CORRELATIONS OF PLASMA DENSITY AND MAGNETIC FIELD STRENGTH IN THE HELIOSHEATH

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ABSTRACT

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) and is now in the heliosheath, the region of fluctuating, dynamic, shocked solar wind between the TS and heliopause. The one-dimensional MHD 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...
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 \textit{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 either to 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 \textit{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 (d) angles measured by \textit{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 \(\approx 4\) minutes (limited by the temporal resolution) to \(\approx 2\) 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 \(\pm 3\) 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 \(\approx 10\) 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 ≈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.

cohherent way. The dashed line distinguishes the maximum and minimum of the cross-correlation coefficient, which are +0.7 and −0.7, respectively. In this particular case, the difference of the corresponding lags (≈230 minutes) is approximately equal to a half of the period of the dominant MHD wave. However, the cross-correlation profile suggests the presence of a wave with a much shorter period, about 55 minutes. The presence of two (or more) waves can explain why the typical value of the cross-correlation coefficient for zero lag was found to be arbitrary (close to zero in Figure 2), whereas MHD theory predicts that $B$ and $N$ would change in phase or anti-phase for fast and slow waves, respectively.

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 presence of two (or more) waves can explain why the typical value of the cross-correlation coefficient for zero lag was found to be arbitrary (close to zero in Figure 2), whereas MHD theory predicts that $B$ and $N$ would change in phase or anti-phase for fast and slow waves, respectively.

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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.

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 sequence level for subintervals of ≈600 minute long. This result indicates that the coherent features persist for about 10 hr in the analyzed frequency range.
The distribution of correlations (2009) reported that correlation coefficients of 0.4 were typical region. These values are surprisingly large; Gutynska et al. coefficients are around 0.6 and are slightly higher in the unipolar 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 in the Earth’s magnetosheath. The distribution of correlations for zero lag (red line in Figure 4) is very broad and centered around zero. This suggests that there is no preferred wave mode in the heliosheath, whereas Gutynska et al. (2009) found slow or mirror mode to be more frequent in the magnetosheath.

Figure 5(a) shows a typical spectrum of magnetic field fluctuations, and the dashed line indicates the period of a dominant wave. The correlation coefficient plotted versus this period in each interval is given in Figure 5(b). The correlation coefficient increases with the wave period. This trend is more pronounced in the unipolar region, which has a larger number of intervals with low frequencies. The larger correlations observed in the unipolar region (see Figure 4) may result from the damping of higher-frequency waves as they convect through the heliosheath, leaving more low-frequency waves (which have higher correlations) in the unipolar region. We note that the longest periods correspond to the duration of the intervals. Heliosheath fluctuations could have longer periods but the available data do not allow them to be identified.

Variations of the magnetic field magnitude are not accompanied with correlated changes of its direction. It is clear in the unipolar region where the field direction is almost constant (Figure 1) on any timescale, and we have found the same behavior in the post-TS region. This supports the interpretation of the fluctuations as trains of solitons (Avinash & Zank 2007); on 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 the quasi-perpendicular bow shock (e.g., Schwartz et al. 1996; Tátrallyay et al. 2008) were similar, the typical wavelength would be of the order of 10⁶ 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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Facility: Voyager II

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