Chapter 5
Compressive Turbulence

Interplanetary medium is slightly compressive, magnetic field intensity and proton number density experience fluctuations over all scales and the compression depends on both the scale and the nature of the wind. As a matter of fact, slow wind is generally more compressive than fast wind, as shown in Fig. 5.1 where, following Bavassano et al. (1982b) and Bruno and Bavassano (1991), we report the ratio between the power density associated with magnetic field intensity fluctuations and that associated with the fluctuations of the three components. In addition, as already shown by Bavassano et al. (1982b), this parameter increases with heliocentric distance for both fast and slow wind as shown in the bottom panel, where the ratio between the compression at 0.9 AU and that at 0.3 AU is generally greater than 1. It is also interesting to notice that within the Alfvénic fast wind, the lowest compression is observed in the middle frequency range, roughly between 10^{-4} and 10^{-3} Hz. On the other hand, this frequency range has already been recognized as the most Alfvénic one, within the inner heliosphere (Bruno et al. 1996).

As a matter of fact, it seems that high Alfvénicity is correlated with low compressibility of the medium (Bruno and Bavassano 1991; Klein et al. 1993; Bruno and Bavassano 1993) although compressibility is not the only cause for a low Alfvénicity (Roberts et al. 1991, 1992; Roberts 1992).

The radial dependence of the normalized number density fluctuations $\delta n/n$ for the inner and outer heliosphere were studied by Grappin et al. (1990) and Roberts et al. (1987) for the hourly frequency range, but no clear radial trend emerged from these studies. However, interesting enough, Grappin et al. (1990) found that values of e^- were closely associated with enhancements of $\delta n/n$ on scales longer than 1 h.

On the other hand, a spectral analysis of proton number density, magnetic field intensity, and proton temperature performed by Marsch and Tu (1990) and Tu et al. (1991) in the inner heliosphere, separately for fast and slow wind (see Fig. 5.2), showed that normalized spectra of the above parameters within slow wind were only marginally dependent on the radial distance. On the contrary, within fast wind, magnetic field and proton density normalized spectra showed not only a clear radial

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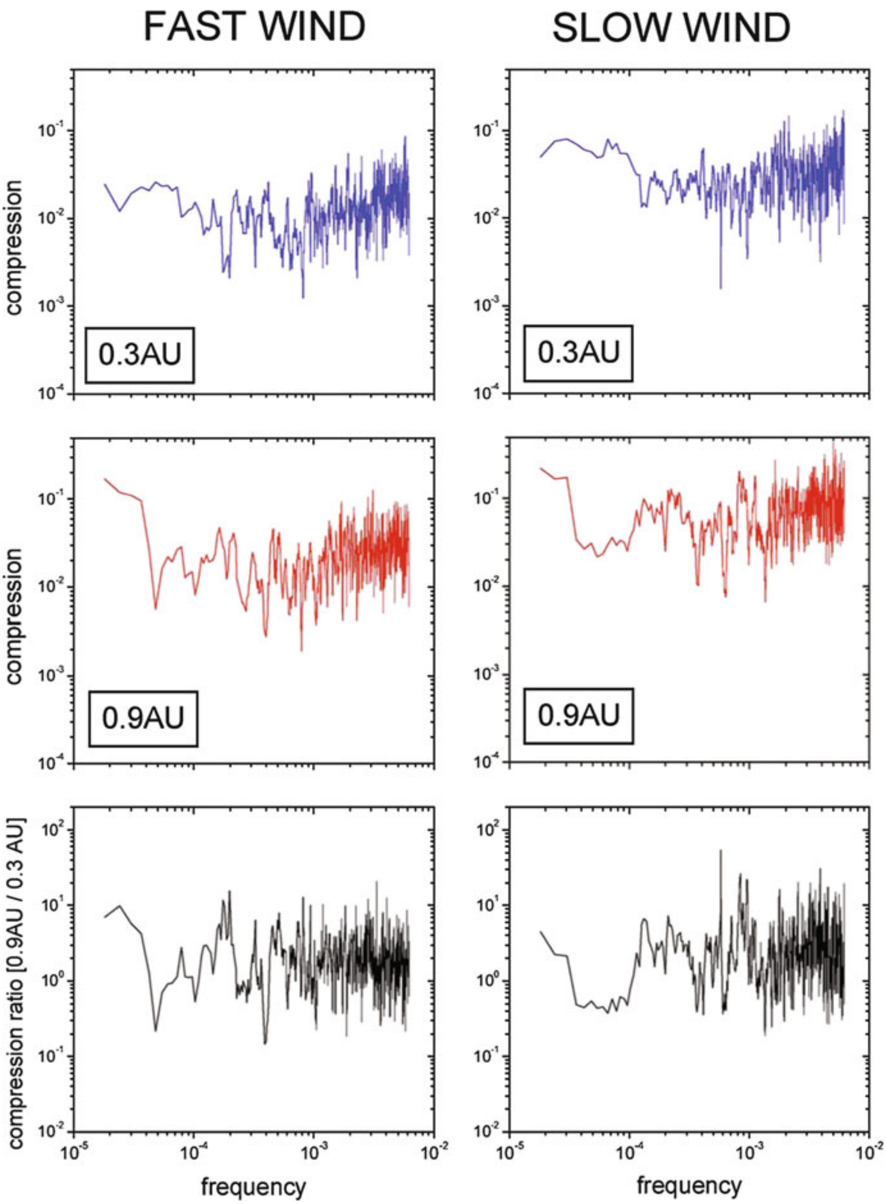

Fig. 5.1 The *first two rows* show magnetic field compression (see text for definition) for fast (*left column*) and slow (*right column*) wind at 0.3 AU (*upper row*) and 0.9 AU (*middle row*). The *bottom panels* show the ratio between compression at 0.9 AU and compression at 0.3 AU. This ratio is generally greater than 1 for both fast and slow wind

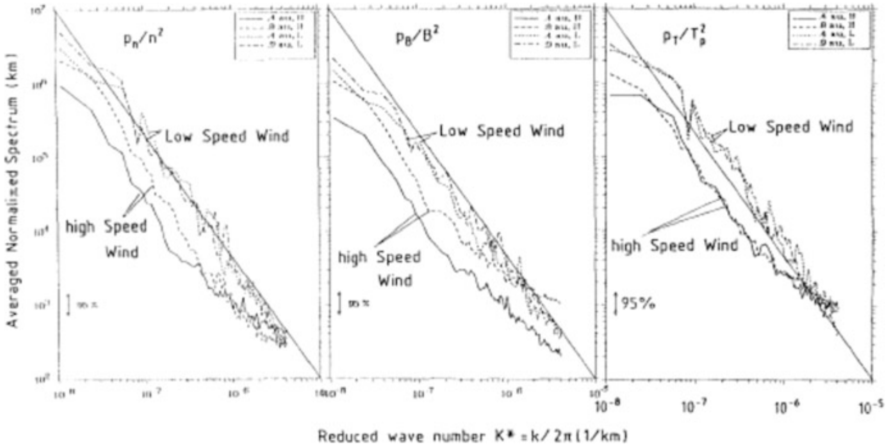

Fig. 5.2 *From left to right*: normalized spectra of proton temperature (from Tu et al. 1991), number density, and magnetic field intensity fluctuations (from Marsch and Tu 1990, copyright by AGU, reproduced by permission). *Different lines* refer to different heliocentric distances for both slow and fast wind

dependence but also similar level of power for $k < 4 \times 10^{-4}\,\mathrm{km\,s^{-1}}$. For larger k these spectra show a flattening that becomes steeper for increasing distance, as was already found by Bavassano et al. (1982a) for magnetic field intensity. Normalized temperature spectra does not suffer any radial dependence neither in slow wind nor in fast wind.

Spectral index is around $-5/3$ for all the spectra in slow wind while, fast wind spectral index is around $-5/3$ for $k < 4 \times 10^{-4}\,\mathrm{km}^{-1}$ and slightly less steep for larger wave numbers.

5.1 On the Nature of Compressive Turbulence

Considerable efforts, both theoretical and observational, have been made in order to disclose the nature of compressive fluctuations. It has been proposed (Montgomery et al. 1987; Matthaeus and Brown 1988; Zank et al. 1990; Zank and Matthaeus 1990; Matthaeus et al. 1991; Zank and Matthaeus 1992) that most of compressive fluctuations observed in the solar wind could be accounted for by the Nearly Incompressible (NI) model. Within the framework of this model, Montgomery et al. (1987) showed that a spectrum of small scale density fluctuations follows a $k^{-5/3}$ when the spectrum of magnetic field fluctuations follows the same scaling. Moreover, it was showed (Matthaeus and Brown 1988; Zank and Matthaeus 1992) that if compressible MHD equations are expanded in terms of small turbulent sonic Mach number, pressure balanced structures, Alfvénic and magnetosonic fluctuations naturally arise as solutions and, in particular, the RMS of small density fluctuations would scale like M^2, being $M = \delta v/C_s$ the turbulent sonic Mach number, δv the

RMS of velocity fluctuations and C_s the sound speed. In addition, if heat conduction is allowed in the approximation, temperature fluctuations dominate over magnetic and density fluctuations, temperature and density are anticorrelated and would scale like M. However, in spite of some examples supporting this theory (Matthaeus et al. (1991) reported 13 % of cases satisfied the requirements of NI-theory), wider statistical studies, conducted by Tu and Marsch (1994), Bavassano et al. (1995) and Bavassano and Bruno (1995), showed that NI theory is not generally applicable *sic et simpliciter* to the solar wind. The reason might be in the fact that interplanetary medium is highly inhomogeneous because of the presence of an underlying structure convected by the wind. As a matter of fact, Thieme et al. (1989) showed evidence for the presence of time intervals characterized by clear anti-correlation between kinetic pressure and magnetic pressure while the total pressure remained fairly constant. These pressure balance structures were for the first time observed by Burlaga and Ogilvie (1970) for a time scale of roughly 1–2 h. Later on, Vellante and Lazarus (1987) reported strong evidence for anti-correlation between field intensity and proton density, and between plasma and field pressure on time scales up to 10 h. The anti-correlation between kinetic and magnetic pressure is usually interpreted as indicative of the presence of a pressure balance structure since slow magnetosonic modes are readily damped (Barnes 1979).

These features, observed also in their dataset, were taken by Thieme et al. (1989) as evidence of stationary spatial structures which were supposed to be remnants of coronal structures convected by the wind. Different values assumed by plasma and field parameters within each structure were interpreted as a signature characterizing that particular structure and not destroyed during the expansion. These intervals, identifiable in Fig. 5.3 by vertical dashed lines, were characterized by pressure balance and a clear anti-correlation between magnetic field intensity and temperature.

These structures were finally related to the fine ray-like structures or plumes associated with the underlying chromospheric network and interpreted as the signature of interplanetary flow-tubes. The estimated dimension of these structures, back projected onto the Sun, suggested that they over-expand in the solar wind. In addition, Grappin et al. (2000) simulated the evolution of Alfvén waves propagating within such pressure equilibrium ray structures in the framework of global Eulerian solar wind approach and found that the compressive modes in these simulations are very much reduced within the ray structures, which indeed correspond to the observational findings (Buttighoffer et al. 1995, 1999).

The idea of filamentary structures in the solar wind dates back to Parker (1963), followed by other authors like McCracken and Ness (1966), Siscoe et al. (1968), and more recently has been considered again in the literature with new results (see Sect. 7.3). These interplanetary flow tubes would be of different sizes, ranging from minutes to several hours and would be separated from each other by tangential discontinuities and characterized by different values of plasma parameters and a different magnetic field orientation and intensity. This kind of scenario, because of some similarity to a bunch of tangled, smoking "spaghetti" lifted by a fork, was then named "spaghetti-model".

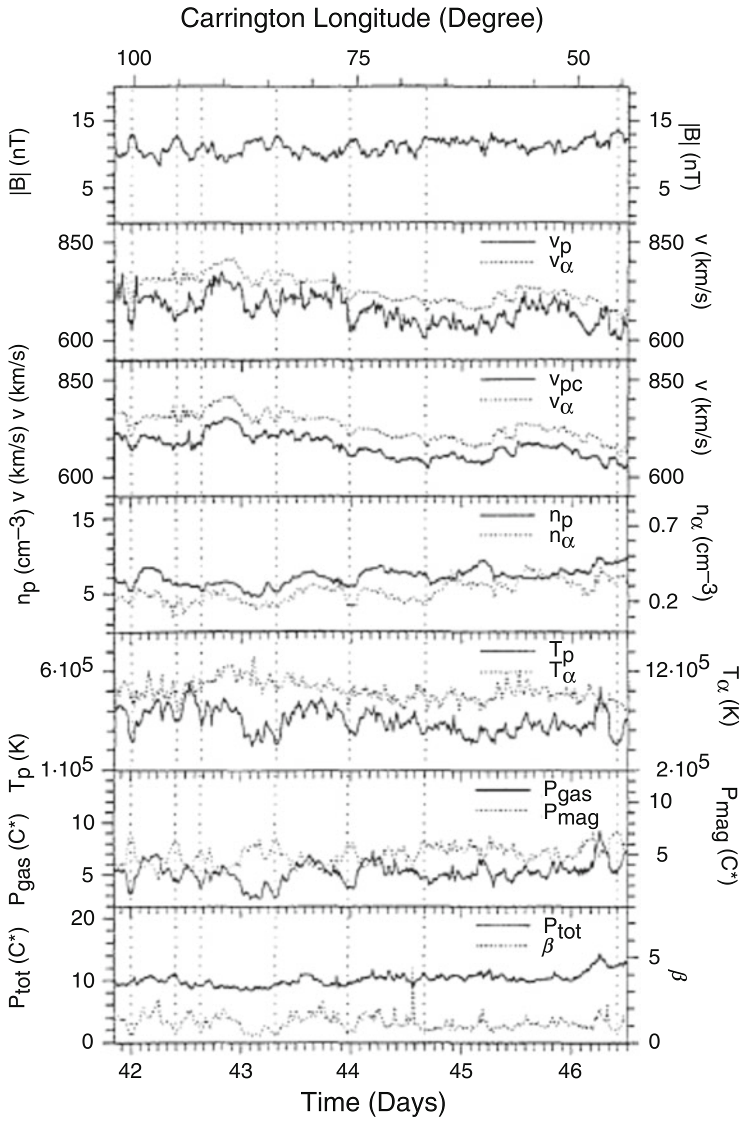

Fig. 5.3 *From top to bottom*: field intensity $|\mathbf{B}|$; proton and alpha particle velocity v_p and v_α; corrected proton velocity $v_{pc} = v_p - \delta v_A$, where v_A is the Alfvén speed; proton and alpha number density n_p and n_α; proton and alpha temperature T_p and T_α; kinetic and magnetic pressure P_k and P_m, which the authors call P_{gas} and P_{mag}; total pressure P_{tot} and $\beta = P_{\mathrm{gas}}/P_{\mathrm{mag}}$ (from Thieme et al. 1989)

A spectral analysis performed by Marsch and Tu (1993b) in the frequency range 6×10^{-3}–6×10^{-6} showed that the nature and intensity of compressive fluctuations systematically vary with the stream structure. They concluded that compressive fluctuations are a complex superposition of magnetoacoustic fluctuations and

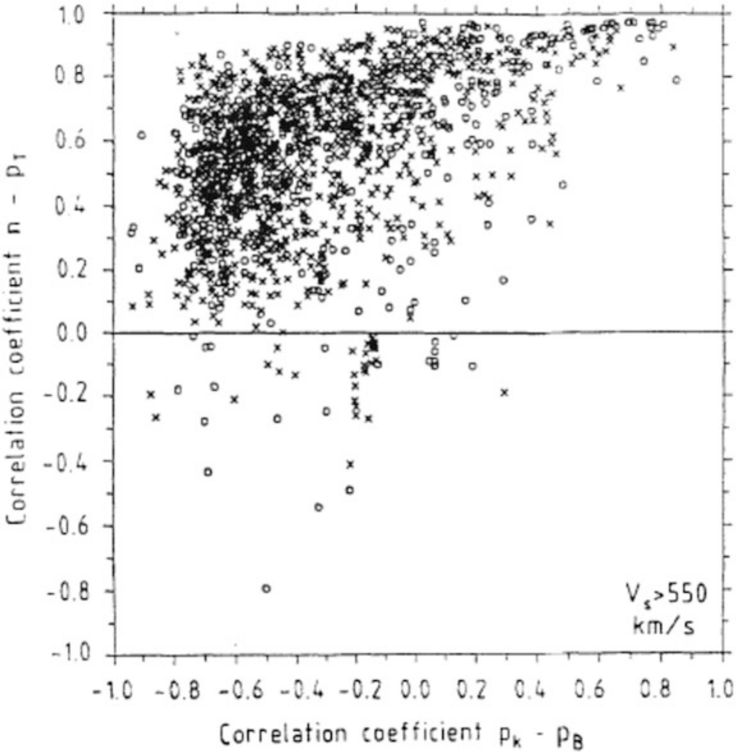

Fig. 5.4 Correlation coefficient between number density n and total pressure p_T plotted vs. the correlation coefficient between kinetic pressure and magnetic pressure for both Helios relatively to fast wind. Image reproduced by permission from Marsch and Tu (1993a)

pressure balance structures whose origin might be local, due to stream dynamical interaction, or of coronal origin related to the flow tube structure. These results are shown in Fig. 5.4 where the correlation coefficient between number density n and total pressure P_{tot} (indicated with the symbols p_T in the figure), and between kinetic pressure P_k and magnetic pressure P_m (indicated with the symbols p_k and p_b, respectively) is plotted for both Helios s/c relatively to fast wind. Positive values of correlation coefficients $C(n, p_T)$ and $C(p_k, p_b)$ identify magnetosonic waves, while positive values of $C(n, p_T)$ and negative values of $C(p_k, p_b)$ identify pressure balance structures. The purest examples of each category are located at the upper left and right corners.

Following these observations, Tu and Marsch (1994) proposed a model in which fluctuations in temperature, density, and field directly derive from an ensemble of small amplitude pressure balanced structures and small amplitude fast perpendicular magnetosonic waves. These last ones should be generated by the dynamical interaction between adjacent flow tubes due to the expansion and, eventually, they would experience also a non-linear cascade process to smaller scales. This model was able to reproduce most of the correlations described by Marsch and Tu (1993b) for fast wind.

Later on, Bavassano et al. (1996a) characterized compressive fluctuations in terms of their polytropic index, which resulted to be a useful tool to study small scale variations in the solar wind. These authors followed the definition of polytropic fluid given by Chandrasekhar (1967): “a polytropic change is a quasi-static change of state carried out in such a way that the specific heat remains constant (at some prescribed value) during the entire process”. For such a variation of state the adiabatic laws are still valid provided that the adiabatic index γ is replaced by a new adiabatic index $\gamma' = (c_P - c)/(c_V - c)$ where c is the specific heat of the polytropic variation, and c_P and c_V are the specific heat at constant pressure and constant volume, respectively. This similarity is lost if we adopt the definition given by Courant and Friedrichs (1976), for whom a fluid is polytropic if its internal energy is proportional to the temperature. Since no restriction applies to the specific heats, relations between temperature, density, and pressure do not have a simple form as in Chandrasekhar approach (Zank and Matthaeus 1991). Bavassano et al. (1996a) recovered the polytropic index from the relation between density n and temperature T changes for the selected scale $Tn^{1-\gamma'} =$ const. and used it to determine whether changes in density and temperature were isobaric ($\gamma' = 0$), isothermal ($\gamma' = 1$), adiabatic ($\gamma' = \gamma$), or isochoric ($\gamma' = \infty$). Although the role of the magnetic field was neglected, reliable conclusions could be obtained whenever the above relations between temperature and density were strikingly clear. These authors found intervals characterized by variations at constant thermal pressure P. They interpreted these intervals as a subset of total-pressure balanced structures where the equilibrium was assured by the thermal component only, perhaps tiny flow tubes like those described by Thieme et al. (1989) and Tu and Marsch (1994). Adiabatic changes were probably related to magnetosonic waves excited by contiguous flow tubes (Tu and Marsch 1994). Proton temperature changes at almost constant density were preferentially found in fast wind, close to the Sun. These regions were characterized by values of B and N remarkable stable and by strong Alfvénic fluctuations (Bruno et al. 1985). Thus, they suggested that these temperature changes could be remnants of thermal features already established at the base of the corona.

Thus, the polytropic index offers a very simple way to identify basic properties of solar wind fluctuations, provided that the magnetic field does not play a major role.

5.2 Compressive Turbulence in the Polar Wind

Compressive fluctuations in high latitude solar wind have been extensively studied by Bavassano et al. (2004) looking at the relationship between different parameters of the solar wind and comparing these results with predictions by existing models.

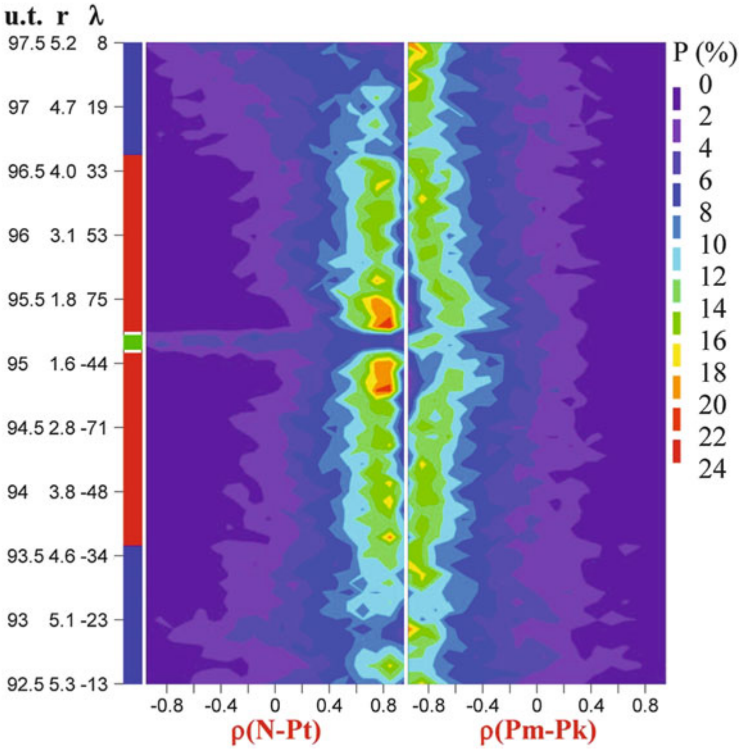

Fig. 5.5 Histograms of $\rho(N - P_t)$ and $\rho(P_m - P_k)$ per solar rotation. The *color bar* on the *left side* indicates polar (*red*), mid-latitude (*blue*), and low latitude (*green*) phases. Moreover, universal time UT, heliocentric distance, and heliographic latitude are also indicated on the *left side* of the plot. Occurrence frequency is indicated by the *color bar* shown on the *right hand side* of the figure. Image reproduced by permission from Bavassano et al. (2004), copyright EGU

These authors indicated with N, P_m, P_k, and P_t the proton number density n, magnetic pressure, kinetic pressure and total pressure ($P_{\text{tot}} = P_m + P_k$), respectively, and computed correlation coefficients ρ between these parameters. Figure 5.5 clearly shows that a pronounced positive correlation for $N - P_t$ and a negative pronounced correlation for $P_m - P_k$ is a constant feature of the observed compressive fluctuations. In particular, the correlation for $N - P_t$ is especially strong within polar regions at small heliocentric distance. In mid-latitude regions the correlation weakens, while almost disappears at low latitudes. In the case of $P_m - P_k$, the anticorrelation remains strong throughout the whole latitudinal excursion. For polar wind the anticorrelation appears to be less strong at small distances, just where the $N - P_t$ correlation is highest.

The role played by density and temperature in the anticorrelation between magnetic and thermal pressures is investigated in Fig. 5.6, where the magnetic field magnitude is directly compared with proton density and temperature. As regards the polar regions, a strong B-T anticorrelation is clearly apparent at all distances (right

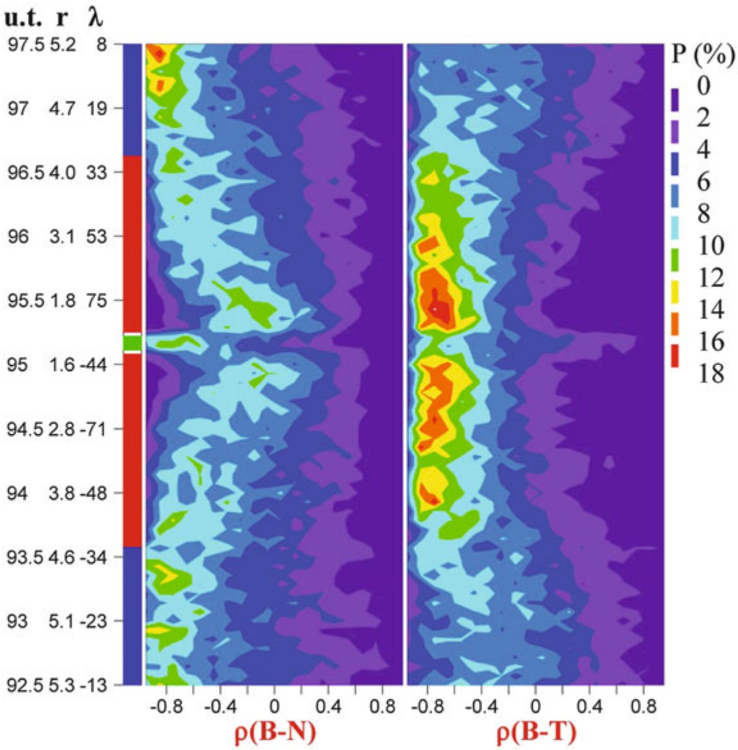

Fig. 5.6 Solar rotation histograms of B-N and B-T in the same format of Fig. 5.5. Image reproduced by permission from Bavassano et al. (2004), copyright EGU

panel). For B-N an anticorrelation tends to emerge when solar distance increases. This means that the magnetic-thermal pressure anticorrelation is mostly due to an anticorrelation of the magnetic field fluctuations with respect to temperature fluctuations, rather than density (see, e.g., Bavassano et al. 1996a,b). Outside polar regions the situation appears in part reversed, with a stronger role for the B-N anticorrelation.

In Fig. 5.7 scatter plots of total pressure vs. density fluctuations are used to test a model by Tu and Marsch (1994), based on the hypothesis that the compressive fluctuations observed in solar wind are mainly due to a mixture of pressure-balanced structures (PBS) and fast magnetosonic waves (W). Waves can only contribute to total pressure fluctuations while both waves and pressure-balanced structures may contribute to density fluctuations. A tunable parameter in the model is the relative PBS/W contribution to density fluctuations α. Straight lines in Fig. 5.7 indicate the model predictions for different values of α. It is easily seen that for all polar wind samples the great majority of experimental data fall in the $\alpha > 1$ region. Thus, pressure-balanced structures appear to play a major role with respect to magnetosonic waves. This is a feature already observed by Helios in the ecliptic

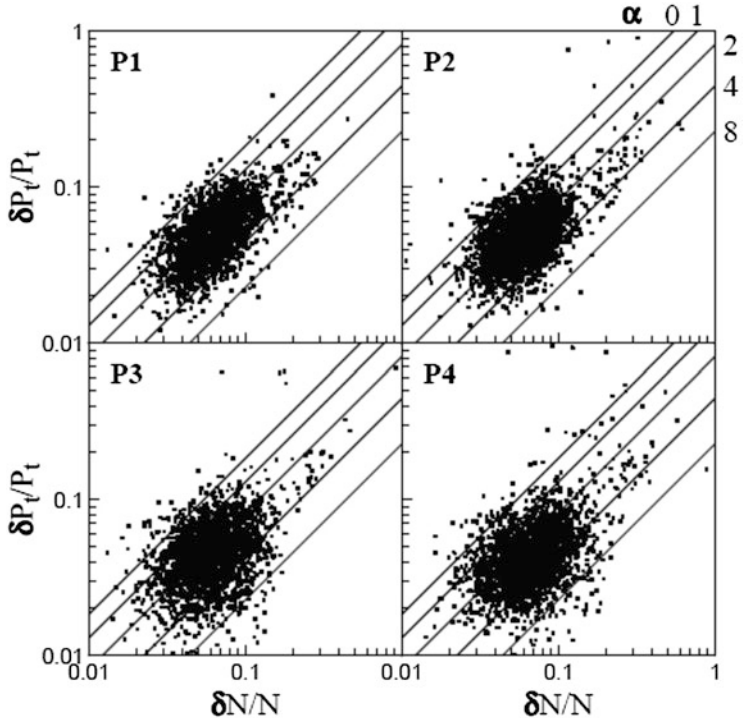

Fig. 5.7 Scatter plots of the relative amplitudes of total pressure vs. density fluctuations for polar wind samples P1 to P4. *Straight lines* indicate the Tu and Marsch (1994) model predictions for different values of α, the relative PBS/W contribution to density fluctuations. Image reproduced by permission from Bavassano et al. (2004), copyright EGU

wind (Tu and Marsch 1994), although in a less pronounced way. Different panels of Fig. 5.7 refer to different heliocentric distances within the polar wind. Namely, going from P1 to P4 is equivalent to move from 1.4 to 4 AU. A comparison between these panels indicates that the observed distribution tends to shift towards higher values of α (i.e., pressure-balanced structures become increasingly important), which probably is a radial distance effect.

Finally, the relative density fluctuations dependence on the turbulent Mach number M (the ratio between velocity fluctuation amplitude and sound speed) is shown in Fig. 5.8. The aim is to look for the presence, in the observed fluctuations, of nearly incompressible MHD behaviors. In the framework of the NI theory (Zank and Matthaeus 1991, 1993) two different scalings for the relative density fluctuations are possible, as M or as M^2, depending on the role that thermal conduction effects may play in the plasma under study (namely a heat-fluctuation-dominated or a heat-fluctuation-modified behavior, respectively). These scalings are shown in Fig. 5.8 as solid (for M) and dashed (for M^2) lines.

It is clearly seen that for all the polar wind samples no clear trend emerges in the data. Thus, NI-MHD effects do not seem to play a relevant role in driving the

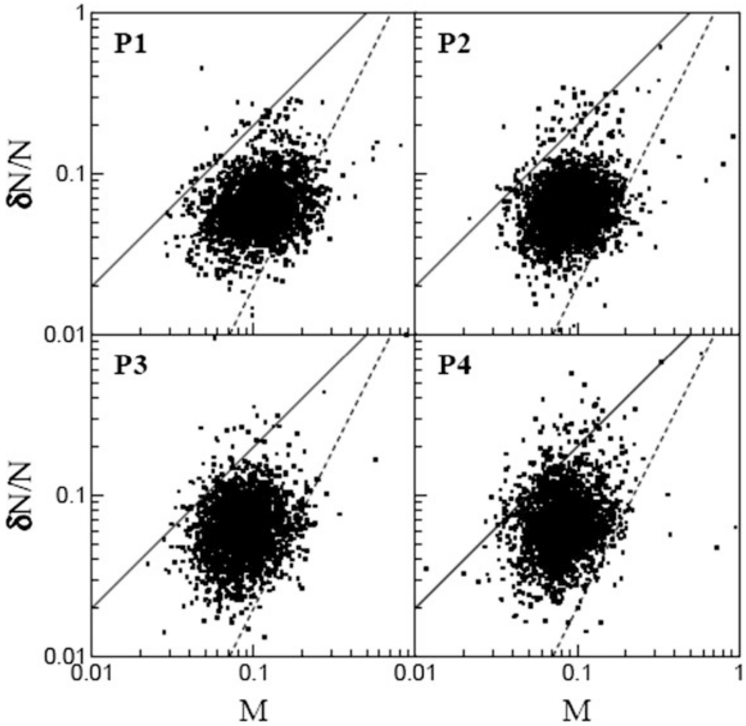

Fig. 5.8 Relative amplitude of density fluctuations vs. turbulent Mach number for polar wind. *Solid and dashed lines* indicate the M and M^2 scalings, respectively. Image reproduced by permission from Bavassano et al. (2004), copyright EGU

polar wind fluctuations. This confirms previous results in the ecliptic by Helios in the inner heliosphere (Bavassano et al. 1995; Bavassano and Bruno 1995) and by Voyagers in the outer heliosphere (Matthaeus et al. 1991). It is worthy of note that, apart from the lack of NI trends, the experimental data from Ulysses, Voyagers, and Helios missions in all cases exhibit quite similar distributions. In other words, for different heliospheric regions, solar wind regimes, and solar activity conditions, the behavior of the compressive fluctuations in terms of relative density fluctuations and turbulent Mach numbers seems almost to be an invariant feature.

The above observations fully support the view that compressive fluctuations in high latitude solar wind are a mixture of MHD modes and pressure balanced structures. It has to be reminded that previous studies (McComas et al. 1995, 1996; Reisenfeld et al. 1999) indicated a relevant presence of pressure balanced structures at hourly scales. Moreover, nearly-incompressible (see Sect. 5.1) effects do not seem to play any relevant role. Thus, polar observations do not show major differences when compared with ecliptic observations in fast wind, the only possible difference being a major role of pressure balanced structures.

5.3 The Effect of Compressive Phenomena on Alfvénic Correlations

A lack of $\delta\mathbf{V}-\delta\mathbf{B}$ correlation does not strictly indicate a lack of Alfvénic fluctuations since a superposition of both outward and inward oriented fluctuations of the same amplitude would produce a very low correlation as well. In addition, the rather complicated scenario at the base of the corona, where both kinetic and magnetic phenomena contribute to the birth of the wind, suggest that the imprints of such a structured corona is carried away by the wind during its expansion. At this point, we would expect that solar wind fluctuations would not solely be due to the ubiquitous Alfvénic and other MHD propagating modes but also to an underlying structure convected by the wind, not necessarily characterized by Alfvén-like correlations. Moreover, dynamical interactions between fast and slow wind, built up during the expansion, contribute to increase the compressibility of the medium.

It has been suggested that disturbances of the mean magnetic field intensity and plasma density act destructively on $\delta\mathbf{V} - \delta\mathbf{B}$ correlation. Bruno and Bavassano (1993) analyzed the loss of the Alfvénic character of interplanetary fluctuations in the inner heliosphere within the low frequency part of the Alfvénic range, i.e., between 2 and 10 h. Figure 5.9, from their work, shows the wind speed profile, σ_c, the correlation coefficients, phase and coherence for the three components (see Sect. 3.2.3), the angle between magnetic field and velocity minimum variance directions, and the heliocentric distance. Magnetic field sectors were rectified (see Sect. 4.1) and magnetic field and velocity components were rotated into the magnetic field minimum variance reference system (see Sect. 3.3.6). Although the three components behave in a similar way, the most Alfvénic ones are the two components Y and Z transverse to the minimum variance component X. As a matter of fact, for an Alfvén mode we would expect a high $\delta V - \delta B$ correlation, a phase close to zero for outward waves and a high coherence. Moreover, it is rather clear that the most Alfvénic intervals are located within the trailing edges of high velocity streams. However, as the radial distance increases, the Alfvénic character of the fluctuations decreases and the angle Θ_{bv} increases. The same authors found that high values of Θ_{bv} are associated with low values of σ_c and correspond to the most compressive intervals. They concluded that the depletion of the Alfvénic character of the fluctuations, within the hourly frequency range, might be driven by the interaction with static structures or magnetosonic perturbations able to modify the homogeneity of the background medium on spatial scales comparable to the wavelength of the Alfvénic fluctuations. A subsequent paper by Klein et al. (1993) showed that the $\delta\mathbf{V} - \delta\mathbf{B}$ decoupling increases with the plasma β, suggesting that in regions where the local magnetic field is less relevant, compressive events play a major role in this phenomenon.

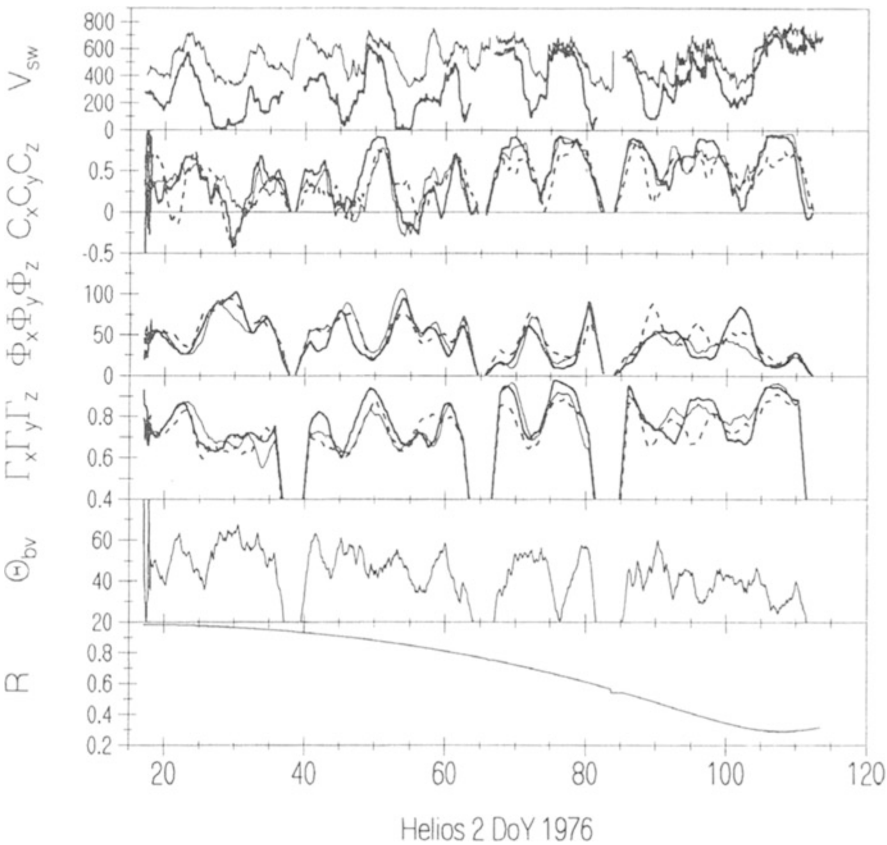

Fig. 5.9 Wind speed profile V and $|\sigma_c|V$ are shown in the *top panel*. The *lower three panels* refer to correlation coefficient, phase angle and coherence for the three components of δV and δB fluctuations, respectively. The *successive panel* indicates the value of the angle between magnetic field and velocity fluctuations minimum variance directions. The *bottom panel* refers to the heliocentric distance (from Bruno and Bavassano 1993)

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