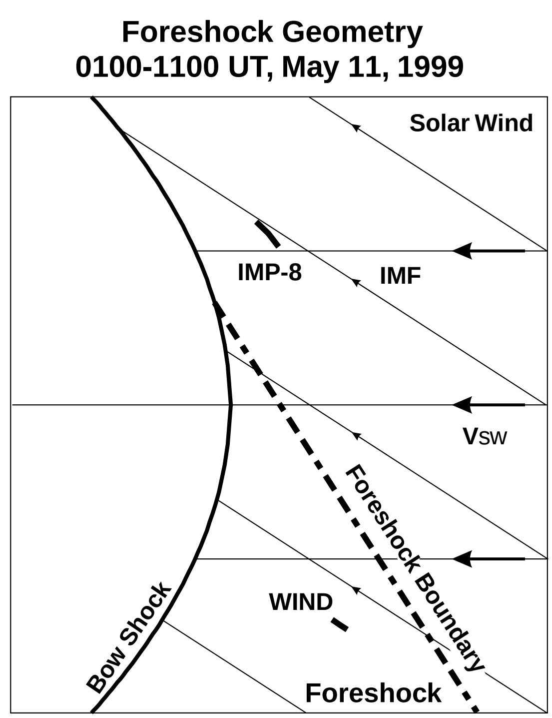

Figure 1. Schematic of foreshock geometry and spacecraft locations in the $\mathbf{V}-\mathbf{B}$ plane (the plane that contains the solar wind velocity and the IMF) for 01-11 UT, May 11.

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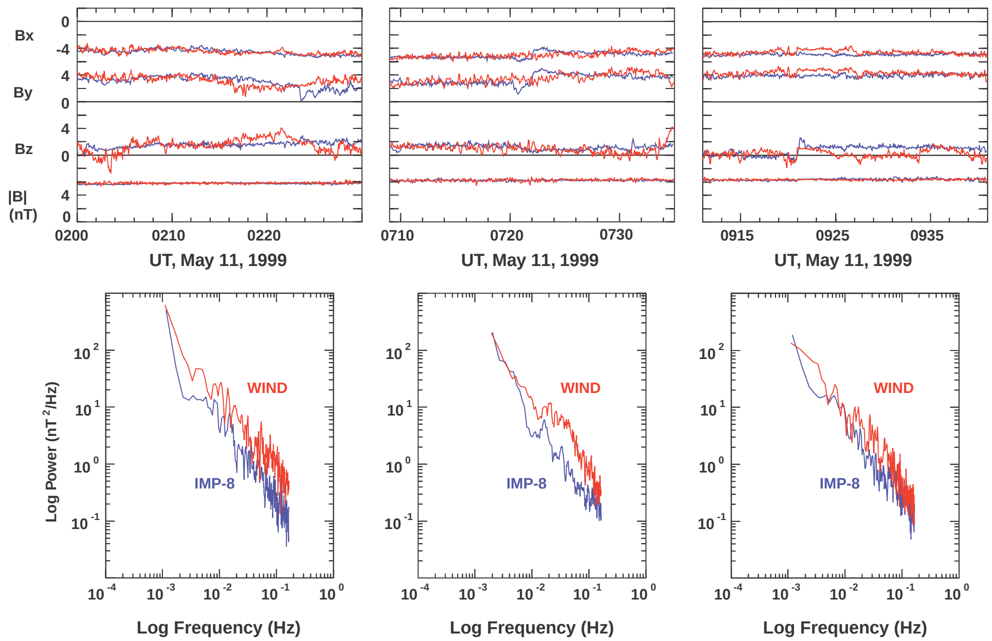

Figure 2. Simultaneous observed magnetic field data in the foreshock (red) and in the undisturbed solar wind (blue) on May 11. The top panels are time series of the magnetic field. The bottom panels are corresponding power spectra (the sum of power in all three components.)

In this paper, we compare both Polar and ground-based observations of magnetic pulsations on May 11 to those on a control day, May 14. The interplanetary magnetic field (IMF) and solar wind data for both days have been shown in Figure 1 in our earlier paper [*Le et al.*, 2000]. Here we emphasize the difference in solar wind conditions (mainly the density) and the similarity of IMF conditions for these two days. The IMF cone angles (the angle between the IMF and the sun-Earth line) that determine the foreshock geometry, were very similar ($\sim 40^\circ$) on May 11 and 14. This enables us to isolate the effect of solar wind density (as well as properties that depend on the solar wind density) on the generation of upstream waves and their entry into the magnetosphere.

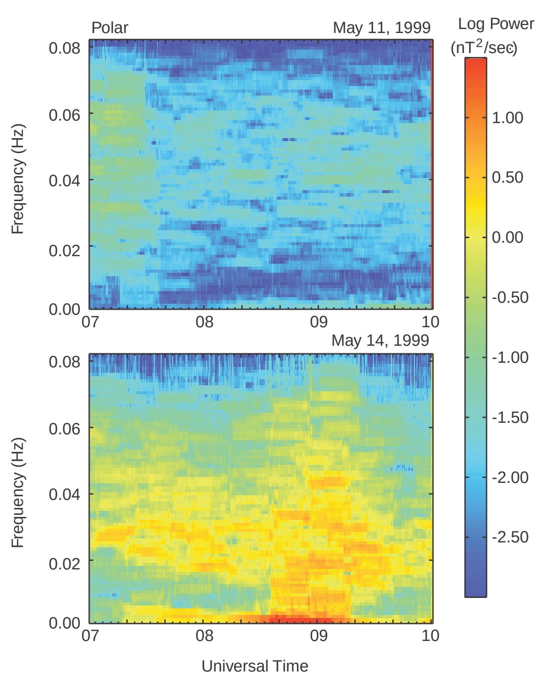

Figure 3. Dynamic power spectra of Polar magnetic field data in By GSM component from 07 to 10 UT on May 11 (top) and May 14 (bottom).

Wind Observations of Upstream Waves

On May 11, the day the solar wind almost disappeared, the WIND spacecraft was located $\sim 50\ R_E$ upstream from the Earth and $\sim 40^\circ$ dawnward from the sun-Earth line. If the bow shock were in its nominal location, the Wind would have been in the undisturbed solar wind because of its large distance from the usual bow shock location given the IMF orientation on that day, but the bow shock moved to unusually large distances and was even seen by Wind briefly (1730-1936 UT) due partially to the expanded radius of the magnetopause and partially to the low Mach number. These placed the Wind spacecraft much closer to the bow shock and into the foreshock region before 1030 UT and after 1936 UT on May 11. Meanwhile, the IMP-8 spacecraft was also located close to the bow shock on May 11. The IMP-8 data show that the spacecraft was in the region upstream from the bow shock before 1050 UT and downstream from the bow shock after 1308 UT with a data gap between 1050 to 1308 UT on May 11. Since the IMP-8 spacecraft was located duskward from the sun-Earth line, it thus remained in the undisturbed solar wind before 1050 UT on May 11. Figure 1 shows the schematic of the foreshock geometry and the spacecraft locations in the $\mathbf{V}-\mathbf{B}$ plane (the plane that contains the solar wind velocity, the IMF, and the spacecraft) on May 11. The $\mathbf{V}-\mathbf{B}$ planes for the two spacecraft differ but have been superimposed here under the assumption that the upstream waves are dependent mainly on the

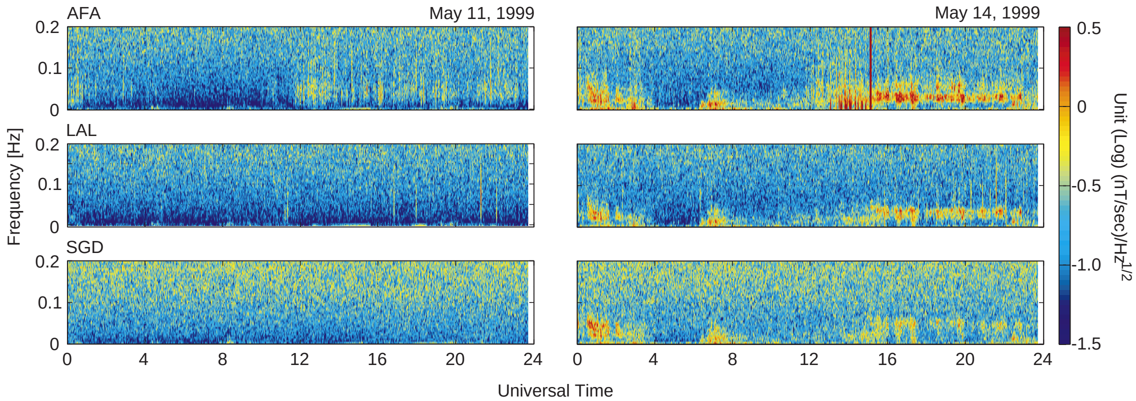

Figure 4. Dynamic power spectra of the H-component of ground-based magnetic field from IGPP/LANL mid-latitude stations AFA, LAL, and SGD.

relative location to the bow shock. Due to the outward motion of the bow shock during this period, we used average location of the bow shock in Figure 1. The Wind and IMP-8 locations in Figure 1 are for the interval ~ 01 to 11 UT on May 11 when both spacecraft were in the upstream region, showing that they were on either side of the foreshock boundary.

We compare the magnetic field data observed simultaneously by Wind [*Lepping et al.*, 1995] and IMP-8 as shown in Figure 2. The top panels of Figure 2 are time series of magnetic field for three sample intervals of simultaneous Wind and IMP-8 data at 3 s resolution. The bottom panels show the corresponding power spectra (the sum of power in all three components). The power spectra clearly show the existence of upstream waves seen by Wind, but they have extremely weak enhancements of power. In the Pc 3-4 band, the peak power seen by Wind is at ~ 10 nT^2/Hz. This is true for all upstream waves observed by Wind on May 11. In comparison, the peak power of upstream waves under nominal solar wind conditions is ~ 100 nT^2/Hz [*Le and Russell*, 1990]. Furthermore, the upstream waves had very little compressional power as evident in the magnetic field strength. Thus, the foreshock was unusually quiet and the upstream waves were about one order of magnitude weaker on May 11, when the Mach number became small. Based on the preliminary calculations, the magnetosonic Mach number was only slightly above the unity for most of the day and possibly fell below the unity for a few hours. The weak bow shock resulted in few backstreaming ions present in the foreshock, thus only weak wave generation.

We could not, however, maintain the same locations of our upstream monitors, IMP-8 and Wind on the control day, May 14, although the foreshock geometry was similar. On May 14, Wind was not in the foreshock region because it was too far away from the bow shock. Fortunately we know very well what waves are seen in the upstream region under normal solar wind conditions [*Le*, 1991]. Since both the solar wind and IMF conditions are nominal on May 14, we know that the subsolar upstream region was filled with large-amplitude waves for ~ 40° IMF cone angle based on numerous previous observations [*Greenstadt et al.*, 1980; *Hoppe et al.*, 1981; *Le and Russell*, 1992]. If the current paradigm for the association of Pc 3-4 waves in the magnetosphere with the foreshock generated waves is correct we would expect that the magnetosphere was quite quiet on May 11 when compared with May 14.

Polar Observations of Pc 3-4 Magnetic Pulsations

We now examine Pc 3-4 waves observed by Polar Magnetic Field Experiment [*Russell et al.*, 1995] on event day May 11 as well as the control day May 14 using dynamic power spectra of the Polar magnetic field while in the dayside magnetosphere. Figure 3 shows the dynamic power spectra of δBy GSM component (mainly the transverse component) from 07 to 10 UT on May 11 and 14. The Polar orbit can be found in Figure 2 of our earlier paper [*Le et al.*, 2000]. During this time period on both days, Polar was in the dayside magnetosphere at ~ 1100 local time, and its ionospheric footprint moved from 64° N to 77° N in magnetic latitude. This is the high-latitude region where strong Pc 3-4 pulsations are seen under favorable IMF orientations. As we have stated the IMF cone angles were very similar for these two intervals, 40° for May 11 and 38° for May 14, both favorable for occurrence of Pc 3-4 waves in the dayside magnetosphere. However, Polar only observed strong Pc 3-4 pulsations in the dayside magnetosphere under the nominal solar wind conditions of May 14. In the bottom panel of Figure 3, enhanced wave power in Pc 3-4 band is evident. The wave frequency decreased gradually due to the decreasing of resonant frequency of the magnetic field lines as the spacecraft traveled away from the Earth. In contrast, the dayside magnetosphere was extremely quiet and Pc 3-4 waves were nearly absent on May 11.

Ground-Based Observations of Pc 3-4 Magnetic Pulsations

The observations in mid-latitudes are consistent with those in high latitudes. The ground-based geomagnetic observations from mid-latitude stations show that the magnetosphere was much quieter on May 11 than on May 14. The data from three stations in IGPP/LANL magnetometer array are shown in Figure 4 including Air Force Academy site (AFA, MLat: 48.1° N) in Colorado, Los Alamos site (LAL, Mlat: 44.6° N) in New Mexico, and San Gabriel Dam site (SGD, 40.7° N) in California. Local noon is at ~ 19 UT at AFA and LAL and $\sim$ 20 UT at SGD. On May 14, there was enhanced power in Pc 3-4 band throughout the dayside hours at all three stations. As expected, the wave power was strongest at the higher latitude station AFA. However, Pc 3-4 waves were completely absent at the two lower latitude stations, LAL and SGD, on May 11. At AFA, some isolated pulses of Pc 3-4 waves are present in the dayside but the wave power was much smaller in comparison with those on May 14.

Summary

We have examined both the upstream waves and waves at Polar and mid-latitude ground stations in the Pc 3-4 band on May 11, 1999, when the solar wind density was well below 1 cm^{-3}, and compared with those in the control day of May 14, when the solar wind density was normal and the IMF conditions were similar. The near absence of upstream ULF waves on May 11 appears to be the result of a weakened bow shock, due to the low Mach number of the solar wind flow past the Earth. We expect that the low Mach number shock reflected very few backstreaming particles into the foreshock. Thus, the resulting upstream waves were one order of magnitude weaker in power than usual and had little compressional power. The Pc 3-4 waves, clearly seen in the dayside magnetosphere on May 14, were nearly absent on May 11 both in space as observed by Polar and on the ground at mid-latitudes, even though the foreshock geometry was favorable for the generation of Pc 3-4 waves in the magnetosphere for both days.

The simultaneous observations of Pc 3-4 waves in the upstream region, in the magnetosphere and on the ground in this study provide further support to the solar wind source of magnetospheric Pc 3-4 waves. Previous observations have established the relationship between the IMF magnitude and the Pc 3-4 wave (as well as upstream wave) frequency and between the IMF cone angle and the Pc 3-4 wave occurrence [*Bol'shakova and Troitskaya*, 1968; *Troitskaya et al.*, 1971; *Gul'elmi*, 1974]. Previous work also found correlations between the wave power and the solar wind velocity, which correlation was attributed to the presence of the Kelvin-Helmholtz instability acting at the magnetopause [*Singer et al.*, 1977]. This study does not address the role of the solar wind velocity in stimulating the Kelvin-Helmholtz instability because the solar wind velocity was nearly the same on the two days examined. Nevertheless it does raise the issue of whether the solar wind Mach number, which depends on both the solar wind density and velocity, may be responsible for both the number density and velocity correlations. If true, the physical process that controls the wave amplitude take places at the bow shock rather than the magnetopause. The effect of solar wind Mach number on the amplitude of upstream waves and magnetic pulsations in the magnetosphere should be considered in future studies, and control studies using intervals with similar solar wind Mach number but different solar wind velocities should be undertaken.

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