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The crossing of the termination shock (TS) by Voyager 2 in 2007 at 84 AU allows a comparison of fluctuations in different heliosheath regions. The Letter concentrates on MHD waves that exhibit a significant correlation between the magnetic field strength and plasma density. The correlations between both quantities were computed on 2 hr time intervals in the frequency range of $1 \times 10^{-4}$ to $4 \times 10^{-3}$ Hz. We separate the data into two regions with different magnetic field behavior: the post-TS region with many crossings of the current sheet and the unipolar region where the magnetic field direction remains nearly constant. We find that typical correlation coefficients in these regions are about 0.55–0.65, larger than in Earth’s magnetosheath. The largest correlations occur when the spectrum of magnetic field fluctuations is dominated by low frequencies.

Key words: magnetic fields – Sun: heliosphere – waves

1. INTRODUCTION

Voyager 2 (V2) crossed the termination shock (TS) at least five times from 2007 day of year (DOY) 242–245 (Burlaga et al. 2008; Decker et al. 2008; Richardson et al. 2008; Stone et al. 2008) and is now in the heliosheath, the region of fluctuating, dynamic, shocked solar wind between the TS and heliopause. The TS was a relatively weak, quasi-perpendicular shock with a shock strength of about 2 (Richardson et al. 2008; Burlaga et al. 2008). The solar wind plasma was slowed, compressed, and heated at the TS. According to Richardson et al. (2008), the flow remained supersonic (super-Alfvénic) with respect to the thermal ions downstream of the TS. Most of the solar wind energy is transferred to the pickup ions or other energetic particles both upstream of and at the TS. The heliosheath boundaries move in response to a large merged interaction region (MIR; Burlaga et al. 1985) driven shocks and due to solar cycle changes in the solar wind pressure, but these motions are small compared to the size of the heliosheath.

Burlaga et al. (2009) analyzed high-resolution measurements of the magnetic field, $B$, and find that V2 (similarly to Voyager 1) observed compressible “turbulence” in the heliosheath. Large-amplitude fluctuations of $B$ occur at small scales (i.e., on scales of tens of minutes to tens of days) with very complex profiles. These include “kinetic-scale” features that are characterized by a series of depressions/enhancements in the field strength such as isolated magnetic holes and humps, and their trains (Burlaga et al. 2006). Avinash & Zank (2007) have shown that these structures can be considered as solitons propagating with an arbitrary angle to the ambient magnetic field. The turbulence also includes “micro-scale” features ($>100$ proton gyroradii) that can be described by magnetohydrodynamic (MHD) theory. The small-scale fluctuations (both kinetic-scale and micro-scale fluctuations) may be mirror mode disturbances generated by temperature anisotropies generated at the TS (Liu et al. 2007).

Burlaga & Ness (2009) described two regions behind the TS with different magnetic field behavior: (1) “the post-TS region” from 2007 DOY 245 to 301, where the magnetic field strength fluctuates about 0.09 nT but with large jumps in $B$ on timescales of minutes to several hours, and the magnetic field direction fluctuates in a complicated way during intervals of several hours and (2) “the unipolar region” from 2008 DOY 2 to 76, a region with a nearly constant magnetic field azimuthal angle and with an elevation angle near zero. The magnetic field strength fluctuated around a linear trend. The unipolar region was caused by an excursion of the heliospheric current sheet past the latitude of V2 (Burlaga & Ness 2009). Their analysis of both regions indicates that fluctuations on scales less than 1 day were significant in both the post-TS and unipolar regions. These magnetic fluctuations, characterized by a series of depressions in the field magnitude, are similar to those observed downstream of quasi-perpendicular interplanetary and planetary bow shocks which have been identified as mirror mode structures (e.g., Bavassano Cattaneo et al. 1998).

On its path from 1 AU, V2 observed different types of correlations between the plasma speed, density, and magnetic field strength. Using 25 day averages, Richardson et al. (2003) looked at the correlations between the plasma speed, density, and the magnetic field magnitude. They found that the correlation between the density and magnetic field decreases with distance from 0.6 near Earth to about zero at 30 AU but was as high as 0.64 in the 2002 data at 67 AU. A numerical model (Wang & Richardson 2001) was used to propagate the solar wind observed at Earth to the position of V2. The one-dimensional MHD model includes the effect of pickup ions (Wang & Richardson 2001) and shows a high correlation between $B$ and $N$ throughout the heliosphere near solar maximum, but the high value probably results from the one-dimensional nature of the model which forces $B$ and $N$ changes to occur synchronously.

In this Letter, we used the Burlaga & Ness (2009) definition of heliosheath regions and performed a study of correlation properties of fluctuations of the plasma density, $N$, and magnetic field strength, $B$, measured by V2 in both the post-TS and unipolar regions. The purpose of the study is to find the dominant wave modes in the heliosheath and to deduce possible sources of these waves. Among many types of fluctuations observed in these regions, we concentrate on MHD waves that exhibit significant correlation between the plasma density and magnetic field strength.

2. DATA SET AND METHODOLOGY

The Voyager plasma experiment registers solar wind protons simultaneously in three Earthward-pointing Faraday cups over...
Figure 1. Overview of the V2 observations in the post-TS and unipolar regions. (a) Daily averages of the magnetic field strength, (b) 7 hr averages of the plasma density, daily averages of the magnetic field azimuthal (c) and elevation (d) angles.

an energy range of 10–5950 eV with a time resolution of 192 s (Bridge et al. 1977). When possible, the three spectra are fit with convected isotropic Maxwellian distributions to determine the proton velocity, density, and temperature. Data quality often does not allow this fitting procedure. For this study, we use moment densities obtained by integrating over the plasma distribution which allows us to use all the spectra and thus gives better time resolution.

The Voyager magnetometer measures the magnetic field with two sensors mounted on a boom, one at the end of the boom and the other closer to the spacecraft (Behannon et al. 1977). We use 48 s averages of the magnetic field strength. The proton density is linearly interpolated to obtain the same time resolution as that of magnetic field measurements. The data are only available when the spacecraft is tracked by the Deep Space Network. Thus, the final data set consists of intervals of 8–14 hr in duration that repeat each day. This feature allows us to either study fast fluctuations within these intervals or to average the parameters over the whole interval and to investigate fluctuations with periods of several days and longer. However, the number of days that V2 spent in the heliosheath is still insufficient for the latter investigation.

An overview of the observations is presented in Figure 1 which shows daily averages of the magnetic field strength (a), 7 hr averages of the plasma density (b), and daily averages of the magnetic field azimuthal (c) and elevation angles (d) measured by V2. For this correlation analysis, we divide the data into two time subintervals: (1) from 2007 DOY 245 to 301—the post-TS region (38 intervals) and (2) from 2008 DOY 2 to 76—the unipolar region (55 intervals). The magnetic field and proton density behave differently; neither correlation nor anti-correlation is seen on the scale of the figure. Nevertheless, enhanced levels of magnetic field fluctuations often correspond to enhanced levels of density fluctuations which suggests that the fluctuations may be associated with MHD waves. We try to identify these waves with our correlation analysis.

Taking into account the above constraints, we investigate only fluctuations with periods from ≈4 minutes (limited by the temporal resolution) to ≈2 hr (limited by the duration of the continuous intervals of data). For each of these intervals, we compute a cross-correlation coefficient using a subinterval of proton density measurements in the center of the time interval and a time lag with respect to the magnetic field measurements within a range of ±3 hr. Both signals were pre-processed by applying a bandpass filter $1 \times 10^{-4}$ to $4 \times 10^{-3}$ Hz.

3. RESULTS AND DISCUSSION

Figure 2 shows an example of the magnetic field and plasma density profiles measured in one ≈10 hr time interval on DOY 277 of 2007 in the post-TS region. The duration of the data we correlate is 120 minutes. The bottom panel shows the auto-correlation coefficients of the magnetic field (blue line), as well as the proton density (red line) and their cross-correlation coefficients (black line). The auto-correlation does not decrease to zero for large time lags, which suggests the presence of coherent periodic components. The same is true for the profile of the density auto-correlation but the periodicity is different. The cross-correlation techniques allow us to filter from the whole spectrum of fluctuations those in which $B$ and $N$ behave a
Figure 2. Example of measured and computed profiles through one \(\approx 10\) hr time interval on DOY 277 of 2007: (a) the magnetic field, (b) the plasma density, and (c) the computed cross-correlation coefficient between the magnetic field and plasma density (black line) and the auto-correlation coefficients of the magnetic field (blue) and the proton density (red). The light dashed lines distinguish one half of the period of the dominant MHD wave.

The same features were found in both regions, but the correlation is slightly higher in the unipolar region. Since the MHD fluctuations are generated either at the TS or locally in the heliosheath near the TS, the small increase of the correlation at larger distances from the TS suggests that the incoherent fluctuations are gradually damped as they are convected from the source through the post-TS region to the unipolar region.

The theory of correlation functions assumes unlimited time intervals (numbers of points), but our time intervals are rather short. To test whether our results are significant or arise from the errors caused by the use of a limited number of points, we generated 1000 pairs of random sequences and processed them using the same method as for the real signals. The comparison is shown in Figure 3. The black squares show the average maximum (top) or minimum (bottom) correlations computed using different data subintervals within the post-TS region (38 intervals). The black bars show the standard deviations. The green squares show the correlations for the unipolar region (55 intervals) and the red for the random signals. The magnetic field and plasma density exhibit a statistically significant correlation. The mean correlation coefficient decreases nearly linearly with the duration of the subinterval and approaches the random sequence level for subintervals of \(\approx 600\) minute long. This result indicates that the coherent features persist for about 10 hr in the analyzed frequency range.

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Figure 4 presents histograms of the maxima (positive values) and minima (negative values) of correlation coefficients between \(N\) and \(B\) in both regions. The distributions are nearly identical, which suggests that the periodic behavior shown in the last
panel of Figure 2 is typical. The most frequent values of the coefficients are around 0.6 and are slightly higher in the unipolar region. These values are surprisingly large; Gutynska et al. (2009) reported that correlation coefficients of 0.4 were typical. The most frequent values of the coefficient plotted vs. the period of the dominant wave. The standard deviations are shown at the top of the figure.

Figure 5. (a) Typical spectrum of magnetic field fluctuations (the dashed line indicates the period of a dominant wave). (b) Maxima of the correlation coefficient plotted vs. the period of the dominant wave. The standard deviations are shown at the top of the figure.

The other hand, such solitons would exhibit an anti-correlation between the density and field strength which is not the case (Figure 4).

One-point measurements are insufficient for a reliable determination of the wave mode. If the mirror mode waves in the heliosheath (Liu et al. 2007) and in Earth’s magnetosheath behind of the quasi-perpendicular bow shock (e.g., Schwartz et al. 1996; T´atrallyay et al. 2008) were similar, the typical wavelength would be of the order of 10^6 km. Since the mean Alfvén velocity is about 50 km s^-1 and mean flow speed ≈150 km s^-1 in the heliosheath, the wavelength of other modes would be of the same order. Such waves cannot propagate (or be convected) through planetary magnetosheaths (Hubert et al. 1998), thus a comparison of these apparently similar environments is difficult.

4. CONCLUSION

We analyzed MHD fluctuations in two regions of the heliosheath and found:

1. Strong fluctuations in the frequency range of 1 × 10^{-4} to 4 × 10^{-3} Hz with correlated changes of the magnetic field and density which were identified in both regions.
2. The cross-correlation coefficient of these quantities is ≈0.6 in both regions, significantly larger than the value of 0.4 in Earth’s magnetosheath and is slightly larger in the unipolar region that is located farther from the TS.
3. Typical periods of the fluctuations range from 50 to 220 minutes.
4. The value of the cross-correlation coefficient increases with the period of the dominant wave in the frequency spectrum.
5. Larger values of cross-correlation coefficients observed in the unipolar region are consistent with a larger portion of long-period fluctuations.

Above observations suggest that the heliosheath fluctuations are generated at the TS. The waves of higher frequencies are gradually damped, and lower frequencies prevail at larger distances from the TS.

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