Radial evolution of cross helicity in high-latitude solar wind

B. Breech,[1] W. H. Matthaeus,[1] J. Minnie,[2] S. Oughton,[3] S. Parhi,[1] J. W. Bieber,[1] and B. Bavassano[4]

Received 27 December 2004; revised 7 February 2005; accepted 23 February 2005; published 23 March 2005.

[1] We employ a turbulence transport theory to explain the high-latitude radial evolution of cross helicity, or Alfvénicity, observed by the Ulysses spacecraft. Evolution is slower than at low latitudes due to weakened shear driving. **Citation:** Breech, B., W. H. Matthaeus, J. Minnie, S. Oughton, S. Parhi, J. W. Bieber, and B. Bavassano (2005), Radial evolution of cross helicity in high-latitude solar wind, *Geophys. Res. Lett.*, *32*, L06103, doi:10.1029/2004GL022321.

1. Introduction

[2] The inner heliospheric solar wind is populated by magnetohydrodynamic (MHD) fluctuations that often exhibit a correlation of velocity and magnetic fluctuations similar to that of "outward propagating Alfvén waves." Here we examine the high-latitude radial variation of this correlation assuming it can be described by a shear-driven MHD turbulence formulation.

[3] Turbulence effects have been shown to account for many features of observed spectra of velocity and magnetic fluctuations from 0.3 AU (Helios apogee) to several AU [e.g., *Tu*, 1988]. Models for evolution of large scale fluctuations, which drive the smaller scale cascade, have accounted well for low-latitude radial evolution of turbulence energy density, correlation scale, and proton temperature, compared with Voyager and Pioneer data to 60 AU or more [*Zank et al.*, 1996; *Matthaeus et al.*, 1999; *Smith et al.*, 2001; *Isenberg et al.*, 2003]. A model of this type was employed recently to describe the low-latitude radial evolution of cross helicity [*Matthaeus et al.*, 2004]. So far, turbulence transport models have been tested only against low-latitude solar wind observations. A question that naturally arises—and one that represents a major challenge to the turbulence theory approach—is whether using similar parameters the same formalism can explain the very different evolution of solar wind fluctuations observed at high latitudes. In this Letter we address that issue, directly comparing turbulence transport theory with radial evolution of cross helicity and proton temperature observed by the Ulysses spacecraft.

[4] There are several possibilities for the origin of the "Alfvénic correlation," i.e., high correlation between plasma velocity fluctuations and magnetic field fluctuations. It might originate in the initial state of the solar wind, or it might be due to the tendency for growth of correlation known as "dynamic alignment" [*Dobrowolny et al.*, 1980; *Grappin et al.*, 1982]. In the inner heliosphere at low latitudes, it is thought that shear [*Roberts et al.*, 1992], associated with strong stream interactions, drives the turbulence towards lower cross helicity. This effect was quantified recently using a turbulence transport formalism [*Matthaeus et al.*, 2004]. High-latitude evolution of cross helicity has proven to be a matter of some debate. The high-latitude solar wind plasma remains Alfvénic to larger radial distance [*Goldstein et al.*, 1995], and there has been discussion [*Bavassano et al.*, 2000a, 2000b; *Grappin*, 2002; *Malara et al.*, 2000] concerning the cause of the observed slow(er) decrease in Alfvénicity. Perhaps cross helicity evolution might saturate in the region between 2 and 4 AU [*Bavassano et al.*, 2000a, 2000b]. Here we show that a turbulence transport theory, differing from that applied at low latitudes in a minimal and reasonable way, can account also for the radial evolution of cross helicity at high latitudes, in accord with Ulysses observations. The slowing of the decrease of cross helicity is attributed to the weaker shear driving at high latitudes.

2. Background, Model, and Parameters

[5] Several features of MHD turbulence are relevant to understanding the evolution of solar wind fluctuations. First, the general scenario of cascade and decay of homogeneous MHD turbulence is found to proceed in much the same way as in hydrodynamics [e.g., *Hossain et al.*, 1995]. Second, MHD cascades can be strongly anisotropic. Spectral transfer is stronger in the directions perpendicular to the large-scale mean magnetic field, and is weaker in the parallel direction, leading to relatively stronger cross-field gradients of magnetic, velocity, and small-scale density fluctuations [*Shebalin et al.*, 1983]. Third, for the weakly inhomogeneous solar wind flow, a generalization of WKB theory [*Zhou and Matthaeus*, 1990; *Marsch and Tu*, 1989; *Matthaeus et al.*, 1994b] describes the transport of "locally homogeneous" MHD turbulence. Fourth, for low plasma-frame Mach number the local turbulence can be described approximately by a nearly incompressible (NI) MHD theory [*Zank and Matthaeus*, 1992, 1993] in which the leading-order nonlinear effects are anisotropic and incompressible. These factors may be assembled into a quantitative description of turbulence transport and decay that, with some simplifications, can be applied to the solar wind in relatively tractable form [*Zank et al.*, 1996; *Matthaeus et al.*, 1999; *Smith et al.*, 2001; *Isenberg et al.*, 2003].

[6] To complete the picture, we include cross helicity effects, as well as sources of turbulence energy (driving). In

[1]Bartol Research Institute, University of Delaware, Newark, Delaware, USA.
[2]School of Physics, North-West University, Potchefstroom, South Africa.
[3]Department of Mathematics, University of Waikato, Hamilton, New Zealand.
[4]Istituto di Fisica dello Spazio Interplanetario, Consiglio Nazionale delle Ricerche, Rome, Italy.

0094-8276/05/2004GL022321$05.00

the absence of strong large-scale velocity shear, dynamic alignment [*Dobrowolny et al.*, 1980; *Pouquet et al.*, 1986] tends to increase the Alfvénicity, in the sense that the cross helicity $H_c = \frac{1}{2}\langle \mathbf{v} \cdot \mathbf{b} \rangle$ of the velocity $\mathbf{v}$ and magnetic field $\mathbf{b}$ fluctuations decreases more slowly than does the incompressible energy density (per unit mass) $E = \frac{1}{2}\langle |\mathbf{v}|^2 + |\mathbf{b}|^2 \rangle$. (Angle brackets denote an appropriate averaging procedure.) Quantitatively, dynamic alignment is signified by growth of the normalized cross helicity $\sigma_c = 2H_c/E = (Z_+^2 - Z_-^2)/(Z_+^2 + Z_-^2)$. The relationship to propagation effects becomes clear when one considers the Elsässer variables $\mathbf{z}_\pm = \mathbf{v} \pm \mathbf{b}$, and their respective "energies" $Z_\pm^2 = \langle |\mathbf{z}_\pm|^2 \rangle$. Shear driving generally supplies equal energy in "forward" (Z_+, say) and "backward" (Z_-) type fluctuations, which in linear theory are eigenmodes associated with unidirectional propagation. Hence shear driving opposes dynamic alignment, which on its own would act to increase the Alfvénicity.

[7] Here we will compare the predictions of a four-equation turbulence model with Ulysses observations of the radial decrease of normalized cross helicity and temperature. The turbulence model includes equations for turbulence energy $Z^2 = (Z_+^2 + Z_-^2)/2$, similarity or correlation lengthscale λ, temperature T, and normalized cross helicity σ_c. The equations are steady-state, and employ a uniform large-scale solar wind speed U and specified radial profiles for the Alfvén speed and density. Turbulence is considered to be locally homogeneous and incompressible, following an MHD adaptation of a Kármán–Taylor phenomenology [*Zank et al.*, 1996; *Matthaeus et al.*, 1996]. This results in four equations, one each for turbulence energy,

$$\frac{dZ^2}{dr} = -\frac{Z^2}{r} + \frac{C_{\text{sh}} - M\sigma_D}{r} Z^2 + \frac{\dot{E}_{PI}}{U} - \frac{\alpha}{\lambda U} f^+(\sigma_c) Z^3, \quad (1)$$

similarity lengthscale,

$$\frac{d\lambda}{dr} = \frac{M\sigma_D - \hat{C}_{\text{sh}}}{r}\lambda - \frac{\beta}{\alpha}\lambda \frac{\dot{E}_{PI}}{UZ^2} + \frac{\beta}{U} f^+(\sigma_c) Z, \quad (2)$$

normalized cross helicity,

$$\frac{d\sigma_c}{dr} = \alpha f'(\sigma_c)\frac{Z}{U\lambda} - \left[\frac{C_{\text{sh}} - M\sigma_D}{r} + \frac{\dot{E}_{PI}}{UZ^2}\right]\sigma_c, \quad (3)$$

and proton temperature,

$$\frac{dT}{dr} = -\frac{4}{3}\frac{T}{r} + \frac{1}{3}\frac{m_p}{k_B}\frac{\alpha}{U} f^+(\sigma_c)\frac{Z^3}{\lambda}. \quad (4)$$

The model depends upon various parameters, including Kármán–Taylor constants, chosen here as $\alpha = 2\beta = 0.8$, a mixing constant $M = 1/2$, and the normalized energy difference $\sigma_D = \langle |\mathbf{v}|^2 - |\mathbf{b}|^2 \rangle / 2E = -1/3$ (assumed constant) [see, e.g., *Matthaeus et al.*, 1996]. Turbulence is driven by two effects. First, large-scale shear instability supplies turbulence energy. This is represented by constants C_{sh} and $\hat{C}_{\text{sh}}$ that control the shear strength. (Here we take $\hat{C}_{\text{sh}} = 0$ appropriate to driving at roughly the correlation scale.) Second, scattering of ionized interstellar neutrals (pickup ions) supplies energy through wave-particle interactions, represented here by the term $\dot{E}_{PI}$. The form of pickup ion driving we employ is the same as by *Smith et al.* [2001] (for an updated form, see *Isenberg et al.* [2003]). Pickup ion driving of turbulence is important beyond 10 AU and is not the focus of the present study. Several cross helicity dependent quantities are also of importance, namely

$$f^\pm(\sigma_c) = \frac{(1-\sigma_c^2)^{1/2}}{2}\left[(1+\sigma_c)^{1/2} \pm (1-\sigma_c)^{1/2}\right], \quad (5)$$

and

$$f'(\sigma_c) = [\sigma_c f^+(\sigma_c) - f^-(\sigma_c)] \approx \frac{\sigma_c - \sigma_c^3}{2}. \quad (6)$$

[8] The main focus of the present paper is the radial evolution of normalized cross helicity σ_c. Using the approximation given in equation (6), we examine threshold estimates of the interplanetary conditions needed to account for the typical observation that σ_c decreases with increasing heliocentric distance [*Roberts et al.*, 1987]. Rearranging equation (3) we find

$$\frac{d\sigma_c}{dr} \approx \left[\frac{\alpha}{2}(1-\sigma_c^2)\frac{Z}{U\lambda} - \frac{C_{\text{sh}} - M\sigma_D}{r} - \frac{\dot{E}_{PI}}{UZ^2}\right]\sigma_c. \quad (7)$$

Thus, σ_c decays towards zero provided the square-bracketed term is negative. Consequently the observations require, approximately, that

$$C_{\text{sh}} - M\sigma_D + \frac{r\dot{E}_{PI}}{UZ^2} > \alpha\frac{(1-\sigma_c^2)}{2}\frac{rZ}{U\lambda}. \quad (8)$$

Note that usually $M\sigma_D \approx -1/6 \ll C_{\text{sh}}$ [*Matthaeus et al.*, 1994a]. In the middle heliosphere, say 0.3 AU < r < 10 AU, pickup ion effects are not important, and equation (8) simplifies to

$$C_{\text{sh}} > \alpha\frac{(1-\sigma_c^2)}{2}\frac{rZ}{U\lambda}. \quad (9)$$

The fraction $rZ/\lambda U$, interpretable as the ratio of the expansion and nonlinear timescales, is often of order unity in the solar wind. We see that there exists a threshold in shear strength above which σ_c decreases with radius.

[9] The shear constant is estimated using $\Delta U/\Delta r = C_{\text{sh}}\, U/r$ [*Zhou and Matthaeus*, 1990; *Zank et al.*, 1996]. The strength of shear driving of turbulence is expected to differ in low-latitude and high-latitude solar wind. In particular, a lower value of C_{sh} is expected in the high-latitude fast wind, due to the absence of large stream interfaces. In the wavy current sheet region within about 20–25° of the ecliptic plane, the plasma is stirred by shear at stream interfaces, where the flow speed changes by $\Delta U \sim 300$ km/s over a distance of $\Delta r \sim 0.02$ AU (a distance corresponding to flow at speed U for an observed ~10–20 hours). Various heuristic estimates can be constructed for averaging this (non-space filling) shear effect over a solar rotation, using the expected number of stream interfaces per rotation at solar minimum. It transpires that $C_{\text{sh}} \sim$ unity is justifiable and works well to account for solar wind turbulence evolution using equations similar to those above; see, for example, *Matthaeus et al.* [2004], who used $C_{\text{sh}} = 1.5$.

[10] At high latitudes (>30°) large stream interaction regions are absent; instead a very stable (solar minimum) pattern of microstreams is observed [*Neugebauer et al.*, 1995], with $\Delta U \sim 100$ km/sec changes encountered approximately once per day. While these can be assumed to be

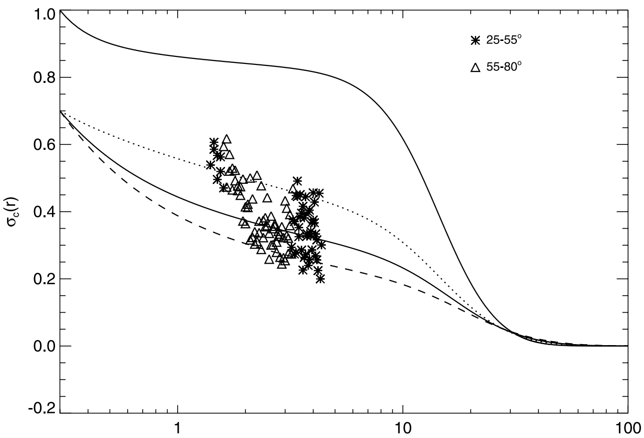

Figure 1. Radial evolution of normalized cross helicity σ_c at high latitudes. Observational points from Ulysses data in two latitude bands (see legend). Three solutions for $\sigma_c(r)$ from the transport equations are shown, for a fixed latitude of 75° and varying values of turbulence level and correlation scale at the boundary: Dotted curve: Z^2 = 10000 km^2 s^{-2} and λ = 0.02 AU; Solid curve: Z^2 = 6000 km^2 s^{-2} and λ = 0.04 AU; Dashed curve Z^2 = 4500 km^2 s^{-2} and λ = 0.07 AU. All other parameters are fixed. Appropriate to high latitudes [*McComas et al.*, 2000], we take U = 774 km/s and an Alfvén speed at 1 AU of 51 km/s. The proton number density, n = 2.38 cm^{-3} at 1 AU, varies as $1/r^2$. The driving parameters are $C_{\rm sh}$ = 0.5 and $M\sigma_D = -1/6$, with a standard pickup driving term [*Smith et al.*, 2001]. The Kármán–Taylor constants are α = 0.8, β = 0.4. Note that higher Z^2 and higher λ at the inner boundary produces more rapid radial decrease of σ_c. An additional solution (upper solid line) has similar inner boundary conditions except that the cross helicity is maximal and shear is weaker (Z^2 = 10000 km^2 s^{-2}, λ = 0.015 AU, σ_c = 1.0 and $C_{\rm sh}$ = 0.2.) This may be appropriate to higher Alfvénicity found in a more pure stream with very low shear.

space-filling, the velocity change is only $\approx$1/8 of the faster $U \sim$ 770 km/sec wind, and 1 encounter/day corresponds to a shear layer thickness of about 0.25 AU. This gives a roughly estimated value of $C_{\rm sh} \approx 1/2$ for high latitudes, and the expectation of a lesser effect of large-scale shear on turbulence for higher-latitude wind.

3. Ulysses Analysis and Results

[11] The Ulysses mission has explored the solar wind between 1.5 AU and 4.5 AU, reaching high latitude (>80°) during two polar passes [*McComas et al.*, 2000]. The persistence of Alfvénic fluctuations in Ulysses data to large radial distances [*Goldstein et al.*, 1995] is anticipated by the similar property of low-latitude high-speed intervals [*Bavassano et al.*, 1982a, 1982b]. At high latitude [*Bavassano et al.*, 2000a, 2000b] cross helicity decreases with radius, but more slowly [*Roberts et al.*, 1987]. While there has been some debate [*Bavassano et al.*, 2002; *Grappin*, 2002] about possible high-latitude variations, there seems little doubt that the radial variation of cross helicity differs at high and low latitudes.

[12] We use data from [*Bavassano et al.*, 2000a, 2000b] to compare Ulysses cross helicity evolution with solutions of the transport equations (1)–(4). Figure 1 shows hourly σ_c values computed from Ulysses data. There is no attempt to examine systematic variation with latitude—we plot values of σ_c for two ranges of latitude (moderately high 25–55° and very high 55–80°). All points have θ > 25°.

[13] We recall the suggestion [*Bavassano et al.*, 2000a, 2000b] that the cross helicity saturates, i.e., approaches a terminal nonzero value in the high-latitude wind. This tendency is apparent in Figure 1: Between 1.5 AU and 3 AU there is a downward trend. However there is weaker downward trend for data beyond 3 AU. Note the substantial spread in observed values of $\sigma_c(r)$ near any r.

[14] Three solutions for $\sigma_c(r)$ from the theory, equations (1)–(4), are compared with the Ulysses data in Figure 1. The three solutions differ in the imposed inner boundary values for the turbulence amplitude Z^2 and the correlation scale λ. Other model parameters are fixed, and differ from reasonable low-latitude values in a minimal way. Relative to low-latitude solutions [*Matthaeus et al.*, 2004] the Figure 1 solutions employ lower $C_{\rm sh}$, higher solar wind speed, and lower density [*McComas et al.*, 2000]. The three solutions show that a moderate (and realistic) variation of inner boundary values produces theoretical curves that vary in a way that is comparable to the scatter in the Ulysses data.

[15] A fourth solution is also shown, with identical parameters, except that σ_c = 1.0 (maximal value) at the inner boundary, and $C_{\rm sh}$ was reduced. This solution represents a pure Alfvénic stream, with higher σ_c, as might be inferred from some studies [e.g., *Goldstein et al.*, 1995].

4. Discussion and Conclusions

[16] These new theoretical solutions for $\sigma_c(r)$ account well for the Ulysses observations, and show a general decrease with increasing heliocentric distance that is gentler than that seen in the low-latitude solar wind. A modest variation of turbulence energy and correlation scale, imposed at the inner boundary, produces theoretical curves that span the scatter of the Ulysses data. The radial decrease of $\sigma_c(r)$ in the theoretical solutions has a flatter slope in the range of distances from one to several AU, consistent with [*Bavassano et al.*, 2000a, 2000b] a slowing in the rate of disappearance of Alfvénicity. This is associated with the weaker shear in the high-latitude solutions (see equations (7)–(9)), since that decreases the margin by which decay of cross helicity overcomes the native tendency of MHD turbulence to amplify cross helicity. There is the interesting possibility that dynamic alignment (increase in Alfvénicity) might occur in the outlying regions of the heliosphere, where (shear) driving may be weaker still.

[17] It is beyond the scope of the present paper to explore fully the implications of the turbulence solutions at both high and low latitudes. However we have shown that the turbulence transport formalism, previously applied only at lower latitudes in slow solar wind, appears to work equally well in describing cross helicity decay in the fast Alfvénic wind. A full comparison with Ulysses data and a detailed comparison of high- and low-latitude solutions will be presented in the near future. To corroborate the present

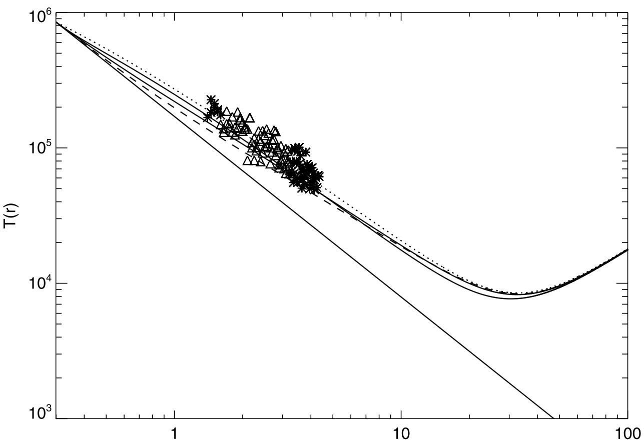

Figure 2. Radial evolution (in AU) of proton temperature $T(r)$ from Ulysses observations, compared with the same four turbulence solutions as shown in Figure 1. For reference, cooling due to adiabatic expansion is also shown (straight solid line).

result we show in Figure 2 the solutions for the proton temperature for the same solutions as in Figure 1, and compare them with Ulysses temperature observations. One sees, once again, that the theoretical curves compare well with the observations, with the three theoretical curves again spanning a range of values comparable to the scatter of Ulysses observations at a given heliocentric distance. Thus, as in the low-latitude case [*Smith et al.*, 2001], the theory can account simultaneously for the steady radial dependence of several key turbulence parameters, while also providing an approach to studying the variability of solar wind fluctuations.

[18] **Acknowledgments.** This research is supported in part by NSF grants ATM-0105254 and ATM-0000315, and NASA grants NAG5-11603, NAG5-6570, NAG5-10911 and NNG04GF81G. Partial support for SO is provided by a grant from the NZ Marsden Fund (02-UOW-050 MIS). BB partially supported by the Italian Space Agency (ASI) under contract IR/064. JM supported by National Research Foundation grant number 2063412.

References

Bavassano, B., M. Dobrowolny, G. Fanfoni, F. Mariani, and N. F. Ness (1982a), Statistical properties of MHD fluctuations associated with high-speed streams from Helios-2 observations, *Solar Phys.*, *78*, 373.

Bavassano, B., M. Dobrowolny, F. Mariani, and N. F. Ness (1982b), Radial evolution of power spectra of interplanetary Alfvénic turbulence, *J. Geophys. Res.*, *87*, 3617.

Bavassano, B., E. Pietropaolo, and R. Bruno (2000a), Alfvénic turbulence in the polar wind: A statistical study on cross helicity and residual energy variations, *J. Geophys. Res.*, *105*, 12,697.

Bavassano, B., E. Pietropaolo, and R. Bruno (2000b), On the evolution of outward and inward Alfvénic fluctuations in the polar wind, *J. Geophys. Res.*, *105*, 15,959.

Bavassano, B., E. Pietropaolo, and R. Bruno (2002), Alfvnic turbulence in high-latitude solar wind: Radial versus latitudinal variations, *J. Geophys. Res.*, *107*(A12), 1452, doi:10.1029/2002JA009267.

Dobrowolny, M., A. Mangeney, and P. Veltri (1980), Fully developed anisotropic hydromagnetic turbulence in interplanetary space, *Phys. Rev. Lett.*, *45*, 144.

Goldstein, B. E., E. J. Smith, A. Balogh, T. S. Horbury, M. L. Goldstein, and D. A. Roberts (1995), Properties of magnetohydrodynamic turbulence in the solar wind as observed by Ulysses at high heliographic latitudes, *Geophys. Rev. Lett.*, *22*, 3393.

Grappin, R. (2002), Comment on "Alfvnic turbulence in the polar wind: A statistical study on cross helicity and residual energy variations" by B. Bavassano et al., *J. Geophys. Res.*, *107*(A9), 1247, doi:10.1029/2001JA005058.

Grappin, R., U. Frisch, J. Léorat, and A. Pouquet (1982), Alfvénic fluctuations as asymptotic states of MHD turbulence, *Astron. Astrophys.*, *105*, 6.

Hossain, M., P. C. Gray, D. H. Pontius Jr., W. H. Matthaeus, and S. Oughton (1995), Phenomenology for the decay of energy-containing eddies in homogeneous MHD turbulence, *Phys. Fluids*, *7*, 2886.

Isenberg, P. A., C. W. Smith, and W. H. Matthaeus (2003), Turbulent heating of the distant solar wind by interstellar pickup protons, *Astrophys. J.*, *592*, 564.

Malara, F., P. Petkaki, and P. Veltri (2000), Dissipation of Alfvén waves in force-free magnetic fields: Competition between phase mixing and three-dimensional effects, *Astrophys. J.*, *533*, 523.

Marsch, E., and C.-Y. Tu (1989), Dynamics of correlation functions with Elsässer variables for inhomogeneous MHD turbulence, *J. Plasma Phys.*, *41*, 479.

Matthaeus, W. H., S. Oughton, D. Pontius, and Y. Zhou (1994a), Evolution of energy containing turbulent eddies in the solar wind, *J. Geophys. Res.*, *99*, 19,267.

Matthaeus, W. H., Y. Zhou, G. P. Zank, and S. Oughton (1994b), Transport theory and the WKB approximation for interplanetary MHD fluctuations, *J. Geophys. Res.*, *99*, 23,421.

Matthaeus, W. H., G. P. Zank, and S. Oughton (1996), Phenomenology of hydromagnetic turbulence in a uniformly expanding medium, *J. Plasma Phys.*, *56*, 659.

Matthaeus, W. H., G. P. Zank, C. W. Smith, and S. Oughton (1999), Turbulence, spatial transport, and heating of the solar wind, *Phys. Rev. Lett.*, *82*, 3444.

Matthaeus, W. H., J. Minnie, B. Breech, S. Parhi, J. W. Bieber, and S. Oughton (2004), Transport of cross helicity and the radial evolution of Alfvénicity in the solar wind, *Geophys. Rev. Lett.*, *31*, L12803, doi:10.1029/2004GL019645.

McComas, D. J., B. L. Barraclough, H. O. Funsten, J. T. Gosling, E. Santiago-Muñoz, R. M. Skoug, B. E. Goldstein, M. Neugebauer, P. Riley, and A. Balogh (2000), Solar wind observations over Ulysses' first full polar orbit, *J. Geophys. Res.*, *105*, 10,419.

Neugebauer, M., B. E. Goldstein, D. J. McComas, S. T. Suess, and A. Balogh (1995), Ulysses observations of microstreams in the solar wind from coronal holes, *J. Geophys. Res.*, *100*, 23,389.

Pouquet, A., M. Meneguzzi, and U. Frisch (1986), Growth of correlations in magnetohydrodynamic turbulence, *Phys. Rev. A*, *33*, 4266.

Roberts, D. A., M. L. Goldstein, L. W. Klein, and W. H. Matthaeus (1987), Origin and evolution of fluctuations in the solar wind: Helios observations and Helios-Voyager comparisons, *J. Geophys. Res.*, *92*, 12,023.

Roberts, D. A., M. L. Goldstein, W. H. Matthaeus, and S. Ghosh (1992), Velocity shear generation of solar wind turbulence, *J. Geophys. Res.*, *97*, 17,115.

Shebalin, J. V., W. H. Matthaeus, and D. Montgomery (1983), Anisotropy in MHD turbulence due to a mean magnetic field, *J. Plasma Phys.*, *29*, 525.

Smith, C. W., W. H. Matthaeus, G. P. Zank, N. F. Ness, S. Oughton, and J. D. Richardson (2001), Heating of the low-latitude solar wind by dissipation of turbulent magnetic fluctuations, *J. Geophys. Res.*, *106*, 8253.

Tu, C.-Y. (1988), The damping of interplanetary Alfvénic fluctuations and the heating of the solar wind, *J. Geophys. Res.*, *93*, 7.

Zank, G. P., and W. H. Matthaeus (1992), Waves and turbulence in the solar wind, *J. Geophys. Res.*, *97*, 17,189.

Zank, G. P., and W. H. Matthaeus (1993), Nearly incompressible fluids. II: Magnetohydrodynamics, turbulence, and waves, *Phys. Fluids A*, *5*, 257.

Zank, G. P., W. H. Matthaeus, and C. W. Smith (1996), Evolution of turbulent magnetic fluctuation power with heliocentric distance, *J. Geophys. Res.*, *101*, 17,093.

Zhou, Y., and W. H. Matthaeus (1990), Transport and turbulence modeling of solar wind fluctuations, *J. Geophys. Res.*, *95*, 10,291.

B. Bavassano, Istituto di Fisica dello Spazio Interplanetario, Consiglio Nazionale delle Ricerche, I-00133 Rome, Italy.

J. W. Bieber, B. Breech, W. H. Matthaeus, and S. Parhi, Bartol Research Institute, University of Delaware, Newark, DE 19716, USA. (yswhm@bartol.udel.edu)

J. Minnie, School of Physics, North-West University, 2520 Potchefstroom, South Africa.

S. Oughton, Department of Mathematics, University of Waikato, Hamilton, New Zealand.