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Searching for coronal plumes in Ulysses observations of the far solar wind

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Abstract. In the past, from the analysis of data acquired by the Helios spacecrafts within distances ≤ 1 AU, some evidence has been found of the presence of coronal plumes in the solar wind. Ulysses observations offer a unique opportunity to search for plume remnants in the polar wind at larger distances. Pressure balanced structures (PBS), which might possibly be a signature of those features, have in fact been recently identified in its data. On the basis of previous work, which detected significant peaks (possibly related to plumes) in power spectra of solar wind parameters, we present here the results from a similar research. However, our analysis does not confirm previous findings, because power spectra bear no evidence of significant periodicities. This result allows for different interpretations, but does *not* rule out the presence of a typical periodicity in the data. By developing a simple 2-D model for structures traversed by Ulysses, we show how easily, even if they were regularly distributed, the original periodicity may become hardly identifiable in power spectra analyses. We conclude that this is not a viable technique for tracing plumes in the solar wind and we suggest alternative means for an unambiguous identification of these features.

Key words: Sun: corona – solar wind

1. Introduction

Polar coronal plumes have recently been observed in white light, from the ground-based K-coronameter in Mauna Loa and the Spartan 201-01 spacecraft, up to distances of $5R_\odot$ (Fisher and Guhathakurta 1995). At smaller heliocentric distances, these features have been imaged for a long time, and have been observed in eclipse/coronagraph images at visible wavelengths, in EUV spectroheliograms, in X-ray images and, possibly, also in the radio wave band (see, for instance, Koutchmy 1977, Sornette et al. 1980, Widing & Feldman 1992, Ahmad & Withbroe 1977, Gopalswamy, Schmahl & Kundu 1992). Yet, they are still not well known: their density is recognized to be higher than the ambient coronal hole by a factor certainly ≥ 3, but, according to Walker et al. (1993), as large as 50; their temperature, derived from the radial density gradient, shows only 50% variation from the hole temperature. Outflow velocities in plumes are even more uncertain: order of magnitude estimates by Widing and Feldman (1992) set their values below a 35 km/s limit, on the ground that higher velocities would be inconsistent with the observed density gradient; Ahmad and Withbroe (1977), though, from the analysis of soft X-ray images of a polar plume, set a *lower* limit of 100 km/s to the plume expansion velocity. The magnetic field intensity at the plume base has never been measured.

These dense features may be very relevant for our understanding of the solar wind, because they may be responsible for the solar wind mass flux in fast streams originating from coronal holes (Ahmad & Webb 1978; Withbroe 1986; Walker et al. 1993). The recent observation of low-latitude plumes (Wang and Sheeley 1995) makes an identification of their role in solar wind even more crucial and justifies searching for plume signatures in solar wind data. So far, however, only a few works have dealt with this problem.

Thieme et al. (1989, 1990), analyzing Helios high speed streams, were able to establish that flow tubes, likely to be identified with coronal plumes, maintain their identity up to distances $\lesssim 1$ AU. These authors showed that flow tubes were characterized by a typical behavior in gas and magnetic pressure (whose maxima were anticorrelated), as well as in proton and alpha particle speeds. Power spectra of these parameters allowed Thieme et al. also to estimate the typical size of flow

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tubes, which turned out to be consistent with the dimension expected for coronal plumes undergoing a super-radial expansion. A radial alignment study, at the time when the two Helios probes happened to sample the same plasma parcel at successive times, unquestionably proved that fluctuations in these parameters correspond to stable plasma structures and were not of a turbulent nature. However, differences between flow tubes and the adjacent ambient seem to progressively disappear as heliographic distance increases.

Ulysses high latitude observations offer a unique opportunity to search for plume remnants in the polar wind, where interactions between slow and fast streams should be minimal, at larger distances than those explored by the Helios probes. McComas et al. (1995) provided the first report of small-scale compressional structures and pressure balance structures (PBS) – the latter possibly associated with coronal plumes – in Ulysses high latitude data, and gave representative examples of both features. This work shows that fine scale structures are present at distances > 1 AU, although it's not at all clear whether these are remnants of coronal structures or whether they originate in the interplanetary medium. In fact, in a later study, McComas et al. (this issue), after thoroughly analyzing 78 PBS identified in 230 days of Ulysses high latitude ($\geq$ 60 degrees) observations, didn't find evidence for any of the variations between plasma parameters within and outside these structures, which had been predicted by plume models. McComas et al. conclude that only the progressive decrease in the PBS number, as the heliographic distance increases, favors an interpretation of PBS in terms of coronal plumes and suggests microstreams, and their associated compressional regions, possibly to be better candidates for plume remnants. However, microstreams (Neugebauer et al., 1995) a new feature identified by a typical velocity profile, offer little evidence of being closely related to plumes, as they have none of the magnetic properties typically identifying PBS, such as high β factors (where β is the ratio of plasma to magnetic pressure).

To the poor observational knowledge of plume manifestations at distances $\geq$ 1 AU corresponds an equally poor theoretical understanding. Theoretical predictions of the plume behavior at large distances are scanty and contradictory. Velli et al. (1994), Wang (1994), Habbal et al. (1995), studied the plasma behavior at 1 AU, assuming different input parameters at R=$R_{\odot}$. The plume density is taken to be higher than the ambient density by all authors, but, lacking observational data, they make different hypotheses as to the behavior of temperature, velocity and magnetic field in the plume/ambient regions. In particular, while Velli et al. (1994) *a priori* assume the overall coronal hole expansion factor to be $f(r) = r^2$ and derive the plume/ambient behavior from the transverse pressure equilibrium condition, Wang (1994) and Habbal et al. (1995) give *a priori* the magnetic field variation with distance and solve the mass, momentum and energy conservation equations along the radial direction. Wang's magnetic field is the same in both the plume and the interplume regions; Habbal et al. (1995) choose a radial geometry for plumes and a super-radial expansion for the ambient. Taking into account that also the energy equations include different terms in different studies, it is not surprising that the predicted behavior of plumes at large distances is model-dependent and that no precise indication can be drawn from these simulations.

The purpose of the present work is to analyze Ulysses high latitude data and to check whether power spectra of physical parameters provide any evidence of a peak, possibly related to plumes, as Thieme et al. (1990) previously found. Although those authors pointed out, as we mentioned, that these fine structures become hardly recognizable at increasing heliocentric distances, we expect the polar wind to provide an environment where possibly fine scale structures can be preserved up to large distances. We evaluated power spectra both with the standard Fourier technique and with an alternative method, the Scargle periodogram, which doesn't require evenly spaced data. Data, and their spectral analysis, are described, respectively, in Sects. 2 and 3. The spectral analysis gives a negative result, as no significant periodicity shows up in the data.

There are several explanations for such a result, the most obvious being that power spectra are not an appropriate analysis technique for this problem, because plumes are distributed randomly on the solar surface. We will discuss this, and other possibilities, in the final section of the paper. However, we also explored the case when regularly distributed structures are traversed by the spacecraft, with the purpose of showing how even an oversimplified situation gives rise to power spectra complicated enough, to make their interpretation not at all straightforward. To this end, we developed a model, representative of an unrealistically simple scenario, where structures in pressure equilibrium are randomly crossed by a spacecraft trajectory, and we built artificial sets which simulate Ulysses observations. The model, and the power spectra evaluated on simulated data, are described in Sect. 4. On this basis, we show how periodicities become hardly identifiable in the data. We conclude that power spectra are not a viable means to explore the spatial distribution of fine scale solar wind structures and/or determine their nature. Future works that may help us understand whether plumes are/are not preserved in the far solar wind are also suggested.

2. The data

The observations we analyzed cover a 10 month interval from February to November 1994, thus including data from Ulysses South polar passage. At the beginning of February 1994 Ulysses was at 3.7 AU and -51 degrees heliolatitude. It reached a peak southerly latitude of -80.2 degrees in September 1994 at 2.3 AU. At the end of November the spacecraft had returned to -60 degrees at 1.7 AU. The data we used have been acquired by the Los Alamos solar wind ion and electron spectrometer (Bame et al. 1992) and the Imperial College/Jet Propulsion Laboratory magnetometer (Balogh et al. 1992).

Because coronal plumes seem to be rather stable structures (the recent observations of Fisher and Guhathakurta, 1995, didn't detect any variation over a 10 hour observing time), they should be in lateral pressure equilibrium with the ambient medium, which is at lower density and approximately the

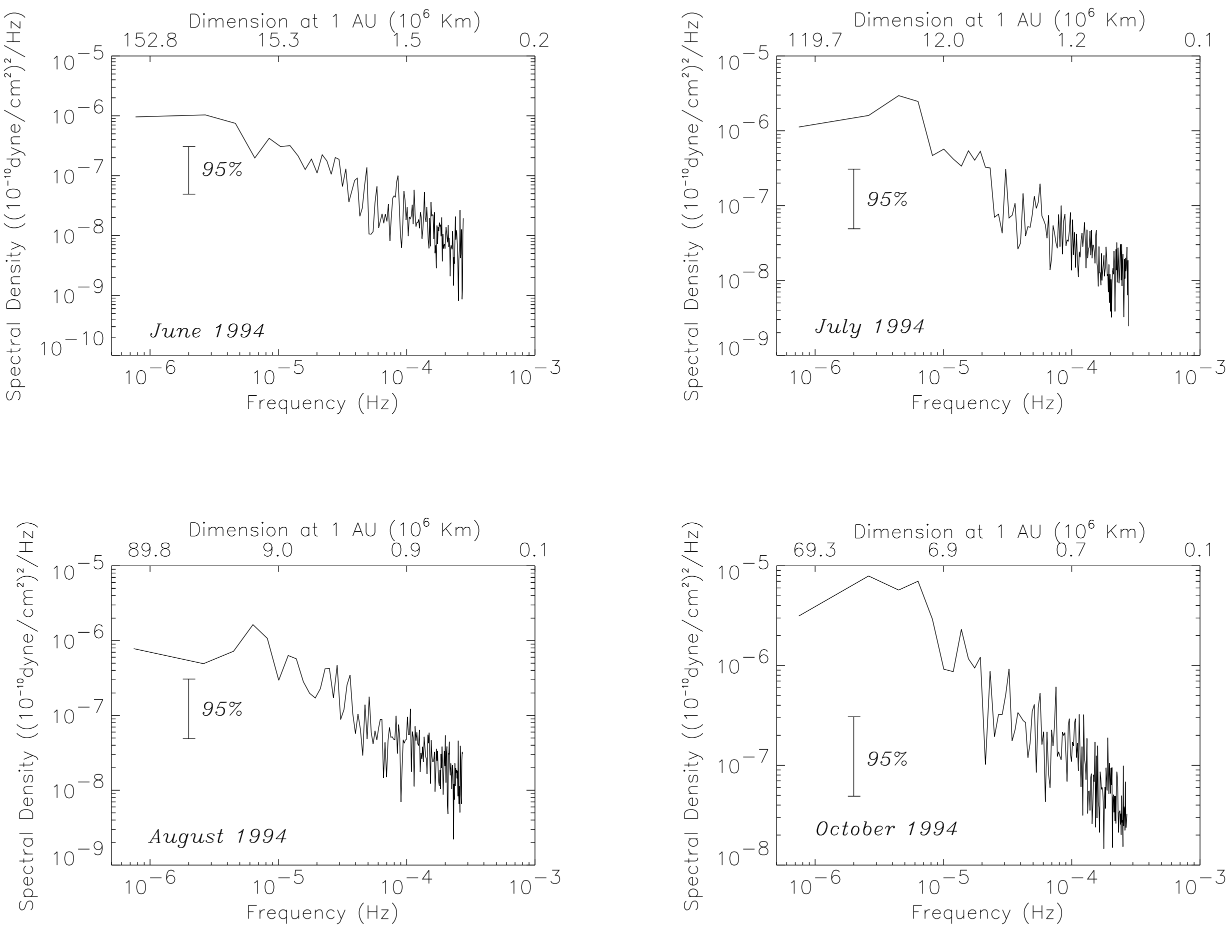

Fig. 1. Representative power spectra of the magnetic pressure for four out of the ten months of data we analyzed. The 95% level marks the confidence range. The upper horizontal scale gives the linear dimensions, scaled to 1 AU, of features whose temporal frequency is given on the abscissa. Values of the power density at each frequency have been evaluated as mean values over five adjacent frequencies, to provide a smoother-looking spectrum.

same temperature. Hence, gas pressure reaches its maximum value within plumes, while magnetic pressure maximizes outside plumes. As a consequence, we may expect the anticorrelation between gas and magnetic pressure to be one of the plume signatures (although other structures can also present this property). Taking into account that Thieme et al. (1990) examined power spectra of these quantities, we decided to analyze the behavior of pressures. Magnetic pressure has been evaluated from magnetic field data acquired with a typical time resolution of 4 minutes. The gas pressure has been computed summing up the contributions from the proton, electron, and alpha particles. In this case, our data have a typical time resolution of $\approx$ 1 hour and provide proton and alpha densities, proton, electron and alpha temperatures. Electron densities have been computed assuming charge neutrality with the other two components.

The data set has been divided into smaller segments, each one including about one month of observations, for reasons which will become clear later. The first months covered by our data are still occasionally affected by solar activity phenomena (see, e.g., Lemen et al. 1996, Hudson et al. 1996; Alexander et al. 1996). Those intervals have been discarded, and therefore, in this case, our analysis include a lower number of data. Typically, however, we dealt with $\approx$ 10000 4-minutes samples, for magnetic pressures, and $\approx$ 660 one-hour samples, for plasma pressures. The decrease of Ulysses heliocentric distance, within the time-period we analyzed, resulted in a definite trend of the physical parameters we analyzed: by fitting a straight line to each data sub- section, we removed this bias, which is, within a month, hardly noticeable.

3. Power spectra of magnetic and gas pressures

3.1. Analysis of data without significant periodicities

Power spectra of magnetic pressure data have been computed by the Fast-Fourier-Transform method with ten degrees of freedom, after filtering with the Hanning window function (Press et al. 1992). Because the structures we expect to detect should have a periodicity of the order of a few hours, at the distance where observations are taken, original high temporal frequency

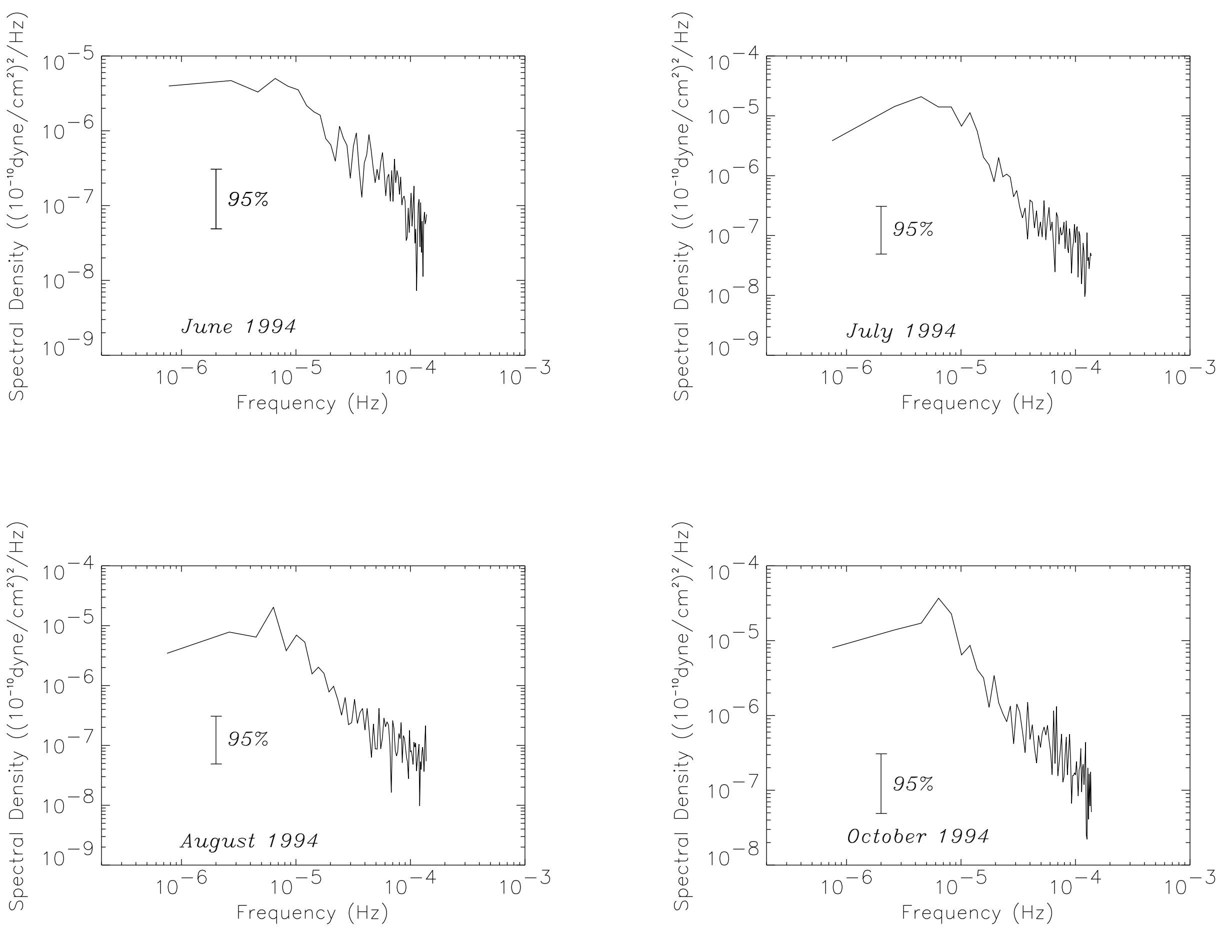

Fig. 2. Representative power spectra of the plasma pressure for the four months which appear in Fig. 1. The 95% level marks the confidence range. The upper horizontal scale gives the linear dimensions, scaled to 1 AU, of features whose temporal frequency is given on the abscissa. Values of the power density at each frequency have been evaluated as mean values over five adjacent frequencies, to provide a smoother-looking spectrum.

data have been accumulated over half an hour and reconstructed, within intervals where no observations were taken, by appropriate interpolations. At a representative distance of $\approx$ 3 AU and a latitude of $\approx 60°$, a feature as large as those identified by Thieme et al. (1990) will go past Ulysses in $\approx$ 13 hours: hence, our procedure is well justified. We will come back to this point later on.

Fig. 1 illustrates typical power spectra for our data set. Only May data have a different behavior, and we will discuss that case separately. Quite obviously the signal is always well within the 95% confidence interval shown in the figure. In the upper part of the panels we give the linear size (km) of periodic features whose temporal frequency can be read along the abscissa. Assuming radial expansion beyond 1 AU, these dimensions have been scaled to 1 AU, to permit an easy comparison with Thieme et al. results (1990).

It is worth pointing out that the variable latitude of Ulysses, during the time covered by our data set, prevents us from adding up data from the whole observational set and evaluating a single power spectrum. Depending on their latitude, features of the same size, at the solar surface, require different times to corotate past Ulysses. An additional effect may be provided by the differential rotation of the Sun. In evaluating the upper horizontal scale given in Fig. 1, we have assumed stationary corotation at the coronal rotation rate values given by Weber et al. (1994).

The magnetic pressure power spectra are mimicked by those of plasma pressure and do not show any evidence for a significant periodicity. As we mentioned, the gas pressure data we used have been calculated by summing up the contributions from the proton, alpha and electron pressures. Because data have a time resolution of $\approx$ one hour, no further averaging has been done. Fig. 2 shows the gas pressure power spectra for the four months for which Fig. 1 gives the magnetic pressure power spectra.

A comparison of Figs. 1 and 2 shows that the power in the gas pressure variations exceeds the power in the magnetic pressure variations, at least in the low frequency region. Should this behavior cover the whole frequency dominion of our plots, we could consider this as a valid argument against PBS structures contributing significantly to the spectra. However, because the gas pressure power profile declines with frequency more steeply

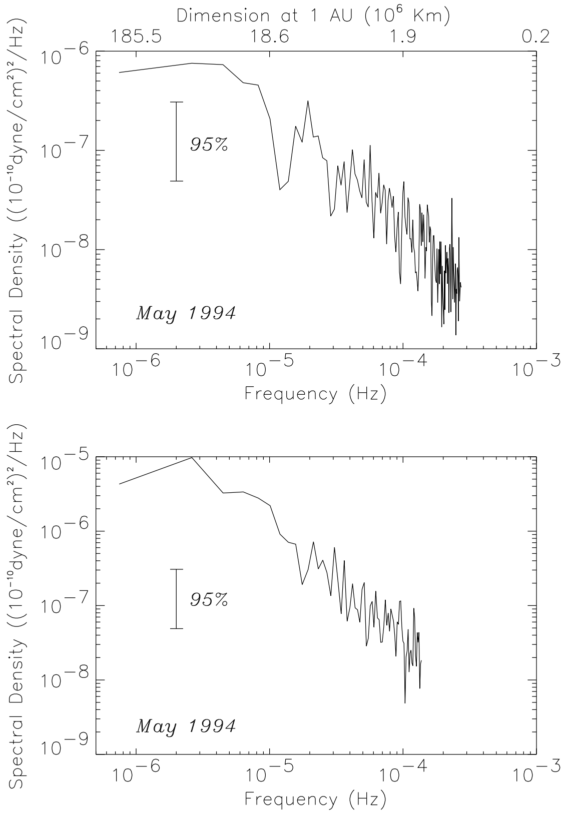

Fig. 3. Power spectra of the magnetic pressure (upper panel) and of the gas pressure (lower panel), evaluated with the FFT technique, for data acquired in May 1994. The 95% level marks the confidence range. The upper horizontal scale gives the linear dimensions, scaled to 1 AU, of features whose temporal frequency is given on the abscissa. Values of the power density at each frequency have been evaluated as mean values over five adjacent frequencies, to provide a smoother-looking spectrum.

than the magnetic pressure power profile, there is a frequency range where the two attain comparable values. In the four panels of Figs. 1 and 2, only the top left one (June 1994) shows gas pressure power in excess of the magnetic pressure power throughout the entire frequency range of the plot. In the other three panels, the frequency at which the two power spectra reach similar values is $\approx 2\ 10^{-5}$ Hz: this is exactly the region where Thieme et al. found a peak in their spectra. Nevertheless, the lack of periodicity in the power spectra contrasts Thieme et al.'s findings. Before going on to discuss the implications of the present result, we analyze the single case where there was (marginal) evidence of a peak in power spectra. This is described in the next section.

3.2. Data with marginal evidence for a typical periodicity

The only data whose power spectra provide indications for a significant periodicity were acquired in May 1994. The spectrum of the magnetic pressure shows a feature, which, although its significance level is not greater than 95%, seems hard to dismiss. The peak is broad enough to include a few data points; moreover, the linear dimension corresponding to the peak frequency favorably compares with the size derived by Thieme et al. for their periodic structures. We may surmise that magnetic flux tubes, usually unrecognizable because "washed out" by unknown processes, because of some special conditions, maintained their identity.

Should this be a realistic hypothesis, we also expect to find a peak, at the same frequency, in the power spectra of the gas pressure. However, there is no significant peak in the power spectrum of the gas pressure, although a small feature, well within the confidence level, at the frequency of the magnetic pressure peak, is recognizable in this spectrum. Fig. 3 shows the power spectra of both the magnetic (upper panel) and the gas pressure (lower panel): these have been calculated as described in the previous sub-section. Due to the lack of any significant periodicity in the gas pressure, an interpretation of the magnetic pressure peak in terms of pressure balanced structures is in jeopardy.

Before discarding this interpretation, we make a further check by evaluating power spectra through an alternative procedure, the Scargle periodogram (Scargle 1981, 1982). The periodogram technique can be applied to unevenly spaced data, and allows us to rule out the possibility that the magnetic pressure peak is an artificial feature, related to the procedure by which regularly spaced data are reconstructed. The technique, already used in the analysis of astronomical data (see, e.g., Horne and Baliunas, 1986), is equivalent to least-square fitting of sinusoids to the data and, with respect to the Fourier analysis, has the advantage of weighing data by point, rather than by time interval.

Figure 4 gives the power spectra for the magnetic and gas pressure for May data, evaluated via the normalized periodogram technique (Press and Rybicki, 1989). In this case, no interpolation has been made to fill in the data gaps. Otherwise, data have been processed as we did when evaluating Fourier spectra, to make results from the two procedures easily comparable. The periodogram for the magnetic pressure shows a feature, with a 5% false alarm probability, at the same frequency where a peak was found in the Fourier magnetic pressure spectrum. Once more, there seems to be no peak whatsoever in the plasma pressure power spectrum. We may tentatively conclude that we found marginal evidence for the presence of a periodicity in magnetic data, which has no counterpart in plasma data. In the last section of the present paper, we suggest some additional analysis that may help us to interpret the present result.

4. Modeling Ulysses random crossing of flow tubes

The most obvious interpretation of the lack of periodicities in power spectra, invokes the absence of regularly spaced structures. As we discuss later on, this is in fact a viable explanation of the present results. However, we may alternatively hypothesize that regularly spaced pressure balanced structures pervade the solar wind, but that their periodicity is hardly detectable by a power spectra analysis of *in situ* observations.

In order to check whether this can be actually the case, we have built a very simple model which envisages Ulysses, as it

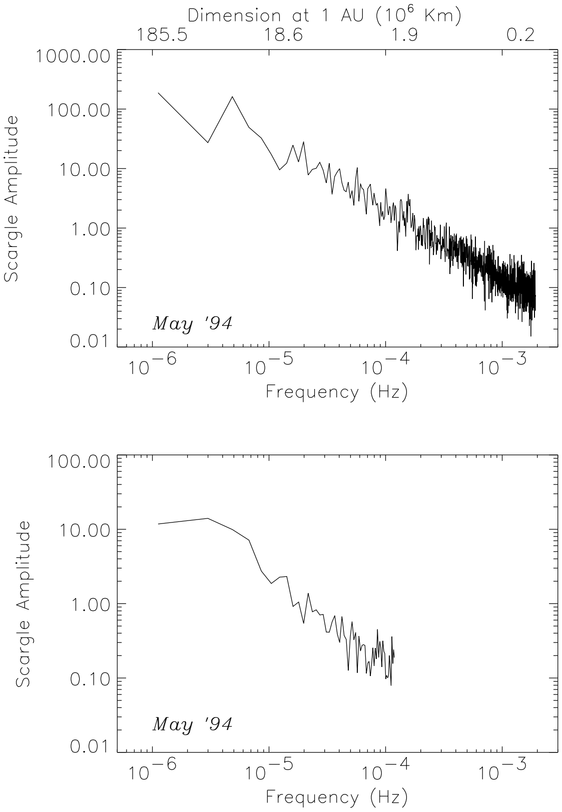

Fig. 4. Power spectra of the magnetic pressure (upper panel) and of the gas pressure (lower panel) for data acquired in May 1994, evaluated with the normalized periodogram technique. Data have not been interpolated, nor made evenly spaced, as periodograms can be evaluated from unevenly spaced data. The upper horizontal scale gives the linear dimensions, scaled to 1 AU, of features whose temporal frequency is given on the abscissa. Values of the power density at each frequency have been evaluated as mean values over five adjacent frequencies, to provide a smoother-looking spectrum.

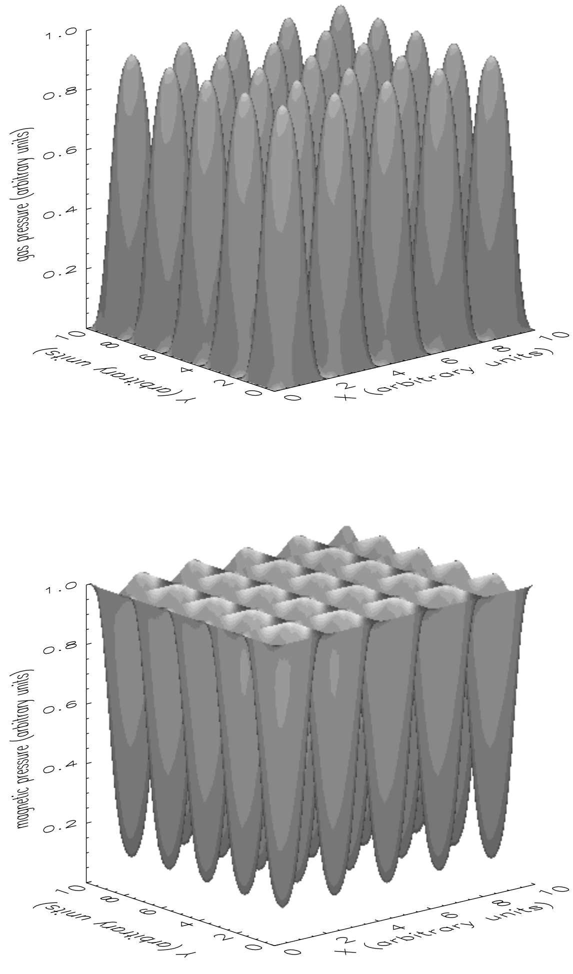

Fig. 5. Typical 2-D distribution of structures – representative of plumes – characterized by a large peak value of the gas pressure (upper panel). The gas pressure distribution has been derived from eq. 2, with $s = 2$, $c = 2$, $a = .4$. The bottom panel shows the 2-D magnetic pressure distribution (see eq. 1): peak values of gas pressure correspond to minima in the magnetic pressure and viceversa. Pressures, given along the z axis, have been normalized to their peak value, here arbitrarily taken to be unity.

randomly traverses a plume distribution made up of cylindrical flux tubes. Obviously, we consider this an oversimplified scheme, which is not meant to be realistic but provides us with a tool for checking how easily can be interpreted power spectra derived from *in situ* observations. The only feature we introduce in the model is the off-diameter crossing of flux tubes, because only occasionally the spacecraft will cut structures through their diameter. Hence, if the gas pressure peaks at the tube axis and steadily declines towards the tube boundaries, peak values will be measured quite rarely and repeated peripheral crossing may possibly mask a periodicity otherwise quite easily revealed.

In order to model this situation we constructed a 2-D distribution of structures and we simulated Ulysses's trajectory by a straight line randomly crossing through the distribution. For the sake of simplicity, we adopted flat, rather than spherical geometry. Plumes have been assumed to be in lateral pressure equilibrium with the ambient, whose total pressure keeps constant. In this representation, plumes are pressure balanced structures: although PBS are not uniquely related to plumes (Vellante and Lazarus 1987, Roberts 1990), most likely plumes, if capable of maintaining their identity in the solar wind, satisfy this condition.

In the x,y plane, containing the spacecraft orbit, the gas and magnetic pressure distributions are defined by the functions

$$p_{mag}(x_i, y_i) \;=\; exp\left\{-\frac{[sin(x_i\pi/s)sin(y_i\pi/s)]^c}{a}\right\} \qquad (1)$$

$$p_{gas}(x_i, y_i) \;=\; 1 - exp\left\{-\frac{[sin(x_i\pi/s)sin(y_i\pi/s)]^c}{a}\right\} \qquad (2)$$

which allow the total pressure to be constant all over the xy plane. By varying the parameters s, c, a different plume distributions can be simulated: changing s (which gives the periodicity of the function along the x,y directions), plumes change their typical separation; changing c, plumes change their *width*, i.e. the distance over which their pressure decreases to low values. In the following, plume is a structure whose diameter, in the xy plane, is given by twice the distance over which the gas pressure decreases to $1/10$ of its peak value: at larger distances we assume plumes to be indistiguishable from the ambient. The parameter a allows for different peak values of gas/magnetic pressure. Fig. 5 gives a typical distribution of structures in the xy plane: gas pressure – upper panel – and magnetic pressure – lower panel – are clearly anticorrelated, as required by the transverse pressure balance condition.

On the basis of pre-selected plume distributions, we proceed now to build strings of data, representative of the observations made by a spacecraft. In order to create data sets mimicking those used in power spectra analysis, we simulated observations taken over an entire solar rotation, at time intervals of one hour. With a solar rotation rate of 13°/day, a simulated data set contains $\approx$ 660 points.

Artificial data have been constructed from plume distributions that represent two situations, which correspond, respectively, to high and low filling factors (filling factor is here defined as the percentage area occupied by plumes). A high filling factor can be intuitively justified on the ground that the magnetic pressure decreases with heliographic distance much more rapidly than gas pressure: hence, the plume plasma, not confined by adequate magnetic fields, is likely, at large distances, to occupy the whole space. On the other hand, visual inspection of data shows only a few clearly identifiable PBS structures over a month: typically no more than 10-12 features. This may either mean that only a few strongly confined flux tubes survive over large distances, or that PBS are *not* sun-related features (cf. McComas et al. this issue), or that the random sampling process "washes out" most of the flux tubes. In the absence of precise indications favoring either interpretations, we also simulate a low filling factor case. We remind the reader that high and low filling factors can be reproduced, in our model, by different values of the parameters s and c: in the examples that we discuss shortly, we have used the same value of s, for both high and low filling factors, but we varied the plume diameter by changing the value of c.

Obviously, a power spectrum analysis will unequivocally identify periodic structures, when a single periodicity holds throughout the sample. This turns out to be true, in the trivial case of power spectra of data sets, artificially built from high filling factor (on the order of unity) distributions. However, when plumes' populations with low filling factors (order of 5%) are constructed, the periodicity can be easily identified *only* by summing over a few spectra. This procedure is necessary to get rid of spurious periodicities, arising because of a repetitive pattern met when randomly traversing the regularly spaced plume population. The spurious periodicities cancel out, when summing over spectra corresponding to different trajectories through the structures.

Fig. 6 illustrates this case. In the upper panel, we show the gas pressure sampled by a spacecraft, during one solar rotation, when traversing a low filling factor plume distribution. The magnetic pressure distribution is not given, but it can be easily visualized, being $p_{mag} = 1 - p_{gas}$ (eqs. 1 and 2). The middle and lower panels give, respectively, the power spectrum evaluated from the data set shown in the top panel and the power spectrum evaluated by summing over 10 spectra obtained by intersecting the same plume distribution with 10 different trajectories. The distribution periodicity s, which is here assumed to be 3.5°, in agreement with Thieme et al. findings (1990), is quite evident in the lower plot. The figure clearly demonstrates that the random crossing of plumes by a spacecraft, adding to the real one spurious periodic components that do not show up when plumes are cut through their diameter, makes the identification of the structure periodicity much harder. In particular, in the top panel of Fig. 6, the periodicity corresponding to a repetitive pattern, and other components, are easily recognizable and traceable in the power spectrum. However, we already mentioned that Ulysses power spectra cannot be added up, because the changing latitude of the spacecraft makes periodic features of the same size correspond to different frequencies.

As we mentioned, the situation illustrated in Fig. 6 is unrealistic, because is altogether unlikely to assume plumes to have exactly the same periodicity. Thieme et al. (1988), in fact, found marginal evidence for a second peak in their power spectra. Hence, we simulated a case when there are two separate populations of plumes, randomly intermixed, characterized by two periodicities, and contributing, respectively, by a 60 and a 40% to the total population. Following the indications by Thieme et al. (1988) we chose the two populations to have a 3.5° and a 5.5° periodicity. In this case, we still considered a high and a low filling factor distribution. The introduction of a second typical periodicity does not modify the conclusions drawn in the previous case.

In the last case we examined, instead of assuming two distinct periodicities, we constructed plumes whose periodicity varies randomly between 3.5 and 5.5°: this is the less unrealistic approximation to the plume behavior, among the scenarios we dealt with. In this simulation, we only considered a high filling factor, because low filling factor periodicities are hard to identify, even in the simpler simulations described above. Fig. 7 gives, in the top panel, the gas pressure sampled by a spacecraft traversing a high filling factor plume distribution: the plot shows about 1/5 of the whole data set, which comprises one solar rotation. The bottom panel shows the power spectrum evaluated on the simulated data set shown in the upper plot: an interpretation of the power spectrum in terms of characteristic periodicities is not at all obvious. If the same plume distribution were crossed through the diameters of the structures, the power spectrum would be simpler, because non-zero power would be limited to the frequency interval between 1 and 0.64 (the latter being the frequency $(1/5.5)^{\circ -1}$ in $3.5^{\circ -1}$ units), thus making the *range* of possible periodicities identifiable.

5. Discussion and conclusions

Power spectra of gas/magnetic pressure from Ulysses data, acquired at distances of $\approx$ 2-3 AU, show hardly any evidence for

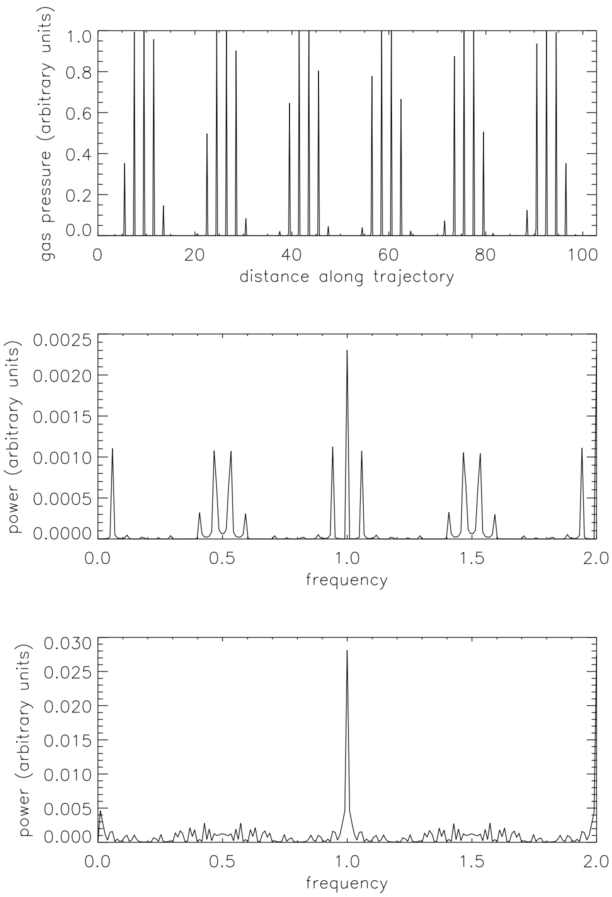

Fig. 6. Representative power spectra of the gas/magnetic pressure for an artificial data set, representative of a low filling factor (7%) plume population. The upper panel shows the gas pressure sampled by a spacecraft which crosses through the distribution. The abscissa gives the position along the spacecraft trajectory in units of 3.5°. Gas pressure values are given in arbitrary units on the ordinate axis. The parameters used in this simulation are: $s = 3.5^\circ$; $c = 5$; $a = 0.1$. The middle and lower panels give, respectively, the power spectrum calculated from the data set shown in the top panel and the power spectrum obtained by summing over ten spectra evaluated from data corresponding to ten different trajectories through the distribution. Power is given in arbitrary units, frequencies are given in units of $(3.5^\circ)^{-1}$: the peak at frequency 1 corresponds to the plume periodicity s.

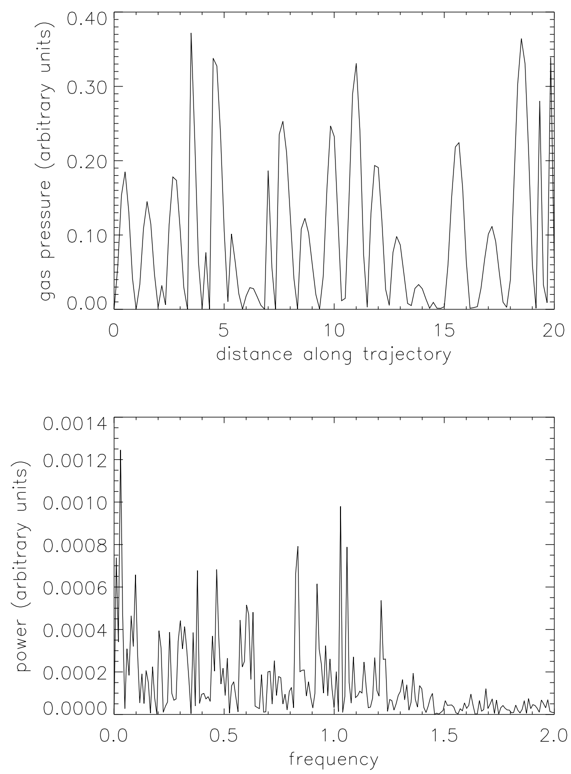

Fig. 7. Representative power spectra of the gas/magnetic pressure for an artificial data set, representative of a high filling factor population of plumes, whose periodicity varies randomly between $s_1 = 3.5^\circ$ and $s_2 = 5.5^\circ$. The upper panel shows the gas pressure sampled by a spacecraft which crosses through the distribution. The abscissa gives the position along the spacecraft trajectory in units of 3.5°: only about 1/5 of the data acquired during an entire solar rotation are shown in the figure. Gas pressure values are given in arbitrary units on the ordinate axis. The parameters used in this simulation are: $3.5^\circ \leq s \leq 5.5^\circ$; $c = 2$; $a = 1$. The lower panel gives the power spectrum evaluated from the artificial data set shown in the upper panel. Power is in arbitrary units, frequencies are given in $3.5^{\circ -1}$ units.

typical periodicities. This allows for different interpretations. Here we examine and discuss a few of them, in an attempt to find possible means to reach a correct interpretation of the present results.

Quite obviously, if plumes were not regularly distributed at the surface of the Sun, no periodicity could be expected in the solar wind. In the past, Newkirk and Harvey (1968) suggested plumes to be rooted at the boundaries of supergranular cells, possibly at vertices where cells meet. Typical periodicities of solar wind structures related to plumes would correspond to typical supergranular dimensions, although a super-radial expansion might lead to larger sizes. However, in the case of polar plumes seen at eclipses, it is difficult to determine where plumes are rooted, because the plume base cannot be observed. Hence, alternative possibilities have been advanced.

Plumes are not necessarily distributed uniformly within coronal holes, but they may be rooted in a circular belt, some distance from the poles (Sornette et al. 1980, Fisher and Guhathakurta 1995), possibly corresponding to the polar crown filament belt. Or, as recently proposed by Wang and Sheeley (1995), plumes are associated with occasional, randomly distributed bipoles, which reconnect with adjacent unipolar fields within coronal holes. If the latter suggestions are proved true by additional observational evidence, there is no justification for a search of periodicities in the solar wind, as a manifestation of plumes.

The apparent lack of periodicity of plume flow-tubes, in the hypothesis of a periodicity of the structures at low coronal levels, may also be ascribed either to a progressive cancellation of tube boundaries, with increasing heliocentric distances, or to the difficulty of interpretation of spectra, which, as we have shown in the previous section, are exceedingly complex, even in oversimplified scenarios. It should be noticed that we have altogether neglected, in our discussion, temporal factors, which may further complicate the interpretations of power spectra. There are so few indications, up until now, about the behavior of plumes in time, that it is hard even to hypothesize on the role of the temporal variations of plumes. Neugebauer et al. (1995) discussed this issue in relation to the microstream behavior.

An interpretation of the lack of periodicities in terms of the progressive disappearance of solar-related features would be in agreement with McComas et al. findings of an absence of any behavior, in the physical parameters of PBS, that could be related to solar structures (1996). We already mentioned this issue in the Introduction: in this case, PBS would originate in the interplanetary medium. In view of all the uncertainties we mentioned, power spectra do not appear capable of contributing significant information about the presence of plumes in the distant solar wind.

If structures are progressively erased, we should be able to find out why, in some cases, a few survive up to large distances. We may surmise that magnetic tubes are being canceled by some kind of plasma instability: e.g. by the Kelvin-Helmholtz instability. Should this be the case, we may invoke strong, stabilizing magnetic fields, for the surviving ones. Possibly, the case of May '94, where a hard to dismiss peak appeared in magnetic pressures at the same position where a barely visible peak shows up in gas pressures, deserves further analyses, within this scenario.

Additional evidence for a solar/interplanetary origin of PBS may be derived by reckoning the number of PBS at increasing distances, within the range covered by Ulysses. Should PBS have a solar origin, we expect their number to decrease with heliographic distance, while the opposite holds true for interplanetary originating features (Vellante and Lazarus 1987; Roberts, 1990). This is in fact the only evidence in favor of the interpretation of plumes in terms of solar structures that McComas et al. found (1996). However, because of the stringent conditions that PBS were required to satisfy, probably these authors analyzed a subset of the whole PBS population. A further, undisputable means to identify the nature of PBS, calls for the analysis of abundances within these structures. Should PBS, or at least a percentage of them, be associated with plumes, they should show the same behavior of plumes, in this respect. Widing and Feldman (1989, 1992) pointed out that, while the relative abundances of Na, Mg, and Ca in plumes are the same as those in the photosphere, the abundance of neon, relative to magnesium, is of the order of 1/10 of the photospheric value. A variation in elemental abundances between PBS and the ambient will provide us with first-hand evidence about their nature.

Before concluding, we would like to comment more on the May '94 case. If we dismiss the hypothesis of a significant anticorrelation between magnetic and gas pressure, but we still consider the magnetic pressure peak in power spectra to be significant, we are led to interpret the magnetic pressure behavior in terms of alternative phenomena. These data pose an interesting problem: a paper, at present under preparation (Parenti et al., 1996), will discuss possible scenarios for this puzzling behavior.

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