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Multi-spacecraft measurement of anisotropic power levels and scaling in solar wind turbulence

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Abstract. Measurements by the four Cluster spacecraft in the solar wind are used to determine quantitatively the field-aligned anisotropy of magnetohydrodynamic inertial range turbulence power levels and spectral indexes. We find, using time-lagged second order structure functions, that the spectral index is near 2 around the field-parallel direction, which is consistent with a "critical balance" turbulent cascade. Solar wind fluctuations are found to be anisotropic with power mainly in wavevectors perpendicular to the mean field, where the spectral index is around 5/3.

Keywords. Interplanetary physics (Solar wind plasma) – Space plasma physics (Turbulence; Instruments and techniques)

1 Introduction

The solar wind is a natural laboratory for the study of magnetohydrodynamic (MHD) turbulence (see Goldstein et al., 1995; Tu and Marsch, 1995; Bruno and Carbone, 2005; Horbury et al., 2005; Sorriso-Valvo et al., 2006, and references therein). The presence of a mean magnetic field induces spectral anisotropy (Oughton et al., 1994). However, single spacecraft measurements of the magnetic field fluctuations are limited to the solar wind flow direction, and cannot characterise the full three-dimensional form of the spectral tensor (Fredricks and Coroniti, 1979) or its scaling behaviour. In the absence of complete information, idealised models of the spectral tensor have been adopted.

The "slab" model is the simplest approximation to solar wind fluctuations, where all excited wavevectors lie parallel to the mean magnetic field direction, $k_\parallel$. This produces a one-dimensional spectrum which decays with increasing field-parallel wavenumber, and there is no power in the field-perpendicular wavevectors. In contrast, the "2-D" model is characterised by all excited wavevectors lying in the plane perpendicular to the mean field, $k_\perp$. Therefore, the power spectrum decays with increasing wavenumber perpendicular to the field and is zero parallel to it. Theoretical predictions (Montgomery, 1982; Zank and Matthaeus, 1992), numerical simulations (Oughton et al., 1994; Matthaeus et al., 1996), and experimental work on laboratory plasmas (Robinson and Rusbridge, 1971; Zweben et al., 1979) suggest that 2-D dynamics is the leading order description of turbulence in the presence of a mean magnetic field. Direct measurements in the solar wind have shown that turbulent fluctuations are anisotropic with energy mainly in wavevectors perpendicular to the mean magnetic field (Matthaeus et al., 1990; Carbone et al., 1995; Bieber et al., 1996; Dasso et al., 2005; Osman and Horbury, 2007; Horbury et al., 2008; Osman and Horbury, 2009) and that the spectral index is around 5/3 (Matthaeus and Goldstein, 1982; Roberts and Goldstein, 1991; Bruno and Carbone, 2005).

Goldreich and Sridhar (1995) (referred to as GS95) presented a theory of "critically balanced" incompressible Alfvénic MHD turbulence. This balances the characteristic timescale τ_{NL} on which energy cascades to smaller scales by non-linear coupling with the Alfvén time $\tau_A \propto 1/k\cos\theta_{kB}$, the period of an Alfvén wave with wavenumber k which lies at an angle θ_{kB} to the magnetic field. Partitioning wavevector space according to $\tau_A \sim \tau_{NL}$ relates the maximum excited $k_\perp$ to $k_\parallel$:

$$k_\perp \sim k_\parallel^{3/2} \quad (1)$$

Therefore, this cascade leads to a scale dependent anisotropy. The GS95 model predicts an inertial range power spectrum scaling of 5/3 in $k_\perp$ and 2 in $k_\parallel$ (Boldyrev, 2005). These values were measured by Horbury et al. (2008) in the high speed ($\sim$750 km s^{-1}) polar solar wind using 30 days of Ulysses magnetic field data. While GS95 provides a useful model of

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anisotropy in solar wind turbulence, it does represent an idealised interpretation of real fluctuations. In particular, it is assumed that oppositely directed Alfvén waves carry equal energy fluxes, which is not the case in the solar wind, where the anti-sunward flux exceeds the sunward one (Roberts et al., 1987; Tu et al., 1989). However, we analyse solar wind fluctuations without many of the assumptions and restrictions associated with GS95 theory. Therefore, our analysis is not restricted by the limitations imposed by GS95,

Here we use a multi-spacecraft approach to measure the field-aligned anisotropy of solar wind turbulence power levels and spectral indexes. In particular, we measure low speed ($\sim$340 km s^{-1}) solar wind fluctuations using short (of order an hour) intervals of magnetic field data from the four Cluster spacecraft.

2 Multi-spacecraft technique

Here we use a multi-spacecraft technique, first proposed by Horbury (2000) and later implemented by Osman and Horbury (2007, 2009), to measure the field-aligned power anisotropy and scaling behaviour of solar wind turbulence. A pair of spacecraft, separated by a distance $\mathbf{d}_{12}$, in a fast moving plasma will measure magnetic field time series $\mathbf{b}^1(t)$ and $\mathbf{b}^2(t)$ along the flow direction. A spacecraft time series which satisfies Taylor's hypothesis (Taylor, 1938) – the sampling time of solar wind fluctuations is much less than the time scale on which they vary – can be considered a spatial "snapshot" of the plasma. For multiple spacecraft, this condition is satisfied when (Osman and Horbury, 2009):

$$\frac{v_{sw}\Delta t}{|\mathbf{d}_{12}-\mathbf{v}_{sw}\Delta t|}\cdot\frac{v_A}{v_{sw}} \ll 1 \qquad (2)$$

where $|\ldots|$ denotes a vector magnitude. In practice, this condition is well satisfied in the solar wind for most time lags, Δt. Therefore, the single spacecraft time series are equivalent to spatial series in the plasma frame: $b^1(-\mathbf{v}_{sw}t)$ and $b^2(\mathbf{d}_{12}-\mathbf{v}_{sw}t)$. Varying the time lag corresponds to changing the vector separation between each pair of sampling points in the plasma frame:

$$\mathbf{r}(\Delta t)=\mathbf{d}_{12}-\mathbf{v}_{sw}\Delta t \qquad (3)$$

Therefore, in contrast to single spacecraft studies, the scale and angular dependence of solar wind fluctuations can be measured using only a single data interval.

In order to obtain quantitative estimates of the field-aligned anisotropy, Osman and Horbury (2007, 2009) used the multi-spacecraft approach to construct spatial auto-correlation functions. While correlation functions have been used in solar wind anisotropy studies (e.g. Matthaeus et al., 1990; Dasso et al., 2005), most measure power levels and the spectral index (e.g. Burlaga and Goldstein, 1984; Bieber et al., 1996; Horbury et al., 1996; Leamon et al., 2000). In particular, numerical and theoretical studies often make predictions about the three-dimensional form of the spectral tensor and the field-parallel and perpendicular spectral index values (e.g. Shebalin et al., 1983; Goldreich and Sridhar, 1995; Boldyrev, 2005). Similar predictions regarding the form of the correlation function are uncommon.

Structure functions provide a simple way of analysing turbulent fluctuations. In particular, they can be used to measure the power levels and spectral index of the fluctuations, and have been used extensively in the analysis of spacecraft data (e.g. Marsch and Liu, 1993; Ruzmaikin et al., 1995; Horbury et al., 1997; Chapman and Hnat, 2007). In this work, time-lagged structure functions are used in conjunction with the multi-spacecraft technique, so varying the time lag is equivalent to altering the field angle θ_{SB} (acute angle between the separation vector and the magnetic field direction), and the separation vector in the plasma frame. Hence, for a component i of the magnetic field time series, structure functions are defined as:

$$S_i^{12}(p,\mathbf{r})=\left\langle\left|b_i^2(-\mathbf{v}_{sw}t+\mathbf{r})-b_i^1(-\mathbf{v}_{sw}t)\right|^p\right\rangle \qquad (4)$$

where $<\ldots>$ denotes a spatial average in the plasma frame. Therefore, $S_i^{12}(p,\mathbf{r})$ is the p-th moment of the distribution of absolute variations in b_i on the spatial scale $\mathbf{r}$. The second order structure function is a measure of the variance, which is the integral of the power spectrum over frequency, and is proportional to the power. Therefore, the power levels can be measured as a function of field angle and scale within a single interval. For scales where the power spectrum is a power law, such as within the inertial range, structure functions are expected to vary with scale like:

$$S(p,\mathbf{r})\propto\mathbf{r}^{g(p)} \qquad (5)$$

where $g(p)$ is the scaling exponent. When Eq. (5) is satisfied, $g(2)$ is directly related to the spectral index α by $g(2)=\alpha-1$ (Monin and Yaglom, 1975).

We measure the anisotropy in the power levels and, by considering how they vary with scale, the spectral index. While this paper focuses on the four Cluster spacecraft measuring structure functions, this multi-spacecraft approach can in principle be applied to any number of spacecraft and any time lag dependent analysis technique.

3 Results

We analyse 4 s resolution spin averaged magnetic field data from the fluxgate magnetometers on board the four Cluster spacecraft (Balogh et al., 2001) as provided by the Cluster Active Archive (Perry et al., 2006). The data set used in this analysis consists of three time intervals, obtained between February and March 2006 when Cluster was in the solar wind at separations near 10 000 km. All three intervals are presented, and both field-parallel and perpendicular fluctuations are considered. We begin with an interval from 27

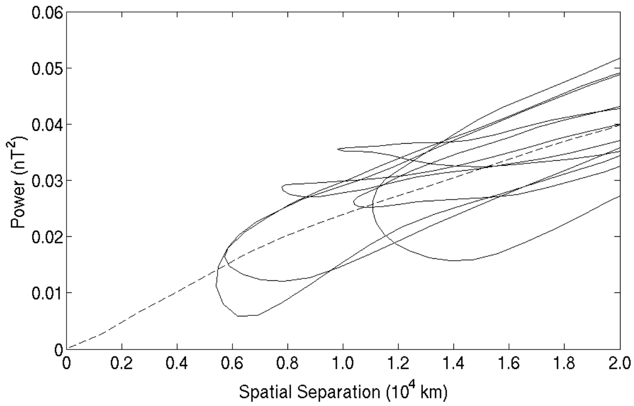

Fig. 1. Second order structure functions between all six pairs of Cluster spacecraft as a function of spatial separation in the plasma frame for the x-component of the magnetic field fluctuations from 27 February at 23:00 UT to 28 February 2006 at 00:00 UT. The single spacecraft structure function is also plotted as a dashed line. The shape of the second order structure functions and the rate at which they increase is a complex function of the separation vectors in the plasma frame, the variation of the separation vectors with time lag, and the anisotropy of the fluctuations.

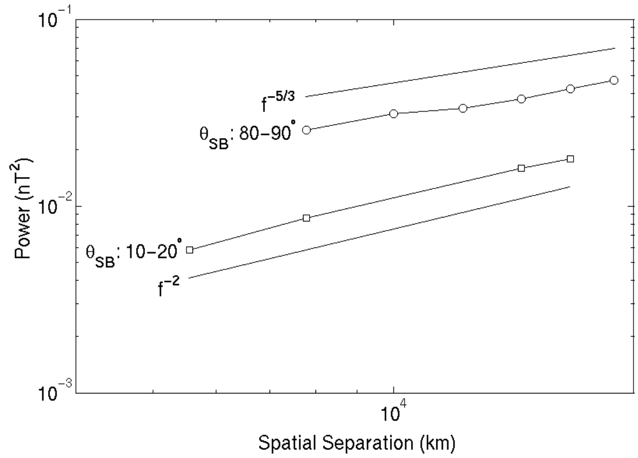

Fig. 2. Spatial variation of the binned and averaged second order structure functions for the x-component of the magnetic field fluctuations, where the field angle bins shown are: 10°–20° (squares) and 80°–90° (circles). The smaller angle has reduced power levels and a steeper gradient. Guide lines corresponding to power spectra with slopes of 5/3 and 2 are shown alongside the data.

February at 23:00 UT to 28 February 2006 at 00:00 UT. The average solar wind speed measured by the CIS instrument (Rème et al., 2001) during this interval was 326 km s^{-1}, and the plasma beta was 2.2.

In order to easily identify slab and 2-D fluctuation symmetries, we use a magnetic field aligned right handed orthogonal coordinate system after Osman and Horbury (2009). The z-axis is aligned with the mean magnetic field direction, the x-axis is in the plane defined by the mean magnetic field and solar wind velocity (nearly anti-sunward) vectors, and the y-axis completes the right-handed system. In addition, a field angle θ_{SB} is also defined. Since the four Cluster spacecraft are joined by six separation vectors, the multi-spacecraft technique is used to compute six time-lagged two-point second order structure functions for each component of the magnetic field aligned coordinate system. The single spacecraft structure function is also computed – spacecraft 2 is used, but all spacecraft give near-identical results.

In order to estimate the field angle dependence of the second order structure functions, time lags that satisfy Taylor's hypothesis are converted to spatial separations in the plasma frame using Eq. (3). Figure 1 shows the spatial variation of the second order structure functions for the x-component of the magnetic field fluctuations. When computing the power levels and spectral indexes, we only consider scales comparable to the Cluster spacecraft separation (∼10 000 km), where greatest coverage in θ_{SB} is obtained. Apart from the single spacecraft case, all the two-point structure functions exhibit a hysteresis-like effect. Physically, this means that the positive and negative time lags associated with the single spacecraft structure function are in the same direction relative to the mean magnetic field in the plasma frame. The hysteresis-like effect is a function of the anisotropy of the fluctuations and each spacecraft in the Cluster tetrahedron measuring a slightly different time series. It is also inconsistent with solar wind fluctuations having an isotropic distribution of energy in wavevctor space, as this would correspond to a single power value at any particular spatial separation.

Axisymmetry about the mean magnetic field direction is assumed here, which is common in studies of spectral anisotropy in solar wind turbulence (e.g. Matthaeus et al., 1990; Bieber et al., 1996; Dasso et al., 2005). Therefore, the second order structure functions can be projected onto a two-dimensional plane spanned by the field angle θ_{SB} and spatial separation r. In order to improve the coverage of the structure functions, the data is binned and averaged. A 9×9 grid of equally sized squares is superimposed on the structure functions, which extend from 0 to 2×10^4 km in spatial separation and from 0 to 90° in field angle. The mean power value and its associated error are then computed for each bin containing data.

In order to obtain a quantitative estimate of the anisotropy, the power at a spatial scale of 10^4 km was estimated at all field angles. Since we are considering inertial range fluctuations, the second order structure function scales as a power law. Figure 2 shows the spatial variation of the binned and averaged second order structure function in logarithmic space for the field angle bins 10°–20° and 80°–90°. While all the field angle bins are analysed, except 0°–10° because there is no coverage for this range of angles, these represent the near field-parallel and perpendicular directions respectively.

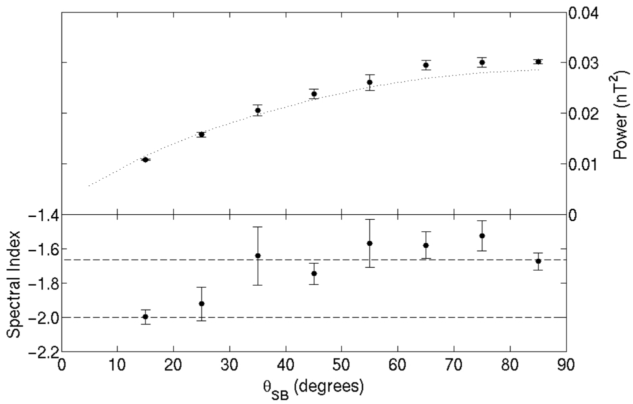

Fig. 3. The second order structure function with a dotted line that represents the best fit to Eq. (6), and the spectral index as a function of separation angle to the mean magnetic field for the x-component of the fluctuations. This is from the same data interval as Fig. 2.

Figure 2 shows that both these field angle bins are well described by power laws, and the power levels for $\theta_{SB} = 10°$–$20°$ are lower than those for $\theta_{SB} = 80°$–$90°$, which is consistent with power being mostly in wavevectors at large angles to the mean magnetic field (e.g. Bieber et al., 1996; Leamon et al., 1998). In addition, the power law gradient, which is proportional to the spectral index, for $\theta_{SB} = 10°$–$20°$ is steeper than that for larger field angles. A straight line is fitted to the data from each field angle bin using a least squares method, and the corresponding gradient and intercept values are used to compute the average second order structure function value at a spatial separation of 10^4 km.

Figure 3 shows the variations in the solar wind turbulence power level and spectral index with θ_{SB} for the x-component of the magnetic field fluctuations. There is a generally smooth variation in power with field angle, and the power levels for $\theta_{SB} = 80°$–$90°$ are greater than those for $\theta_{SB} = 10°$–$20°$. This is consistent with previous studies (Bieber et al., 1996; Horbury et al., 2008) and the expectation that solar wind turbulence is anisotropic with power mostly in wavevectors perpendicular to the mean magnetic field (Matthaeus et al., 1990; Osman and Horbury, 2009).

A single spacecraft cannot measure the full three-dimensional wavevector power spectrum, and instead measures the reduced spectrum which is only a function of the flow-aligned component of the plasma frame wavevector (Fredricks and Coroniti, 1979; Bieber et al., 1994). Therefore, in order to obtain a quantitative estimate of the anisotropy, our data is fitted to an analytical form of the field angle dependent reduced power levels for slab and 2-D fluctuations:

$$P(\theta_{SB}) = C_{\text{slab}}|\cos\theta_{SB}|^{\alpha_{\text{slab}}-1} + C_{\text{2D}}|\sin\theta_{SB}|^{\alpha_{\text{2D}}-1} \quad (6)$$

where C_{slab} and C_{2D} are variables representing the amplitudes of the slab and 2-D components. Following Bieber et al. (1996), the spectral indexes, α_{slab} and α_{2D}, are assumed to be $5/3$ for both components. For the field angle dependent power levels in Fig. 3, the best fit to the analytical model corresponds to (95±4)% of the total power in the 2-D component. The y-component and z-component (parallel to the mean field) of the magnetic field fluctuations have respectively (94±6)% and (95±5)% of the power in 2-D fluctuations. These results are, within errors, equal for all three magnetic field components and consistent with the Bieber et al. (1996) measurement of 95%, obtained using the analytic field angle dependent reduced power.

The bottom panel of Fig. 3 shows the variation in spectral index with θ_{SB} for the x-component of the magnetic field fluctuations. The spectral index is about $5/3$ for most field angles, which is in agreement with previous measurements in the solar wind (e.g. Bruno and Carbone, 2005). However, as $\theta_{SB} \rightarrow 0°$, the spectral index increases to a value around 2. This is the first time a spectral index of 2 at small field angles has been measured in slow speed solar wind using a multi-spacecraft approach, although Horbury et al. (2008) obtained a similar result in the polar solar wind using the Ulysses spacecraft. Figure 3 is consistent with anisotropic energy transfer in MHD turbulence, and with the presence of a critically balanced cascade (Boldyrev, 2005). However, these results alone cannot clearly distinguish between the critical balance and slab/2-D models, since they are also consistent with a dominant 2-D component with α_{2D}=5/3 and a smaller slab component with α_{slab}=2. This scaling behaviour is also observed for the y-component of the magnetic field fluctuations. However, the z-component (parallel to the mean field) spectral index remains around $5/3$ for all field angles. This is consistent with the kinetic reduced MHD description of inertial range solar wind turbulence, which predicts that there is no $k_\parallel$ cascade in the magnetic field strength fluctuations (Schekochihin et al., 2009). However, the limited field angle coverage in Fig. 3 makes it difficult to determine why the small field angle scaling is different for the field-perpendicular and parallel components.

The second data interval that we present was on 5 March 2006 between 04:55–05:45 UT, where the average solar wind speed was 330 km s^{-1}, and the plasma beta was 2.5. Figure 4 shows the power level and spectral index variations with θ_{SB} for the y-component of the magnetic field fluctuations. There is no data coverage in the field angle range 0°–20°, which means the behaviour at small angles cannot be determined. The estimated power in 2-D fluctuations is (100±5)% for the data shown in the top panel of Fig. 4, obtained by fitting to the analytical form of the reduced power levels. For the x-component and z-component (parallel to the mean field) repectively, (98±5)% and (96±6)% of the total power is in 2-D fluctuations. These results are again consistent with the Bieber et al. (1996) study, and with energy being predominatly, if not entirely, in wavevectors perpendicular to the mean magnetic field. The bottom panel of Fig. 4 shows that, while there are some slight deviations, the

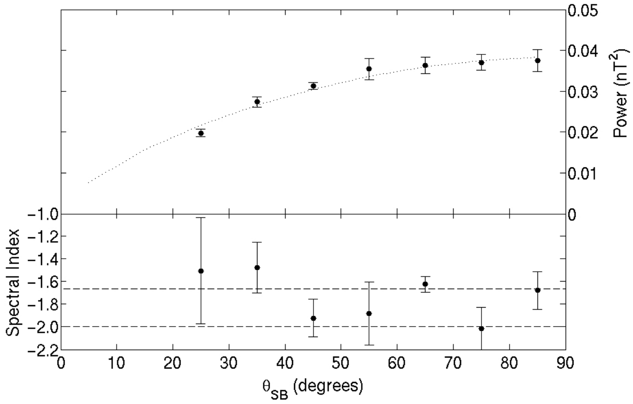

Fig. 4. The power levels with a dotted line that represents the best fit to Eq. (6), and the spectral index as a function of separation angle to the mean magnetic field for the y-component of the fluctuations on 5 March 2006 04:55–05:45 UT.

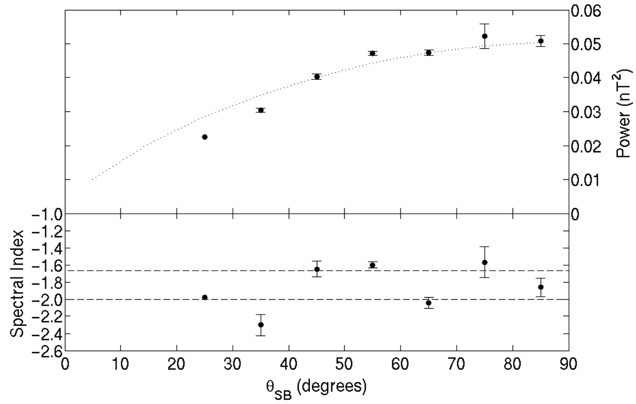

Fig. 5. The power levels with a dotted line that represents the best fit to Eq. (6), and the spectral index as a function of separation angle to the mean magnetic field for the z-component of the fluctuations on 14 March 2006 17:45–19:15 UT.

spectral index is consistent with $5/3$ for all the field angle bins containing data, which is in agreement with both a field-perpendicular critically balanced cascade and a purely 2-D component with α_{2D}=5/3. This scaling was also measured for the x-component and z-component of the magnetic field fluctuations.

The final data interval that we analyse was on 14 March 2006 from 17:45–19:15 UT, where the average solar wind speed was 353 km s^{-1} and the plasma beta was 0.5. Figure 5 shows the power level and spectral index variations with θ_{SB} for the z-component of the magnetic field fluctuations. There is no data in the range 0°–20° and the values in the field angle bin 20°–30° were computed from a straight line fit to only two data points, and so have an infinite standard error. However, despite the poor data coverage, the analytical field angle dependent reduced power is still visually a good fit to the measured power levels in Fig. 5, estimating (100±7)% of the total power in 2-D fluctuations. Indeed, this analytical model has been a good fit to the data for all three of the intervals used in this study, despite their short length and limited field angle coverage. The power in the 2-D component is (100±12)% and (100±12)% respectively for the x-component and y-component of the field fluctuations. Since the measured power is mostly in wavevectors perpendicular to the field, and the critical balance model predicts a power spectrum spectral index of 5/3 in $k_\perp$, we would expect to observe a 5/3 scaling across all field angles. However, the bottom panel of Fig. 5 shows the spectral index values vary from one field angle bin to another without any underlying pattern. This scatter is probably due to the poor data coverage in this interval, which has led to inaccurate determination of the spectral index.

4 Conclusions

We have presented the first multi-spacecraft measurement of the field angle dependent solar wind turbulence power levels and spectral indexes. The spectral anisotropy results, obtained by fitting an analytical model of the field angle dependent reduced power levels to the data, are consistent with energy being mainly in wavevectors perpendicular to the magnetic field. These results are also in agreement with the Bieber et al. (1996) observation of 2-D fluctuations constituting 95% of the measured power, when computed using Eq. (6). However, when the same data set was analysed in a different manner, Bieber et al. (1996) only found a 75% 2-D component. Indeed, Bieber et al. (1994) calculated that a 2-D population of 80% was needed to explain the descrepency between theoretical and observed mean free paths of energetic particles, and a similar result was obtained by Osman and Horbury (2009) when using correlation functions to measure the field-aligned anisotropy of MHD turbulence. While there may be other contributing factors, these studies suggest that equally valid and independent analysis techniques can provide significantly different estimates of the anisotropy in solar wind fluctuations. The origin of this bias and how it manifests itself require further investigation.

The scaling properties of solar wind turbulence were measured as a function of field angle for each magnetic field component within a single data interval. When there is reasonable data coverage, the results are consistent with a critically balanced cascade. Indeed, a spectral index of 2 was obtained at small field angles, which suggests anisotropic energy transfer in MHD turbulence. However, the separation of the Cluster spacecraft meant that the power spectrum scaling could only be measured in the range 0.5–2 $\times 10^4$ km, so agreement with a critical balance cascade at larger and smaller scales has not been shown. Indeed, our results alone cannot distinguish between slab/2-D and critical balance models, since a full analytical form of the spectral tensor for critically balanced turbulence has not, to our knowledge, been published. Determining which MHD turbulence approximation best fits solar wind magnetic field fluctuation data requires further study.

The present analysis uses second order structure functions to measure the field-aligned anisotropy of solar wind turbulence power levels and spectral indexes, and so extension to higher order moments in order to measure properties such as intermittency would be worthwhile. In addition, work has already begun on using this multi-spacecraft approach to study fluctuations near the dissipation scale. Finally, more data intervals with better coverage at small field angles should be used to obtain more accurate and complete estimates of the anisotropic power levels and spectral indexes.

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