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Scaling Anisotropy of the Power in Parallel and Perpendicular Components of the Solar Wind Magnetic Field

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Abstract. Power spectra of the components of the magnetic field parallel (P_{zz}) and perpendicular ($P_{xx}+P_{yy}$) to the local mean magnetic field direction were determined by wavelet methods from Ulysses' MAG instrument data during eighteen 10-day segments of its first North Polar pass at high latitude at solar minimum in 1995. The power depends on frequency f and the angle θ between the solar wind direction and the local mean field, and with distance from the Sun. This data includes the solar wind whose total power ($P_{xx} + P_{yy} + P_{zz}$) in magnetic fluctuations we previously reported depends on f and the angle θ nearly as predicted by the GS95 critical balance model of strong incompressible MHD turbulence. Results at much wider range of frequencies during six evenly-spaced 10-day periods are presented here to illustrate the variability and evolution with distance from the Sun. Here we investigate the anisotropic scaling of $P_{zz}(f,\theta)$ in particular because it is a reduced form of the Poloidal (pseudo-Alfvenic) component of the (incompressible) fluctuations. We also report the much larger $P_{xx}(f,\theta)+P_{yy}(f,\theta)$ which is (mostly) reduced from the Toroidal (Alfvenic, i.e, perpendicular to both **B** and **k**) fluctuations, and comprises most of the total power. These different components of the total power evolve and scale differently in the inertial range. We compare these elements of the magnetic power spectral tensor with "critical balance" model predictions.

Keywords: Plasma turbulence, Magnetohydrodynamics and plasmas in astrophysics, Interplanetary magnetic fields, MHD waves; plasmawaves, turbulence
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INTRODUCTION

Fast solar wind from the poles of the Sun is an excellent example of MHD turbulence, with the fluctuations being approximately incompressible [1,2]. The *Ulysses* spacecraft provides a unique data set with extended periods in this continuous fast polar solar wind [3] and high cadence magnetic field data [4]. Such observations allow us to investigate how turbulence makes the nominally collisionless solar wind behave like a gas with shocks and structures, and why superthermal particles and cosmic rays appear to be diffusively coupled to the solar wind, allowing exchange of energy. The details of that coupling are not yet understood completely, and the poorly understood anisotropy of the turbulence is a part of the problem.

Measurements of magnetic power as a function of frequency using the *Ulysses* data have clearly shown the importance of the magnetic field direction in the turbulence [5,6,7,8,9,10], with different power amplitudes and spectral indices depending on the angle θ_B between the solar wind flow velocity and the local mean magnetic field. Attempts have been made to choose between theories of anisotropic turbulent cascades [e.g., 10, 11; 12; 13] by observing the scaling of the total power at different angles to the mean field [14]. In [9] we examined how the power spectral tensor $Pij(f, \theta_B)$ at one frequency (f=0.098 Hz) depended on the direction of the local mean magnetic field, and how the observed $Pij(f, \theta_B)$ is a "reduced" version of the general tensor form of incompressible turbulence $Pij(\mathbf{k})$ [5]. In [14] we concluded that the Goldreich-Sridar [10,11] critical balance model of anisotropic MHD turbulence was a good fit to the *Ulysses* observations of total power in magnetic fluctuations between about 0.01 and 0.1 Hz.

Here we present *Ulysses* observations of two separate parts of the total power: power in fluctuations of the components perpendicular to the mean magnetic field, $P_{xx}(f, \theta_B) + P_{yy}(f, \theta_B)$, and parallel to the mean magnetic field, $P_{zz}(f,\theta_B)$, at *Ulysses'* in mid-1995. The separation of total power into these two components affords a first look into the (possibly different)

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behavior of the Alfvenic (= Toroidal, or "Tor") and pseudo-Alfvenic (= Poloidal, or "Pol") magnetic fluctuations in the fast polar solar wind at solar minimum.

THEORY

Figure 1 shows the Tor(**k**) and Pol(**k**) components of *incompressible* magnetic turbulence, with respect to the local field **B**. Both are normal to the wave-vector **k**, but Tor is also normal to **k x B**. We showed in [5,14] that

$$P_{xx}(\mathbf{k}) + P_{yy}(\mathbf{k}) = Tor(\mathbf{k}) + \frac{k_z^{\,2}}{|\mathbf{k}|^2} Pol(\mathbf{k})$$

$$and \quad P_{zz}(\mathbf{k}) = \frac{k_x^{\,2} + k_y^{\,2}}{|\mathbf{k}|^2} Pol(\mathbf{k}).$$

$P_{zz}(\mathbf{k})$ arises entirely from pseudo-Alfvenic fluctuations. Our observations are a non-trivial transformation of the spectra in **k**-space, from the 3D plasma frame to the frequency spectra of a 1D time series [5, 14] dependent on the angle between the mean magnetic field and the solar wind velocity **V**:

$$P_{ij}(f,\theta_B) = \iiint P_{ij}(\mathbf{k})\delta(2\pi f - \mathbf{V}\bullet\mathbf{k})d^3\mathbf{k}\,.$$

It remains true, however, that $P_{zz}(f,\theta_B)$ depends only on the pseudo-Alfvenic component Pol(**k**) which is not necessarily compressive. Since $P_{zz}(f,\theta_B)$ is generally much smaller than the perpendicular component in the solar wind, the power in perpendicular fluctuations is almost wholly due to the Alfvenic Tor(**k**) fluctuations.

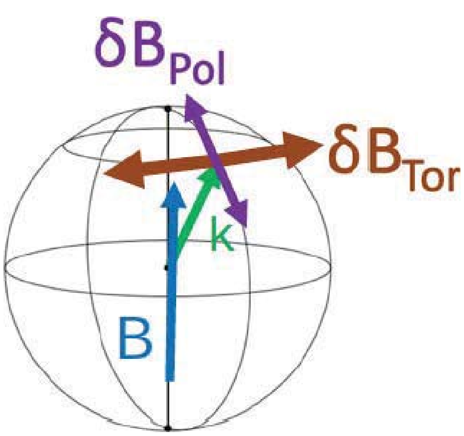


FIGURE 1. Orientation of the Tor(**k**) and Pol(**k**) fluctuations of with respect to **k** and the local mean field **B**.

Knowing the spectra and anisotropy of the observed power in the parallel and perpendicular components separately may allow the identification of the similarities and differences between their cascades, and their interaction, if any. This separate look at the power in fluctuations parallel and perpendicular to the local mean **B** reveals the different behavior of the pseudo-Alfvenic and Alfvenic components of the magnetic turbulence. In fact, we show that they have similar, but not quite the same, spectrum and anisotropy.

DATA

Figure 2 shows where *Ulysses* was in each of the six 10-day periods.

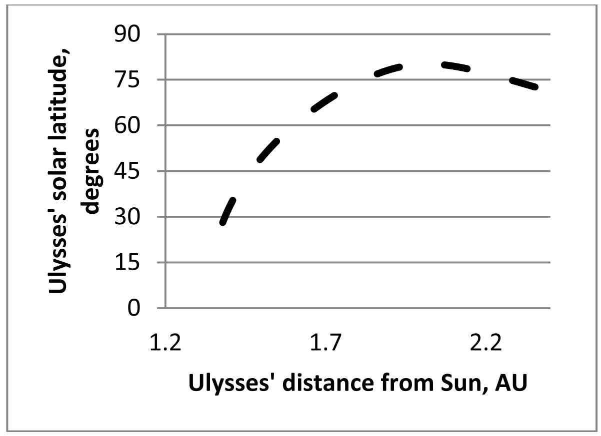
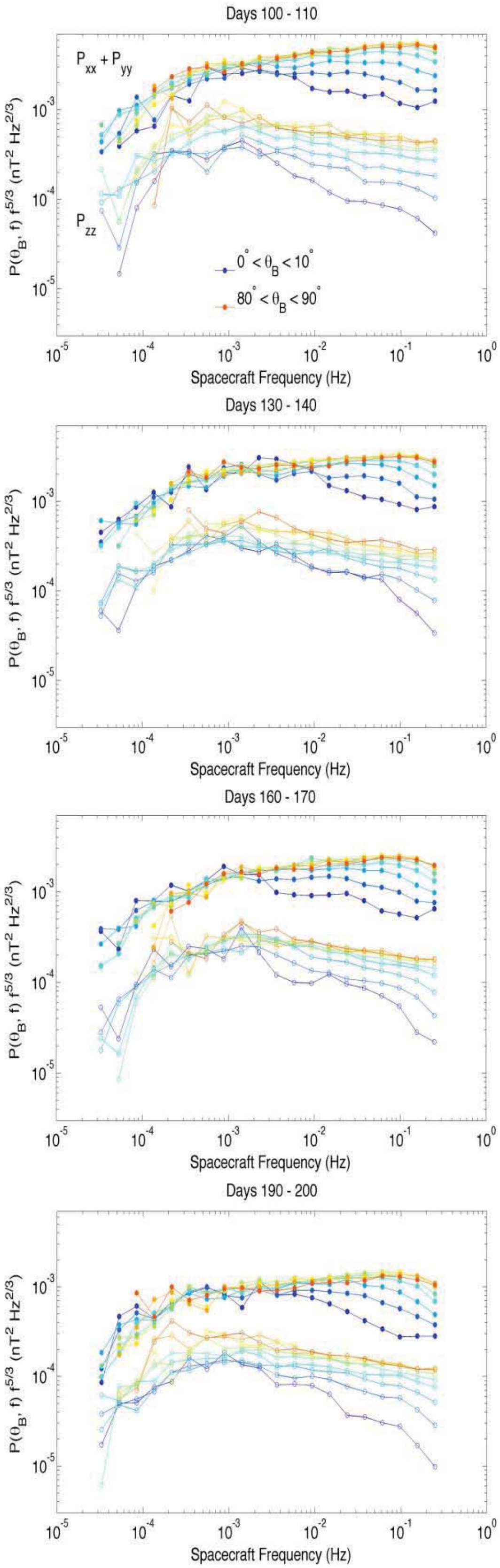


FIGURE 2. *Ulysses* solar latitude and distance during the six periods in this study. *Ulysses* is closest to the Sun on 1995 days 100-110, and furthest on day 260.

The MAG data from *Ulysses* are analyzed into power spectral tensors by the method of complex Morlet wavelet transform of R,T,N components and the local mean field direction in the R,T,N frame, described in [2,5,6,8,9]. The tensor is then expressed in the frame of the local mean magnetic field, with $\hat{z}$ the (outward) direction along the field [9]. Then P_{zz} is the power in fluctuations parallel to the field, and $P_{xx}+P_{yy}$ is the power in perpendicular fluctuations.

Figure 3 shows the $P_{xx}(f,\theta_B)+P_{yy}(f,\theta_B)$ and $P_{zz}(f,\theta_B)$ determined this way from MAG data measured in the solar wind at the time and places in figure 2. All spectra are multiplied by $f^{5/3}$, to emphasize their dependence on the angle θ_B, and subtle deviations even at 90^0 from Kolmogorov $f^{-5/3}$.



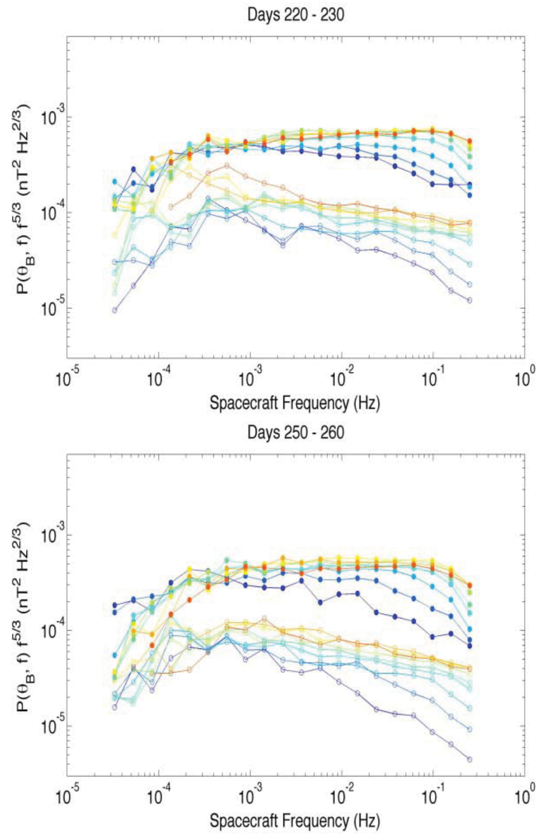


FIGURE 3. Compensated power spectra in perpendicular and parallel magnetic field fluctuations at *Ulysses*, during each of the six ten-day periods shown in figure 2. Because the perpendicular fluctuations are so much larger, $P_{xx}(f, \theta_B) + P_{yy}(f, \theta_B)$ (filled circles) is the top set of spectra in every panel; $P_{zz}(f, \theta_B)$ (open circles) is the bottom set. Spectra are compensated by $f^{5/3}$ to emphasize deviations from the nominal Kolmogorov $f^{-5/3}$. Power in each component is shown for nine 10-degree bins when magnetic field is at angles from 0-10, 10-20…80-90 degrees from the radial direction of the solar wind. In each case, the perpendicular power is a factor about 10 larger than the power in fluctuations parallel to the local mean magnetic field. Note that these spectra are extended to frequencies two orders of magnitude below that used in Horbury, et al. (2008), even to the "1/f" range not discussed here. Note also that in the later intervals furthest from the Sun, the mean magnetic field strength has declined so that the upper end of the frequency range shown is in the "dissipation range" where $2\pi f / V > (\text{ion gyroradius})^{-1}$.

OBSERVATIONS AND CONCLUSIONS

Comparison of parallel and perpendicular component fluctuations:

1. The parallel component fluctuations have smaller amplitude than the perpendicular component fluctuations, from 1.4 to 2.4 AU, but equal or larger anisotropy.
2. The spectra of parallel component fluctuations at angles near 90 degrees have a steeper slope than 5/3, while the perpendicular ones have a slope, at less than 2 AU, slightly flatter than 5/3.
3. The anisotropy in the parallel component fluctuations decreases more slowly toward lower frequencies, than anisotropy in the perpendicular fluctuations.

The interpretation of these results is that pseudo-Alfvenic fluctuations are smaller and have structure different from the Alfvenic fluctuations.

Perpendicular component fluctuations:

1. The spectral slope at 90 degrees appears to evolve steadily from 3/2 to 5/3 over the range 1.4 to 2.4 AU in this fast polar solar wind.
2. The spectral slope at 0 degrees is 2 in all the intervals.

From this we conclude that the Alfvenic component of magnetic turbulence may evolve from B06 to GS95 as the turbulence matures with age of the solar wind. Both models predict the spectrum is ~ f^2 at 0 degrees, as is observed. The spectrum of velocity fluctuations is evolving over 1 to 5 AU [16].

Parallel component fluctuations

1. Spectrum at 90 degrees is steeper than 5/3, but not as steep as 2.
2. Spectrum at 90 degrees does not change with distance from the Sun between 1.4 and 2.4 AU.
3. Spectral index at 0 degrees is close to 2, just as in the perpendicular fluctuations.
4. Anisotropy persists into the 1/f range.

Thus, the pseudo-Alfvenic fluctuations are not consistent with either GS95 or B06. If they are parasitic on the Alfvenic fluctuations, comparative observations like these may help to understand why and how this occurs.

SUMMARY AND CONCLUSIONS

We have separated out the power spectrum and anisotropy of parallel magnetic fluctuations in the inertial range of frequencies (and lower into 1/f range) in the fast polar solar wind, from the perpendicular fluctuations which dominate the total power. Since they are subtly different in both spectrum and anisotropy, the underlying pseudo-Alfvenic and Alfvenic components must also be different. Two major puzzles emerge from this study: (1) the apparent evolution of the dominant Alfvenic fluctuations from a B06-type of critical balance model at less than 2 AU, to a GS95-type model further out; and (2) that from 1.4 to 2.4 AU, the pseudo-Alfvenic component does not fit either model well.

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