*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-5.068 (2009)*

Evolving magnetohydrodynamic turbulence in the quiet fast solar wind

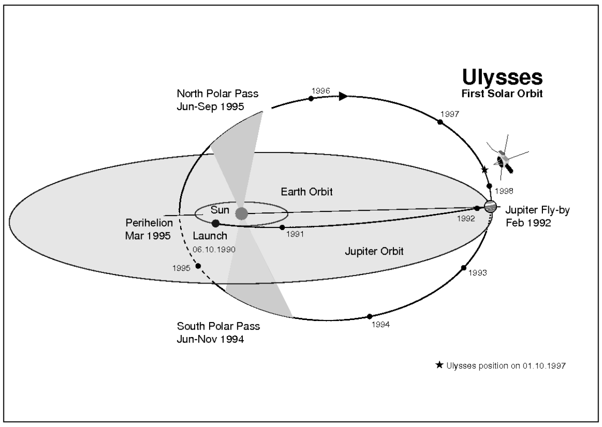
R. M. Nicol[1], S.C. Chapman[1], R. O. Dendy[1,2]

[1] *Centre for Fusion, Space and Astrophysics, Department of Physics, University of Warwick, Coventry, CV4 7AL, UK*

[2] *UKAEA Culham Division, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK*

The solar wind provides unique opportunities for long duration *in situ* studies of magnetohydrodynamic turbulence in a plasma flowing supersonically with high magnetic Reynolds number. Its spectral power density scales approximately as inverse frequency f^{-1} at lower frequencies ($\leq$ 1 mHz); and as $f^{-5/3}$, reminiscent of Kolmogorov's inertial range [Kolmogorov(1941)], at higher frequencies ($\sim$ 10100 mHz). The frequency at which the transition between power laws occurs ($\sim$ 110 mHz) is observed to decline with increasing heliocentric distance in the plane of the ecliptic, and this extension of the $f^{-5/3}$ range at greater distances can be interpreted as evidence for an evolving turbulent cascade. The f^{-1} range is taken to reflect embedded solar coronal turbulence, convected with the solar wind.
In the present paper we concentrate on the quiet fast solar wind, where large transient events, such as those associated with coronal mass ejections, are absent. We exploit the unique out-of-ecliptic orbit of the Ulysses satellite, shown in Figure 1, by focusing on its measurements of fluctuations in the three vector components of the magnetic field **B** in the RTN coordinate system, taken above polar solar coronal holes at times of both minimum (1994-1995) and maximum (2000-2001) solar activity. By applying generalised structure function analysis to this data, combined with extended self-similarity [Benzi et al.(1993)], we address [Nicol et al.(2008)] key nonlinear plasma physics and MHD turbulence issues. These include: the extent to which the f^{-1} spectrum contains frozen information about coronal magnetic activity; the interplay between the coronal driver and the evolving inertial range turbulence; the degree to which the fluctuations exhibit self-similarity; and the dependence of the foregoing on heliocentric latitude and radial distance.

In Figure 2 we see that the power spectra show an inertial range with a Kolmogorov-like behavior at higher frequencies and a characteristic flattening of the spectra at lower frequencies. The existence of this regime is well-known in many physical processes [Bak et al.(1987)], and also the interplanetary magnetic field [Matthaeus & Goldstein(1986), Matthaeus et al.(2007)]. The power spectra reveal power law scaling, but give no information on intermittency or on whether the turbulent cascade is active; for this we turn to the associated GSFs.



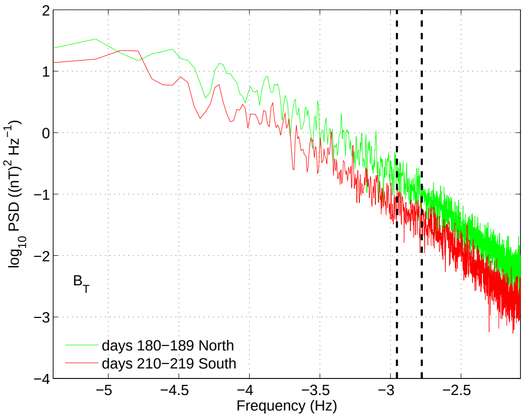


Figure 1: Ulysses orbit (plot courtesy of http://ulysses-ops.jpl.esa.int/ulysses/resources_galleryorbit.html): 1990 – 1995. South polar pass: from days 210 to 269, 1994. Ulysses moved from 2.6141 AU to 2.2014 AU and from an heliographic latitude of $-75.17°$ to $-79.60°$. North polar pass: from days 180 to 239, 1995. Ulysses moved from 1.7926 AU to 2.2043 AU and from an heliographic latitude of $73.76°$ to $77.03°$.

Figure 2: Ulysses tangential magnetic field power spectrum for days 210 – 219, 1994 (South polar pass, red) and days 180 – 189, 1995 (North polar pass, green).

Generally speaking, a time series $y(t)$ exhibits scaling [Sornette(2004)], if

$$\langle |y(t+\tau) - y(t)|^m \rangle \sim \tau^{\zeta(m)} \tag{1}$$

Here the angular brackets denote an ensemble average over t, implying an assumption of approximate stationarity, the scaling is contained in the $\zeta(m)$ scaling exponents. We test equation (1) by computing the associated generalized structure functions or GSF, see for example [Burlaga & Klein(1986), Horbury & Balogh(1997)]:

$$S_m(\tau) = \langle |y(t+\tau) - y(t)|^m \rangle = \langle |\delta y|^m \rangle \tag{2}$$

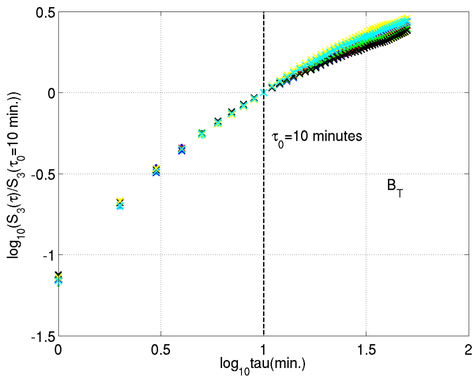
In practice, the scaling in equation (1) is not always found. However, a weaker form of scaling, known as extended self-similarity (ESS) [Benzi et al.(1993)] turns out to be applicable to our datasets. ESS proceeds by replacing τ in equation (1) by an initially unknown generalized timescale $g(\tau)$, such that formally

$$S_m(\tau) \sim [g(\tau)]^{\zeta(m)} \tag{3}$$

It follows from equation (3) that

$$S_m(\tau) = [S_{m'}(\tau)]^{\zeta(m)/\zeta(m')} \tag{4}$$

[Grossmann et al.(1997), Pagel & Balogh(2001)]. The measured vector magnetic field time series, $\mathbf{B}(t)$, is differenced for time lags τ in the range 1 minute to 50 minutes, yielding a series $\delta y_i(t,\tau)$ for its three components. We will focus here on the T component GSF and ESS plots shown in Figures 3 and 4.



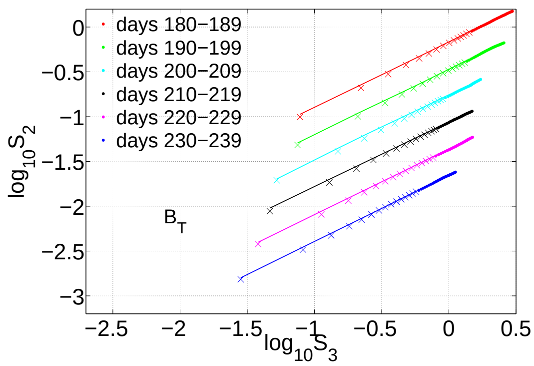


Figure 3: Third order GSF S_3 of the T component of magnetic field plotted versus differencing timescale τ on log-log axes, for all twelve 10 day intervals during Ulysses South ("$\times$") and North ("·") polar passes. Each trace is normalized to $S_3(\tau = 10\ min.)$

Figure 4: Evidence for extended self-similarity (ESS) fitted across the IR ($\tau = 2$ to $\tau = 14$ min.) range. Log-log plots of second order structure function S_2 versus third order structure function S_3 for the T component of magnetic field fluctuations during contiguous 10 day intervals, from day 180 to day 239 of 1995. The different intervals have been uniformly shifted in the y-direction for clarity.

Figure 3 shows that GSF analysis is sufficient to reveal power law scaling in the low frequency "$1/f$" range but not in the inertial range. However when the S_3 for the different time intervals are overlayed in Figure 3 at a common τ, here chosen at $\tau = 10$ minutes, the inertial range scaling has a similar behaviour for all considered intervals. This implies a common $g(\tau)$ dependence, independent of small radial and latitudinal variations. We test this further in Figure 4 by applying ESS to the data. The linear behaviour of the ESS traces in Figure 4 confirms scaling in the inertial range of the form $\langle|y(t+\tau)-y(t)|^m\rangle \sim [g(\tau)]^{\zeta(m)}$. We find that a good fit for $g(\tau)$ is

$$g(\tau) \sim \tau^{-log_{10}(\tilde{\lambda}\tau)},\ \tilde{\lambda} = 10^{-7.575\pm0.246} \quad (5)$$

To summarize, we have analysed Ulysses quiet fast polar solar wind magnetic field measurements to study the evolving turbulence for both North and South polar passes [Nicol et al.(2008), Chapman et al.(2009)]. Over contiguous 10 day intervals, we quantify the scaling behavior of both the inertial range and the lower frequency "f^{-1}" range present in the solar wind. We use generalized structure functions (GSF) and extended self-similarity (ESS) to quantify statistical scaling, and find that GSF is sufficient to reveal power law scaling in the low frequency "f^{-1}" range, but ESS is necessary to reveal scaling in the inertial range. The "f^{-1}" range scaling varies in a non secular way with spacecraft position as found previously [Horbury et al.(1995a)]. This is consistent with a coronal origin for the "f^{-1}" scaling. In contrast, in the inertial range, comparisons of the third order structure function S_3 for the different time intervals show that $g(\tau)$ is independent of spacecraft position. A good fit to the inertial range is $g(\tau) \sim \tau^{-log_{10}(\tilde{\lambda}\tau)}$, where $\tilde{\lambda} = 10^{-7.575 \pm 0.246}$.

Our results clearly differentiate between the dynamics of the fluctuations seen in the "f^{-1}" and in the inertial range. Our function $g(\tau)$ for the inertial range scaling may be the signature of the evolution of the turbulence observed at Ulysses, reflecting both the heating of the fast solar wind at the corona and the subsequent expansion in the presence of the large scale solar magnetic field.

References

[Bak et al.(1987)] Bak, P., Tang, C., & Wiesenfeld, K. 1987, Phys. Rev. Lett., 59, 381

[Benzi et al.(1993)] Benzi, R., Ciliberto, S., Tripiccione, R., Baudet, C., Massaioli, F., & Succi, S. 1993, Phys. Rev. E., 48, 29

[Burlaga & Klein(1986)] Burlaga, L. F., & Klein, L. W. 1986, J. Geophys. Res., 91, 347

[Chapman et al.(2009)] Chapman, S. C., Nicol, R. M., Leonardis, E., Kiyani, K., & Carbone, V. 2009, ApJ Lett., 695, L185

[Frisch(1995)] Frisch, U. 1995, Turbulence : the legacy of A. N. Kolmogorov, 2nd ed. by Uriel Frisch. Cambridge University Press. Cambridge, 1995,

[Grossmann et al.(1997)] Grossmann, S., Lohse, D., & Reeh, A. 1997, Phys. Rev. E., 56, 5473

[Horbury et al.(1995a)] Horbury, T., Balogh, A., Forsyth, R. J., & Smith, E. J. 1995a, Annales Geophysicae, 13, 105

[Horbury & Balogh(1997)] Horbury, T. S., & Balogh, A. 1997, Nonlinear Processes in Geophysics, 4, 185

[Kolmogorov(1941)] Kolmogorov, A. 1941, Akademiia Nauk SSSR Doklady, 30, 301, This translation by Levin, V.

[Matthaeus & Goldstein(1986)] Matthaeus, W. H., & Goldstein, M. L. 1986, Phys. Rev. Lett., 57, 495

[Matthaeus et al.(2007)] Matthaeus, W. H., Breech, B., Dmitruk, P., Bemporad, A., Poletto, G., Velli, M., & Romoli, M. 2007, ApJl, 657, L121

[Nicol et al.(2008)] Nicol, R. M., Chapman, S. C., & Dendy, R. O. 2008, ApJ, 679, 862

[Pagel & Balogh(2001)] Pagel, C., & Balogh, A. 2001, Nonlinear Processes in Geophysics, 8, 313

[Sornette(2004)] Sornette, D. 2004, Critical phenomena in natural sciences : chaos, fractals, selforganization and disorder : concepts and tools, 2nd ed. by Didier Sornette. Springer series in synergetics. Heidelberg: Springer, 2004,