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Ulysses observations of pressure-balance structures in the polar solar wind

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Abstract. Throughout its high-latitude excursion Ulysses has observed several types of solar wind structures. In addition to structures such as Alfven waves, compressional features, and microstreams, the solar wind also contains low contrast pressure-balance structures (PBSs). The PBSs are marked by an anti-correlation of the plasma and field pressures; their signatures are often hidden by the comparatively larger effects of compressions. Previous studies of high-latitude solar wind structures have only shown a few examples of PBSs. In this study we examine Ulysses polar pass solar wind plasma and interplanetary magnetic field data sets to provide the first statistical analyses of high-latitude PBSs. Two independent lines of analysis are pursued: first, we identify 78 PBSs in the data and analyze their average properties compared to the rest of the solar wind; second, we use high pass filtering of the data to separate the pressure balance aspects of the solar wind from the longer period compressional features. While our findings indicate that PBSs occur more frequently at small than at large heliocentric distances, indicating a possible solar origin for these structures, they do not have characteristically different plasma or field properties from that of the rest of the polar solar wind. Such differences would indicate that PBSs are possibly the remnants of differing populations of solar wind source plasma back in the polar corona. Our null result does not support the suggestion that PBSs are the interplanetary signature of polar plumes.

Key words: solar wind – Sun: corona – interplanetary medium

1. Introduction

Over the past several years the joint European Space Agency/National Aeronautics and Space Administration Ulysses mission has been charting the high-latitude heliosphere for the first time. The high-latitude region near solar activity minimum is characterized by a fast ($> 700\,\mathrm{km\,s^{-1}}$) and nearly constant solar wind speed emanating from the Sun's polar coronal holes (Phillips et al. 1994). In addition to a nearly constant speed, the solar wind in this region also exhibits a surprisingly constant helium abundance of 4.3% (Barraclough et al. 1995), unlike the much more variable composition of streamer belt and coronal hole plasma typically observed in the ecliptic plane.

Within the nearly steady polar coronal hole flow, several types of structures are observed. In particular, large amplitude Alfven waves are common in this region (Smith et al. 1995) while coronal mass ejections, and their associated forward and reverse shocks, are observed less often and primarily at lower heliolatitudes (Gosling et al. 1994a; 1994b). In addition, small compressional structures (McComas et al. 1995), driven by microstreams of several tens of $\mathrm{km\,s^{-1}}$ (Neugebauer et al. 1995), are common at high heliolatitudes.

In addition to these larger scale and more easily identifiable structures, the polar solar wind is also mottled by much lower contrast pressure-balance structures (McComas et al. 1995). Such structures are easily masked in the Ulysses observations by compressional structures which tend to be of comparatively large amplitude. McComas et al. provided several examples of pressure-balance structures characterized by dips in magnetic pressure and peaks in plasma pressure.

The literature is rich with observations and analyses of pressure-balance structures at lower heliolatitudes. Burlaga & Ogilvie (1970) used Explorer 34 data at 1 AU to examine the relationship between plasma and magnetic field pressures in the solar wind. They found that these pressures were correlated on time scales of more than about two days and anti-correlated, albeit with a low coherence, on time scales of about one hour. More recent studies of Voyager observations from 1–9.5 AU (Vellante & Lazarus 1987) and 1–24 AU (Burlaga et al. 1990) examined the relationship between plasma ion and magnetic field parameters. Vellante and Lazarus found that the best anti-correlation was between the magnetic field magnitude and the ion density, which they explained as non-propagating pressure-balance structures with time scales less than about 10 hours. These authors showed that, while Alfvenic structures dominate

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Send offprint requests to: D.J. McComas the solar wind microstructure between one and two AU, they are not as significant at larger distances at these low heliolatitudes. Burlaga et al. (1990) went on to infer properties of interstellar pick-up ions from a study of pressure-balance structures.

Pressure-balance structures inside 1 AU were studied using Helios observations of the high-speed solar wind in the ecliptic plane (Thieme et al. 1988; 1990). These structures lasted many hours and were distinguished by brief (1–2 hour) dips (increases) in the plasma (field) pressure at their boundaries. The boundaries also had slightly lower alpha particle concentrations and flow speeds. Tu & Marsch (1994) combined analysis of Helios observations with theory to examine compressional and non-compressional (pressure balance) structures in the solar wind inside of 1 AU. These authors differentiate between pressure-balance structures observed near the Sun by Helios, which are probably of solar origin and fade away with increasing heliocentric distance, and PBSs in the outer heliosphere which are apparently formed in the solar wind and become increasingly common at greater distances (Vellante & Lazarus 1987; Roberts 1990).

The Helios findings and remote observations of polar plumes emanating from the Sun's polar regions initially encouraged us to examine the Ulysses *in situ* observations of the polar solar wind for structures that might be the interplanetary signatures of polar plumes. Polar plumes are observed as brightness enhancements (high density structures) in white light eclipse and coronagraph photographs as well as in ultra-violet observations of the Sun's polar regions (e.g., Newkirk & Harvey 1968; Koutchmy 1977; Ahmad & Withbroe 1977). They generally appear as bright rays emanating along open polar magnetic field lines in or along the edges of polar coronal holes, although recent work has indicated that they also are observable in low-latitude coronal holes (Wang & Sheeley 1995). Widing & Feldman (1992) found that the Mg/Ne abundance ratio is enhanced in polar plumes compared to the photosphere, suggesting that plumes have compositional differences from the non-plume solar wind. Recent results from SPARTAN-201 indicate that polar plumes were present during the Ulysses high-latitude transits (Fisher & Guhathakurta 1995).

Several simple models of polar plumes have been developed recently (Velli et al. 1994; Wang 1994; Habbal et al. 1995). The most complete of these models (Habbal et al. 1995) uses a two-fluid description to simulate expected differences between plume and non-plume solar wind flows. The model predicts densities and proton and electron temperatures which are tens of percent higher, a solar wind speed that is $\sim$ 25% lower, and a helium abundance ratio that is $\sim$ 65% higher than in the surrounding interplume wind at a distance of $\sim$ 1 AU over the poles of the Sun. Because compression and corotation effects are much less over the poles, intrinsic differences between plume and inter-plume flows might be expected to persist to greater heliocentric distances at high latitudes.

In this study we extend our earlier work (McComas et al. 1995) to a statistical analysis of PBSs in the polar solar wind. In Sect. 2 we describe two approaches to examining PBSs. The first is based on an analysis of 78 PBSs identified in the high-latitude Ulysses data while the other uses high pass filtering of the data to separate out the non-compressional, pressure-balance aspects of the solar wind plasma. In Sect. 3 we summarize our results and compare them with polar plume observations and models.

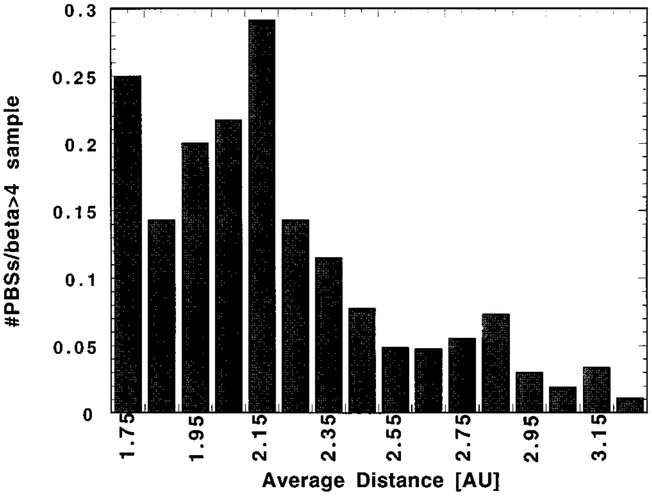

Fig. 1. Normalized likelihood of observing PBSs as a function of heliocentric distance over the poles of the Sun

2. Observations

This study utilizes Ulysses solar wind plasma observations from the Los Alamos solar wind ion and electron spectrometers (Bame et al. 1992) and magnetic field observations from the Imperial College/JPL magnetometer (Balogh et al. 1992). The solar wind electron and ion spectrometers utilize electrostatic analyzers that measure electrons and ions with energies from 0.81 eV to 862 eV and 255 eV/q to 34.4 keV/q, respectively. The plasma moments have been calculated from integrations of the electron and ion distribution functions, providing independent parameters for the proton, alpha particle, core electron, and halo electron components. These are subsequently combined to give the total plasma pressure. In this study we use one-hour averaged values of the solar wind plasma and magnetic field parameters.

In order to identify PBSs, we examined 230 days of observations extending from 60° S through the south polar pass at over 80° S and back equatorward to 60° S. PBSs were identified visually in the data as structures with sharp boundaries where the plasma pressure increased while the magnetic pressure decreased such that the overall pressure stayed roughly constant. Plasma pressure-dominated structures were chosen for analysis because there are many fewer examples of clear PBSs in which the field pressure is enhanced. In addition, we required that the plasma beta rise to $>$ 4 inside these structures and that they persist for at least two or more contiguous 1-hour samples.

In the 230 days examined, 78 events met all of the above criteria. These events represent 4.8% of the entire data set. Their average duration is 3.3 hours. Overall, pressure-balance structures were more common closer to the Sun than at greater heliocentric distances. This is particularly significant since the amount

Table 1. Comparison of bulk properties

	PB	All	Δ	Δ (%)	σ
P-plasma [pPa]	2.33	1.99	0.34	18	1.13
P-mag [pPa]	0.51	0.67	−0.16	−24	0.37
P-total [pPa]	2.71	2.65	0.06	2	1.36
Beta	5.20	3.34	1.86	56	1.28
N-prot [cm^{-3}]	0.50	0.45	0.05	11	0.20
T-prot [K]	2.0×10^5	1.8×10^5	2.0×10^4	11	2.9×10^4
T-alpha [K]	9.2×10^5	8.3×10^5	8.2×10^4	10	1.5×10^5
T-elec [K]	8.5×10^4	8.9×10^4	-4.3×10^3	−5	4.4×10^4
$\|B\|$ [nT]	1.1	1.2	−.15	−12	0.35
V-sw [km s^{-1}]	771	765	6	< 1	22
V-He [km s^{-1}]	780	776	4	< 1	22
$\text{He}^{++}/\text{H}^{+}$ ratio	0.045	0.044	0.001	2	0.001

of data with a $\beta > 4$ (required by our selection criteria) drops significantly at smaller heliocentric distances. Figure 1 displays the ratio of the number of PBSs to the number of 1-hour data samples where $\beta > 4$ in each 0.1 AU bin for this 230-day data set. As Ulysses moved closer to the Sun (moving from right to left in Fig. 1), the average beta dropped and the probability of any given high beta interval being defined as a PBS by our stated criteria increased. Inside of 2.5 AU, a very large fraction of the $\beta > 4$ data were within PBSs.

Perhaps the most surprising aspect of our statistical analysis is that the bulk plasma and field properties inside and outside of the PBSs were very similar, particularly for parameters which are independent of the pressure-based selection criteria. Table 1 compares the properties inside the PBSs with the properties of the entire 230 day data set. The columns, from left to right, represent the average values of the parameters inside the PBSs and across the whole data set, the differences between these two values, and the percentage differences. The last column gives the average of the standard deviations of the value in the PBSs and the entire sample; a single number is used for simplicity since the standard deviations in these two data sets were generally similar.

The top four rows of Table 1, where the largest percentage differences are seen, represent the direct pressure-related criteria so that it is no surprise that there are significant differences in these parameters for PBSs and the data as a whole. The next five rows include parameters used to calculate the plasma and field pressures, and so these are not really independent variables either. Nevertheless, none of these have characteristic variations that are larger than the standard deviations of the measurements. Finally, values for the solar wind (proton) speed, alpha particle speed, and He++/H+ abundance ratio are shown at the bottom of the table. All three of these truly independent parameters have values within the PBSs that are essentially the same as that of the data set as a whole. Clearly, the identified PBSs do not show the sort of characteristic changes predicted by models of polar plumes.

Table 2. Data analysis regions

Region ID	Latitude range	Distance range (AU)	Average distance (AU)
A	−60° to −75°	2.62–3.26	2.95
B	South of −75°	2.03–2.62	2.33
C	−75° to −60°	1.74–2.03	1.89
D	−60° to −40°	1.52–1.74	1.62
E	+40° to +60°	1.43–1.61	1.52

The second approach that we took in examining pressure-balance structure in the polar solar wind is based on frequency domain filtering of the observations. Figure 2 shows scatter plots of plasma pressure versus magnetic pressure for highpass filtered data with periods less than 12 hours (top) and lowpass filtered data with periods greater than 5-days (bottom). Highpass filtering removes the average value of the data, as well as the long period variations, accounting for the zero centered pressures. The reasons for choosing these two cutoff frequencies will become clear below. Note that the low frequency data is compressional in nature as indicated by the strong positive correlation between plasma and magnetic pressures (McComas et al. 1995). The high frequency data, on the other hand, exhibit an anti-correlation between these two pressures. This anti-correlation demonstrates the pressure-balance aspect of the data: when the plasma pressure is higher, the field pressure is lower, and visa versa.

In order to ensure a robust result and to be able to separate possible heliocentric distance and heliolatitude effects, we extended our data set down to 40° S and from 40° N to 60° N; we also broke it up into five subsets. The data in all five subsets represent high speed polar solar wind; latitudes and heliocentric distances for the subsets are given in Table 2. Data from regions A-C were used in the statistical analysis described above while data from all five regions were used to construct Fig. 2.

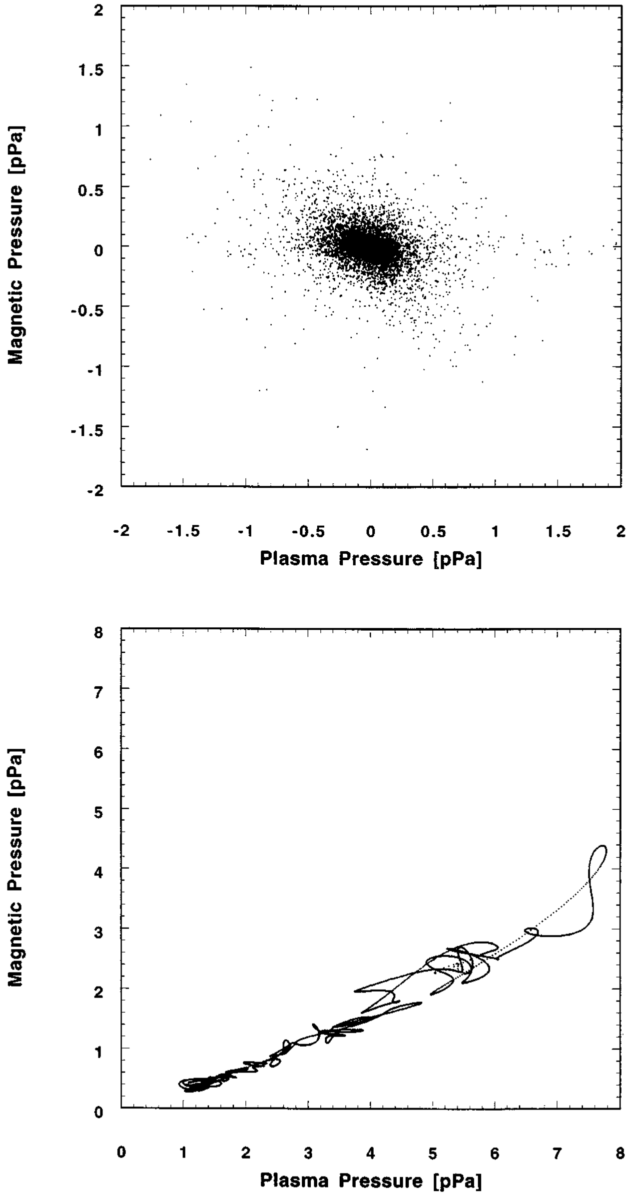

Fig. 2. Scatter plots of magnetic versus plasma pressures for periods less than 12 hours (top) and greater than five days (bottom) for all data used in this study. The high frequency data show a weak anti-correlation between the pressures indicating the pressure-balance regime; the low frequency data show a strong correlation between the pressures indicating the compressional regime

Filtering was accomplished by first Fast Fourier Transforming (FFT) the one-hour averaged time series of data into the frequency domain. The data were then filtered with a fifth order Butterworth filter, which has a very sharp cutoff frequency (e.g., Kulhanek 1976). Finally, the data were transferred back to the time domain with an inverse FFT. Figure 3 displays the slope of the linear least squares fit of the ratio of plasma to magnetic pressures (similar to Fig. 2), as a function of the filter cutoff frequency, for each of the five regions examined. In all five cases the curves have three regimes: 1) a long period, low frequency, compressional domain where the two pressures are correlated; 2) a short period, high frequency, pressure-balance domain where they are anticorrelated; and 3) an intermediate, transition region where both compressional and pressure-balance features are present. Note that the most strongly compressional data set (A) corresponds to the largest heliocentric distances. This is not surprising since the compressional aspects of the solar wind tend to grow with increasing heliocentric distance. The 12-hour highpass and 5-day lowpass cutoff periods used in Fig. 2 and later in this paper were simply read from Fig. 3 by determining where all five curves had flattened out.

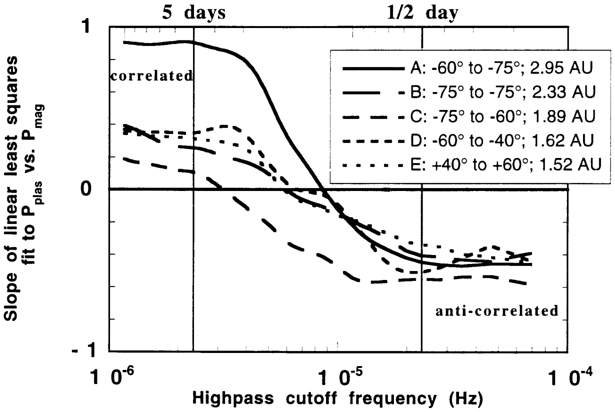

Fig. 3. Slope of linear least squares fit of plasma to magnetic pressures as a function of highpass cutoff frequency. At periods longer than 5 days, the pressures are correlated (compressional regime) while at periods less than half a day they are anti-correlated (pressure-balance regime). Between these two periods, both compressional and pressure-balance aspects are mixed

Our hope was, that by separating the compressional and the pressure-balance aspects in the solar wind via filtering, we might be able to identify aspects of the solar wind which are dependent on the pressure-balance nature of the wind. Beta is the obvious way to parameterize PBSs since this single number identifies the relative contributions of the plasma and magnetic pressures. We looked for correlations between beta and both the solar wind speed and helium abundance ratio in the highpass filtered data to determine if there were any characteristic variations in these independent parameters as suggested by models of polar plumes. No such associations were found, indicating once again that pressure-balance structures in the polar solar wind do not differ significantly from the rest of the polar solar wind.

The surprising thing about this result is that individual pressure-balance structures do appear to show either correlations or anti-correlations between beta and other parameters such as speed and helium abundance. For example, Fig. 4 shows two time series of highpass filtered beta and helium abundance ratio data. Each panel is 2.3 days long and they are separated by ~ 3.5 days. Note that while the correlation in both panels appears to be quite striking, the beta scale is reversed in the bottom panel compared to the top! Thus, these two plasma parameters are seen to cycle back and forth in the highpass data between correlation and anti-correlation. This sort of variation can be

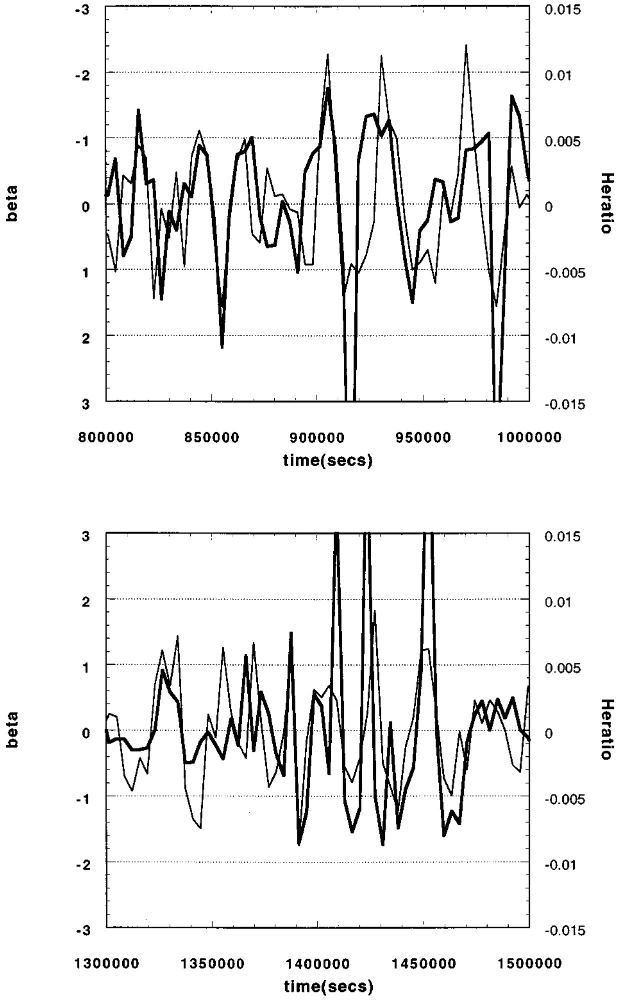

Fig. 4. Plots of beta (heavy line) and helium ratio as a function of time for two intervals roughly 3.5 days apart. Both panels indicate a good correlation, however, the beta scale in the bottom panel has been flipped compared to the top panel. Consequently, the top (bottom) panel shows a strong anti-correlation (correlation)

quite misleading in individual case studies or examinations of limited time periods. Taken over any of our five independent data intervals (Table 2), however, no consistent correlations occur.

3. Discussion and conclusions

In this study we have provided the first statistical examination of pressure-balance structures in the high-latitude heliosphere. PBSs are low contrast structures, where the plasma and magnetic pressures vary inversely. Clear, individual PBSs identified visually in the data constitute $\sim$ 5% of the high heliolatitude data. Since there is an apparent continuum of such structures, stricter or looser criteria would have given smaller of larger numbers of structures, respectively.

While pressure-balance structures are clearly ubiquitous in the polar solar wind, they are not clearly distinguishable in plasma properties unrelated to pressure. In particular, neither the helium abundance ratio nor the solar wind speed are unusual in PBSs. This contrasts with expectations based on previous Helios results and plume simulations, suggesting that PBSs are not the interplanetary manifestations of polar plumes. We did find that pressure-balance structures were more common nearer to the Sun than further away; this is the only line of evidence that we found that suggests a solar origin for such structures.

In an independent line of analysis, we used filtering of the solar wind plasma and magnetic field observations to separate the compressional and pressure-balance aspects of the solar wind and look for further evidence of the source of PBSs. We showed that the data could be separated into at least three unique regimes. At periods longer than 5 days the solar wind was compressional with a strong correlation between the plasma and magnetic pressures. At periods shorter than half a day, it was dominated by pressure balance with a clear anti-correlation between these two pressures; at intermediate time scales both compressional and pressure-balance aspects were present. This independent approach did not indicate any unique correlations between the plasma beta and other independent plasma properties.

Remote observations of polar plumes indicate that some compositional differences might exist between plume and non-plume polar solar wind. Simulations of plumes in interplanetary space predict characteristic variations in other plasma properties such as solar wind speed, temperatures, and densities. Helios observations of PBSs in coronal holes inside of 1 AU showed characteristic variations in speed at structure boundaries. In this statistical study of Ulysses observations we found none of these properties. Rather, pressure-balance structures at high heliolatitudes exhibit plasma properties remarkably similar to the rest of the polar solar wind.

One strange aspect of the high-latitude data is that various plasma properties appear alternately to be both quite well correlated and anti-correlated. The timescale for cycling between these states is several days. These observations emphasize the risks of non-statistical examinations of such structures since numerous individual examples exist which show clearly evident correlations and anti-correlations. The reason for the alternate correlations and anti-correlations is still a mystery to us; possible explanations range from some as yet unidentified artifact of the data processing or analysis to some fundamental process at work in the solar wind.

In short, we find that PBSs observed over the Sun's poles by Ulysses are not consistent with variations expected by present plume models or Helios observations and that there is but one line of evidence for a solar source of these structures. Rather than the PBSs, microstreams (Neugebauer et al. 1995) and their associated compressional regions (McComas et al. 1995) may be a better choice to examine for evidence of coronal and plume remnant structures.

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