Slow Mode Waves in the Heliospheric Plasma Sheet

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Abstract. We report the results of a search for waves/turbulence in the Heliospheric Plasma Sheet (HPS) surrounding the Heliospheric Current Sheet (HCS). The HPS is treated as a distinctive heliospheric structure distinguished by relatively high Beta, slow speed plasma. The data used in the investigation are from a previously published study of the thicknesses of the HPS and HCS that were obtained in January to May 2004 when Ulysses was near aphelion at 5 AU. The advantage of using these data is that the HPS is thicker at large radial distances and the spacecraft spends longer intervals inside the plasma sheet. From the study of the magnetic field and solar wind velocity components, we conclude that, if Alfvén waves are present, they are weak and are dominated by variations in the field magnitude, B, and solar wind density, N_P, that are anti-correlated. To distinguish between slow mode waves, Pressure Balance Structures (PBS) and Mirror Modes, correlations between magnetic, kinetic and total static pressures (p_B, p_K, and p_T) are studied. The slopes of the p_B - p_K, and p_K - p_T regression lines are qualitatively consistent with slow mode waves and rule out the other possibilities. In principle, the slopes are measures of the wave speed relative to the Alfvén and sound speeds and imply the direction of propagation with respect to the ambient field.

Keywords: Slow mode waves, Heliospheric plasma sheet
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INTRODUCTION

We were originally asked by the symposium organizers to describe the properties of the Heliospheric Plasma and Current Sheets (HPS and HCS). In view of the theme of the symposium, Turbulence in Astrophysical Plasmas, we decided to investigate possible waves and turbulence in the plasma sheet treated as a distinctive plasma region or structure in the heliosphere. To our knowledge, no one had previously undertaken such an investigation. Furthermore, we had previously completed a study of the thicknesses of the HCS and HPS that included identifying a representative number of these associated structures and assembling a large set of magnetic field and plasma data [1]. These data were readily available to assist in our proposed study. The results of our investigation and some of the important limitations involved are described below.

The existence of the sector structure is one of the earliest findings in space research. It is now customarily explained in terms of an extended thin current sheet that separates open outwardly-directed solar-heliospheric magnetic fields from inward-directed fields and acts as the heliospheric magnetic equator [2]. It is one of the largest

structures in the heliosphere extending from near the Sun in the solar wind source region throughout the heliosphere and into the heliosheath. The HCS is typically inclined relative to the solar equator and, as the Sun rotates, wobbles up and down in heliographic latitude causing periodic crossings and the appearance of magnetic sectors.

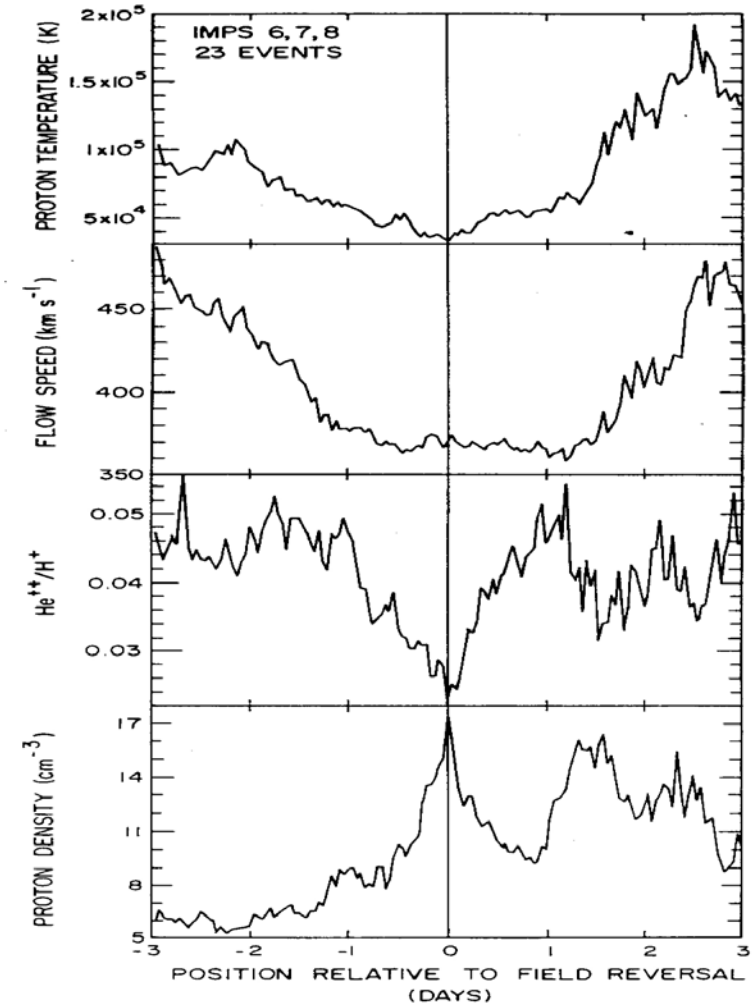

FIGURE 1. Superposed solar wind parameters at 23 well-defined sector boundaries. One-hour averages were employed and sector boundary crossings were used as zero epoch (Borrini et al., [3]).

It has also been known for a very long time that the HCS occurs in slow speed solar wind and is accompanied by high plasma densities, i.e., a plasma sheet [3, 4]. Figure 1 is the early result of a superposed epoch analysis with the "sector boundary" (HCS) as the "key date". The bottom panel shows the large increase in solar wind proton density at the HCS (the HPS) while the upper two panels show the slow speed wind and proton temperature that are closely correlated near 1 AU where these data were acquired. The figure also shows that the HCS/HPS precede an approaching fast solar wind stream that also causes a build-up in plasma density (and pressure) as a Corotating Interaction Region (CIR) forms. This analysis shows the HPS as a relatively thick high-density region lasting a large fraction of a day. The change in

polarity and associated high density were attributed to the HCS/HPS being the counterpart of the Streamer Belt that forms around the solar equator and is a feature of solar minimum.

This view of the current sheet surrounded by a plasma sheet is generally accepted but the acceptance is not universal. Nancy Crooker and her coauthors have recently disputed the existence of the HCS as a pervasive heliospheric structure and of the plasma sheet as a persistent accompanying feature [5]. Their conclusions are based on an approach that emphasizes information available from solar wind electron heat flux measurements. We do not share their view and, since this article is not the place to compare hypotheses, proceed in treating the HCS/HPS as persistent and closely-related heliospheric structures. In any case, such considerations will have no effect on the present study or our conclusions.

Our previous study of HCS/HPS thicknesses extended an earlier study carried out by Winterhalter et al. [6] using data near 1 AU. Our study investigated possible dependences of both structures on heliospheric distance by using Ulysses magnetic field and plasma observations at 3 and 5 AU and ACE data at 1 AU [1]. The relevant aspect of the results to the present study is the thickness of the HPS at 5 AU because of our choice to use those data to study waves and turbulence in the HPS. At 5 AU, we found that the median HPS thickness is ~10^6 km (significantly thicker than at 1 AU) while the median HCS thickness is ~10^3 km. At a solar wind speed of 500 km/sec, the HCS crossings typically take only 20 sec whereas the typical time spent inside the HPS is about 30 minutes. This difference showed that it would be easier to study waves/turbulence inside the HPS at 5 AU rather than in the much thinner HCS or thinner HPS at 1 AU. Consequently, this report concentrates on the HPS at the larger distance.

An important consequence of concentrating on measurements at 5 AU is that the HPS (and HCS) is located within CIRs and behind the Forward shock at the leading edge. The field and plasma have evolved significantly compare to 1 AU, a limitation that could restrict our findings to 5 AU as not necessarily representative of other radial distances (or other HPS crossings). We do not consider that a serious liability since this study is preliminary and the first of its kind.

ANALYSIS

We had already identified 16 current sheet and plasma sheet crossings in Ulysses data at 5 AU (January to May 2004). Because we intended to compare our study with the earlier study at 1 AU, we followed the same procedures as in Winterhalter et al. [6]. Specifically, the HPS was identified as a region of increased Beta, the ratio of the kinetic plasma pressure (p_K) to magnetic pressure (p_B) where $p_K = 2\ nkT$ and $p_B = B^2/8\pi$ as usual. We proceeded to analyze these examples beginning with the widest ones when the times spent in the HPS were longest.

Time resolution was a consideration because plasma data are acquired at much lower rates than magnetic measurements. The latter are available at a rate of 1 sample every 2 seconds and are typically averaged over a minute during fairly long time intervals to reduce the number of points used in the analysis. However, the high

resolution magnetic data continue to be available for a more detailed investigation if that becomes relevant.

Thus, the time resolution was restricted to the cadence of the plasma measurements. Like most solar wind analyzers, the Ulysses instrument sequences through various modes to obtain information on composition, anisotropies, etc. in addition to the usual plasma moments, V, N_P, and T [7]. We found that the highest time resolution was one sample every four minutes although data were not collected in all modes in that interval. A complete data scan takes 36 minutes. We used the 4 min averages while recognizing that artifacts might appear in the data as the entire measurement sequence was executed.

The first step in analysis was to decide which parameters to emphasize and how to represent them so as to have the best chance of identifying waves. Based on the plentiful observations available, numerous possibilities exist that could cause variations in the field and plasma [8]. Although Alfvén waves are typically restricted to high-speed solar wind, it would be imprudent to assume their absence in the HPS. The comprehensive data plots generated at first included information that might reveal the presence of Alfvén waves/turbulence. Since the usual discriminator is a correlation between the magnetic field and velocity vectors, the field and velocity components were plotted simultaneously. The velocity data did, in fact, contain pulses with a 36 minute period that are artifacts. However, they are relatively easy to recognize visually and it was possible to "look around" them at the background variations. We found that the variations in all three velocity components were small as were the variations in the field components and the two sets of variations were generally poorly correlated. We conclude that, if Alfvén waves are present in our HPS samples, their amplitudes are smaller than the variations visible in other parameters.

After ruling out Alfvén waves as a major component, other possibilities were considered based on previous wave studies and theory. Two obvious possibilities are fast and slow magnetosonic waves that are distinguished by simultaneous variations in B, N_P and total pressure, $p_T = p_K + p_B$. The difference in the two modes is that B and N_P are in-phase in fast mode waves and are out-of-phase in the slow mode. In addition, there are variations that result in p_T = constant, namely, Pressure Balance Structures (PBS) and Mirror Mode variations resulting from an anisotropy in pressure with $p_\perp > p_{//}$. There are also microstructures (not waves) that involve simultaneous increases or decreases in both B and N_P but these are correlated with increases or decreases in solar wind speed and are easily identified and excluded.

It was apparent that the most useful parameters to investigate were the pressures, p_K, p_B and p_T supplemented by other selected components and parameters that might help distinguish among the various possibilities. We decided to use the relations between the pressures for magnetosonic and mirror modes. The relevant equations appear in any number of books and articles. We chose one of our favorite sources [9] to obtain the relations between the perturbations in the field and plasma and derive the variations in the three components of pressure. The pressure variations are $\delta p_K = u_o^2 \delta\rho$, $\delta p_B = (u^2 - u_o^2)\delta\rho$ and $\delta p_T = u^2 \delta\rho$ where u_0 is the sound speed and u is the phase speed of the wave. The corresponding relations between the pressure changes are:

$$\partial p_B = (u^2 - u_\circ^2)\partial p_K / u_\circ^2 . \qquad (1)$$

$$\partial p_K = (u_\circ^2 / u^2)\partial p_T \,. \tag{2}$$

Substituting $\delta\, p_K$ into equation (1), one can obtain $\delta\, p_B = (u^2 - u_o^2)\, \delta\, p_T / u^2$. These equations mean that plotting the different pressures against one another should yield the slopes relating u and u_0. Since the latter is known from the measurements of T, the phase speed, u, can be inferred, the mode identified and the direction of propagation relative to the field direction derived from the well-known expression for u^2.

The direction of propagation relative to the magnetic field is given by the angle, θ. The relation between cos θ and u, u_o and u_A is easily derived from the expression for the wave speed that is applicable to both magnetosonic modes of propagation and can be written as $(u^2 - u_o^2)(u^2 - u_A^2 \cos^2\theta) = u^2 u_A^2 \sin^2\theta$. Solving this equation leads to

$$\cos\vartheta = u(u_\circ^2 + u_A^2 - u^2)/u_\circ u_A \,. \tag{3}$$

This relation applies to both slow and fast modes with the slow mode represented by $u_o > u_A$ and $u < u_A$ or $u_o < u_A$ and $u < u_o$.

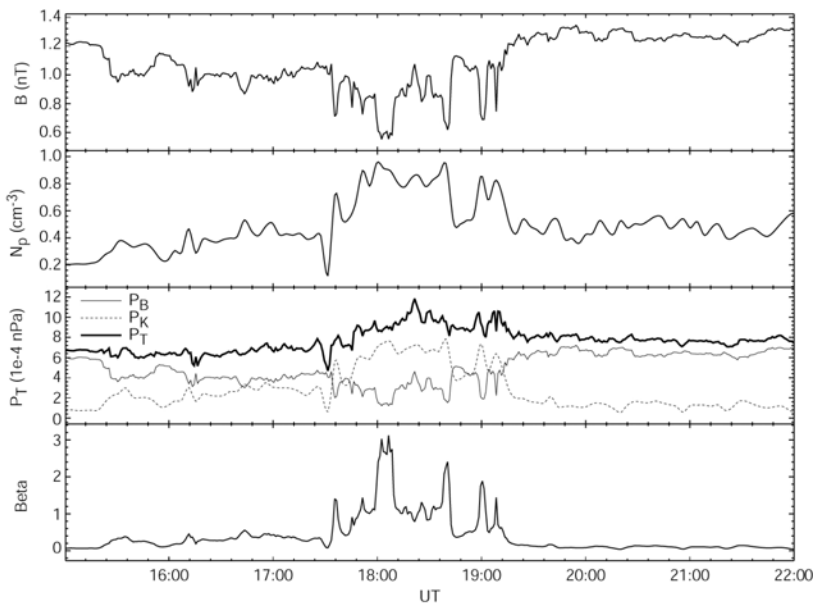

FIGURE 2. Ulysses solar wind parameters on 9 January 2004 when the spacecraft was at 5.3 AU and 2.3° above the equatorial plane. The HPS is at ~1735-1915 UT when Beta is significantly higher than the ambient plasma.

Figure 2 contains plasma and field parameters obtained during an HPS encounter on 9 January 2004. The panels contain B, N_P, the three pressures, p_K, p_B and p_T and the identifier, Beta. Ulysses spent about 1.5 hours inside the HPS with the HCS crossing near the mid-point. The two upper panels contain variations that are anti-correlated, i.e., decreases (increases) in B occur at the same time as increases (decreases) in N_P. The same anti-correlations can be seen in p_B and p_K. A distinct increase in Beta is followed by higher but variable values and a distinct decrease that identify the HPS from ~1735 to 1915 UT.

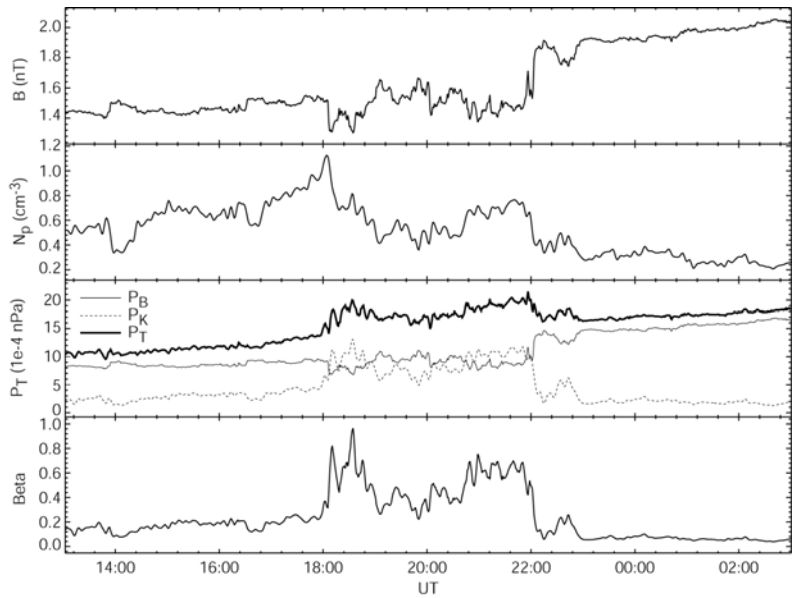

FIGURE 3. Ulysses solar wind parameters on 26 February 2004 when the spacecraft was at roughly the same distance and right beneath the equatorial plane (-0.2°). The HPS is at ~1800-2205 UT when Beta is higher than the ambient plasma, although the Beta magnitude is lower than the other HPS.

A similar presentation appears in Figure 3 containing measurements made during a 4-hour interval on 26 February 2004. Although Beta increases noticeably to outline the HPS from ~1800 to 2205 UT, it is less than a value of 1 inside the HPS. That follows from the relatively large p_B in this interval compared to p_K, It is important to recognize that we are interested here in the variations in the pressures and not their average values. That Beta is less than 1.0 doesn't affect the identification or the analysis. This figure and Figure 2 are representative of the variations found in other HPS crossings, in particular, the anti-correlations between variations in B, N_P and the corresponding pressures.

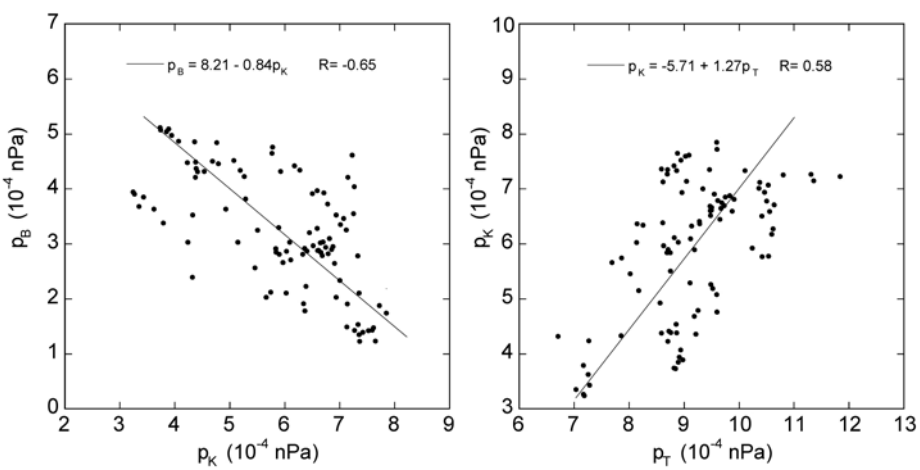

FIGURE 4. Correlation coefficients between p_B and p_K (left), p_K and p_T (right) for the 9 January 2004 HPS. The slopes of the linear fit, which give $\delta p_B / \delta p_K$ and $\delta p_K / \delta p_T$, are determined using σ_Y/σ_X.

The next two figures (4 and 5) show plots of p_B - p_K and p_K - p_T along with straight line fits and correlation coefficients. Qualitatively, the sign of the slopes discriminates among the various possibilities. In each case, they correspond to what is expected for slow mode waves and rule out fast mode or Mirror Mode.

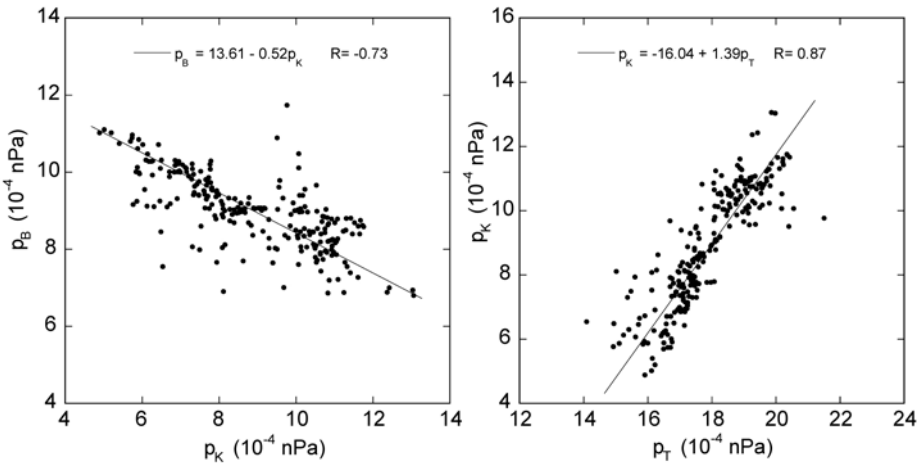

FIGURE 5. Correlation coefficients between p_B and p_K (left), p_K and p_T (right) for the 26 February 2004 HPS. The slopes of the linear fit are determined using σ_Y/σ_X as well.

The slopes of the best-fit lines are equivalent to the ratios involving u, u_0 and u_A given above and, since u_0 and u_A can be calculated from the field and plasma values inside the HPS, fitting results are equivalent to knowing u, the wave speed.

Since we wished to infer u as accurately as possible and then use it to find the angle, θ, i.e., the direction of propagation with respect to the field, the method used to determine the slope of the straight line fit to the data becomes important. The usual approach to least squares fits treats one of the parameters as dependent and one as independent. For example, most software applications use this approach. However, in this instance, as in many others, neither parameter is determined significantly more accurately than the other, the usual justification for treating the more accurate measurable as independent. This is easily seen by reversing the abscissa and ordinate in each case and repeating the least square fitting. In general, the two slopes will differ significantly. (In fact, the product of the slopes equals the cross-correlation or covariance of the two observables.) Instead, we used a superior method that takes the ratio of the standard deviations (σ_Y/σ_X) as the slope of the straight line passing through the average values of the y and x variables. The straight line fits shown in Figures 4 and 5 were obtained in this way.

DISCUSSION

As a continuation and expansion of our previous study of HPS/HCS characteristics near Ulysses aphelion [1], we have analyzed waves/turbulence inside two HPSs observed on 9 January and 26 February 2004. It is found that waves in the HPS are slow mode waves, for the kinetic and magnetic pressure are out of phase and the total pressure is less variable. The waves are of small amplitude ($\delta B \approx 0.2 - 0.5$ nT p-p) with typical periods of ~10 minutes. We have calculated the wave speed and

propagation direction using equations (1) - (3) and linear fits in Figures 4 and 5. Results are shown in Table 1. Here the ratio u/u_o is an average of values obtained from equations (1) and (2), respectively. The sound speed u_o and Alfvén speed u_A are averages over the plasma sheet.

TABLE 1. Slow mode waves in the HPS near 5 AU.

HPS	Slope		Correlation R		u/u_o	u_o (km/s)	u_A (km/s)	u (km/s)	θ
	p_B - p_K	p_K - p_T	p_B - p_K	p_K - p_T					
9 Jan 04	-0.84	1.27	-0.65	0.58	0.60	20	23	12	40°
26 Feb 04	-0.52	1.39	-0.73	0.87	0.87	27	43	23	24°

Since slow mode waves in the HPS have not been studied before, we cannot compare our result to others regarding the consistency. Although the anti-correlations between the magnetic and kinetic pressure turbulences are not ideally high, the quantitative wave speed and propagation direction provided a first insight into the HPS turbulence. For both HPSs, u_o is less than u_A and, therefore, u less than u_o as indicated by (3). Comparing the two HPSs, one can see that when u_o is less than u_A, the slow mode waves propagate closer to the magnetic field direction. This is consistent with the fact that when the sound speed is much smaller than the Alfvén speed, the slow mode propagates along **B** at the sound speed as predicted by the equation (3).

In this paper, we have mainly discussed the analysis method of waves/turbulence characteristics of the HPS. Applying the method to two cases, we obtained that the slow mode wave speed in the HPS of ~10-30 km/s with an angle of 20°-40° between **B** and the propagation direction. Those numbers do not possess statistical significance that can only be obtained on the basis of studies of large numbers of events.

ACKNOWLEDGMENTS

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