GTP Workshop on
Modeling MHD Turbulence; Applications to Planetary and Stellar dynamos
at NCAR, 27-30 June, 2006, Boulder, CO, USA

Turbulence Throughout the Heliosphere

W. H. Matthaeus
[1] *Bartol Research Institute and Department of Physics and Astronomy, University of Delaware*

While the details of the origin of the solar wind in the lower corona remain a puzzle, the supersonic solar wind and the turbulent fluctuations carried with it have become one of the best studied cases of strong plasma turbulence, often examined in the magnetohydrodynamic (MHD) approximation. A natural laboratory for MHD turbulence, the solar wind is a testing ground for ideas about evolution and cascade of turbulence, and for studying turbulence effects such as heating, anisotropy, and scattering of charged test particles.

Here we review the basic features of the large scale and turbulent solar wind, focusing on development of theory to explain the observations. This has led to the prospect of developing a predictive theory that explains the large scale evolution of MHD turbulence throughout the heliosphere. This framework is needed if we are to understand the solar system plasma environment, including, e.g., the transport of solar energetic particles [1], or the distribution of galactic cosmic rays in the solar system.[2] Heliospheric effects of turbulence are frequently associated with the elevated rate of energy dissipation associated with turbulence [8] and the impact of turbulence on transport properties of energetic particles in a low-collisionality plasma. [3]

The framework for describing the transport and dissipation of MHD turbulence in the heliosphere has been developed beginning from basic studies of MHD turbulence [6], along with the extensive observational characterizations of solar wind fluctuations [7]. These weakly compressible fluctuations show both turbulence and wave properties, e.g., in the form of powerlaw spectra [4] and the Alfvénic correlation [5]. Furthermore the anisotropy associated with a mean (DC) magnetic field [9] suggests that the hydrodynamic limit [8], in which the mean field weakly influences cascade rates [10], is appropriate. In addition, of the various relaxation processes available to MHD flows [11, 12], most evidence suggests those associated with cross helicity and Alfvénic couplings [13] are most relevant, even though observations, somewhat paradoxically, indicate decrease of Alfvenicity with heliocentric distance. [14]

We proceed by developing a two scale theory of transport, not unlike engineering models of hydrodynamic turbulence (e.g., [15]) and much simpler than approaches based on two point closures of turbulence. [16] Formally one can proceed algebraically beginning with transport equations for correlation functions or spectra [17, 18], and develop these into equations for the evolution of turbulence energy and the correlation (similarity) scale. This produces as two equation model [19] that can be supplemented by a temperature equation that includes deposition of internal energy (heating) due to turbulence decay [20]; such models show good agreement with observations in the ecliptic plane from 1AU to beyond 60 AU. [21] Notably, the variability of the conditions at 1AU, used as boundary conditions, has a significant effect on the solutions in the outer heliosphere, and including this intrinsic variability is needed to account for the observations.

To extend these models to the inner heliosphere and to high latitudes, it is necessary to modify the phenomenology to include cross helicity effects [22] and to delve into the latitudinal variation of turbulence parameters and boundary conditions [23]. Again these parameters are constrained by observations, especially Ulysses at high latitudes [25]. It transpires that with a minimal accounting for latitudinal effects, one can produce a single theory that agrees well with observations of turbulence energy, correlation scale, cross helicity and temperature, for the entire range of observed heliocentric distances and latitudes. On this basis, we present preliminary results of model computations that account for turbulence at all positions in the heliosphere, and we view that the theory is now prepared for use in more advanced three dimensional heliospheric models, such as are pertinent to solar modulation of galactic cosmic rays. While the present models remain axisymmetric, some progress has been made in using time variable boundary conditions. [24]

This research is supported in part by grants from NASA (NNG04GA54G, NNG05GG83G) and the NSF (ATM-0539995).

References

[1] J. W. Bieber, W. H. Matthaeus, C. W. Smith, W. Wanner, M. Kallenrode, and G. Wibberenz. *Astrophys. J.*, **420**:294, 1994.

[2] S. Parhi, J. W. Bieber, R. A. Burger and W. H. Matthaeus, *Astrophys. J* **585**, 502 (2003)

[3] G. P. Zank, W. H. Matthaeus, J. W. Bieber, and H. Moraal. *J. Geophys. Res.*, **103**:2085, 1998.

[4] Paul J. Coleman. *Phys. Rev. Lett.*, **17**:207, 1966.

[5] J. W. Belcher and L. Davis Jr. *J. Geophys. Res.*, **76**:3534, 1971.

[6] D. C. Montgomery. Theory of hydrodmagnetic turbulence. In *Proceedings of Solar Wind 5*, page 107. NASA Conference Publication 2280, 1983.

[7] C.-Y. Tu and E. Marsch, MHD Structures, Waves and Turbulence in the Solar Wind, Kluwer, Dordrecht, Netherlands, 1995.

[8] T. von Kármán and L. Howarth. *Proc. Roy. Soc. London Ser. A*, **164**:192, 1938.

[9] J. Shebalin and W. H. Matthaeus and D. Montgomery, *J. Plasma Phys.*, **29**, 525 (1983)

[10] M. Hossain, P C Gray, D. Pontius, W H Matthaeus, and S. Oughton, *Phys. Fluids*, **7**, 2886 (1995)

[11] A C. Ting, W H Matthaeus, and D C Montgomery. *Phys. Fluids*, **29**:3261, 1986.

[12] T. Stribling and W. H. Matthaeus. *Phys. Fluids B*, **3**:1848, 1991.

[13] M. Dobrowolny, A. Mangeney, and P. Veltri. *Phys. Rev. Lett.*, **45**:144, 1980.

[14] D A Roberts, M L Goldstein, L W Klein, and W H Matthaeus, *J. Geophys. Res.* **92**,12 023 (1987)

[15] P. Bradshaw, T. Cebeci, and J.H. Whitelaw. *Engineering Calculation Methods for Turbulent Flow.* Academic Press, London, U.K., 1981.

[16] A. Yoshizawa. *Phys. Fluids*, **B2**:1589, 1990.

[17] Eckart Marsch and Chuan-Yi Tu. *J. Plasma Phys.*, **41**:479, 1989.

[18] Y. Zhou and W. H. Matthaeus. *J. Geophys. Res.*, **95**:10 291, 1990.

[19] G. P. Zank, W. H. Matthaeus, and C. W. Smith. *J. Geophys. Res.*, **101**:17 093, 1996.

[20] W. H. Matthaeus, G. P. Zank, C. W. Smith, and S. Oughton. *Phys. Rev. Lett.*, **82**, 3444, 1999.

[21] C. W. Smith, W. H. Matthaeus, G. P. Zank, N. F. Ness, S. Oughton, and J. D. Richardson. *J. Geophys. Res.*, **106** 8253, 2001.

[22] W. H. Matthaeus, J. Minnie, B. Breech, S. Parhi, J. W. Bieber, and S. Oughton, *Geophys. Res. Lett.* **31** L12803 (2004)

[23] B. Breech, W.H. Matthaeus, J.Minnie, S.Oughton, S. Parhi, J.W. Bieber and B. Bavassano, *Geophys. Res. Lett.* **32** L06103 (2005)

[24] C. W. Smith, P. A. Isenberg and W. H. Matthaeus, *Ap. J.* **638**, 508 (2006)

[25] D. J. McComas et al, *J. Geophys. Res.*, **105**, 10419 (2000)