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Anisotropy in imbalanced turbulence above and below the ion gyroscale and the effect of instabilities at the ion gyroscale.

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INTRODUCTION

We have developed a wavelet based technique that can measure the scale dependent anisotropy in turbulent fluctuations relative to the magnetic field in a plasma. We show that in the solar wind at MHD scales the magnetic field and velocity are both anisotropic but scale differently, and that anisotropy and imbalance of Elsässer modes may be linked.

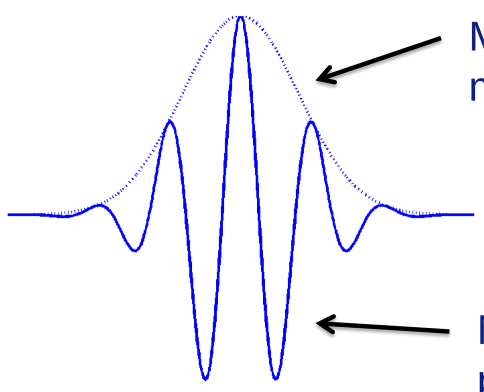
We also show that close to the ion gyroscale there is power injection in parallel modes which resembles the effect of the firehose instability. Below the ion gyroscale multi-spacecraft structure functions can be used to measure the anisotropy at kinetic scales, we show that multi-spacecraft structure functions, single spacecraft wavelets and Fourier transforms can be normalised and plotted on a single scale and that they agree with each other.

WAVELET APROACH TO LOCAL MAGNETIC FIELD POWER OBSERVATIONS

We measure local magnetic field direction (θ_B) and power over a range of scales using Morlet wavelets [1-4].

$$P(s) = \left(\frac{2\pi s}{\delta t}\right)\sum_{\omega=0}^{N-1} \hat{B}\pi^{-\frac{1}{4}} H(\omega) e^{-\frac{1}{2}(s\omega-\omega_0)^2} e^{i\omega n \delta t} \quad (1)$$

$$s(f) = \frac{\omega_0 + \sqrt{2+\omega_0^2}}{f 4\pi} \quad (2)$$



Morlet envelope, used as timescale for calculation of mean magnetic field direction.

Wavelet gives resolution in time (finite width of envelope) and frequency (oscillatory function).

Morlet wavelet, convoluted with time series to calculate power.

ω_0 sets the internal frequency of the Morlet wavelet at scale s, which is related to the Fourier frequency, f, through equation (2). Power is then calculated as the convolution of this wavelet with the magnetic field time series using equation (1) [3].

INERTIAL RANGE OBSERVATIONS OF ELSÄSSER VARIABLES

We can apply the wavelet technique to many kinds of solar wind time series. The result is P(f, θ_B), the mean power, P, of fluctuations at frequencies, f, from times when the local mean magnetic field direction is θ_B. We choose the angle range $0 < \theta_B < 10°$ to be “parallel” and the range $80 < \theta_B < 90°$ to be “perpendicular”. Note we are not measuring the power of the perpendicular or parallel component but the average trace power from times when the magnetic field was pointing in the parallel or perpendicular direction to the flow.

Here we show results from a 7 day period of fast wind (|V| > 600 km/s) observed by the WIND spacecraft in January 2008. The magnetometer and particle instruments provide 3s resolution B, V and ρ observations and therefore allow the calculation of Elsässer variables (3) and their power spectra, which are denoted by lower case letters (4):

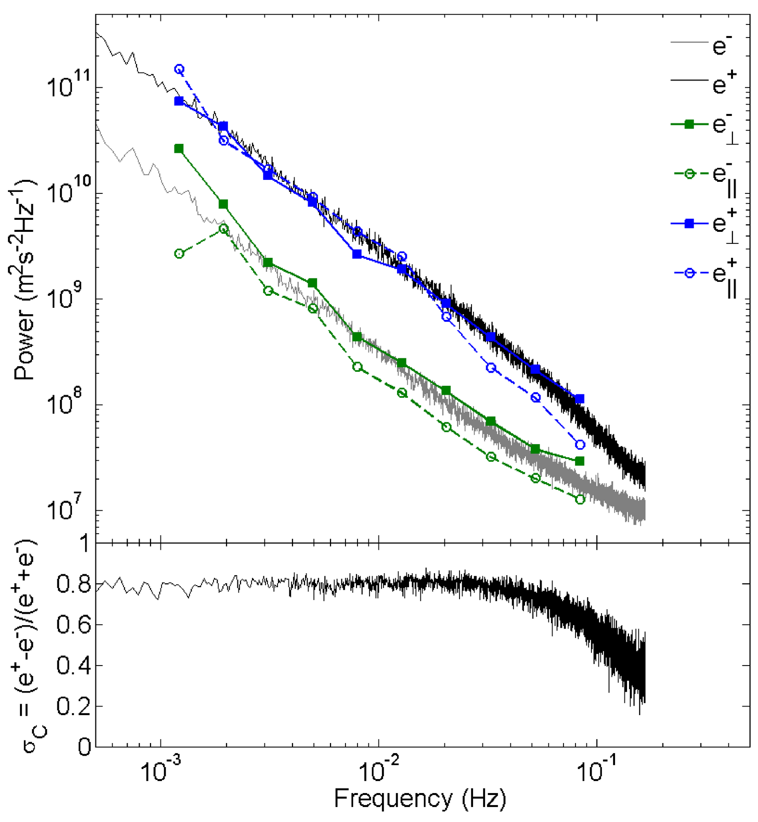
$$Z^{\pm} = V \pm \frac{B}{\sqrt{4\pi\rho}} \quad (3)$$

$$e^{+} = \frac{\hat{Z}^{+}(\omega)\times \hat{Z}^{+*}(\omega)}{2\pi} \quad (4)$$

with e^+ and e^- being the power spectra of Z^+ and Z^- respectively.

FIGURE 1

The top panel plots the power spectra and anisotropic power of Elsässer variables Z^+ (away from the Sun) and Z^- (towards the Sun) and the bottom panel shows normalised cross helicity. Cross helicity is constant where Z^+ is isotropic and decreases where Z^+ is anistropic. Z-behaves very differently from Z+ with anisotropy at all scales and shallower gradient at high frequencies.



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ION GYROSCALE INSTABILITY

Using longer time series of magnetic field data from the ULYSSES polar passes of the Sun we have measured anisotropy of the magnetic field over a wide range of frequencies [4]. We compensate these by multiplying the parallel power by f^2 and the perpendicular component by $f^{5/3}$, the values expected from critically balanced Alfvénic turbulence [5].

The highlighted region in Figure 2 shows the parallel power at 5 different distances from the Sun, covering a total time period of 250 days, all have an increase in power levels at the same scale, close to the ion gyroscale.

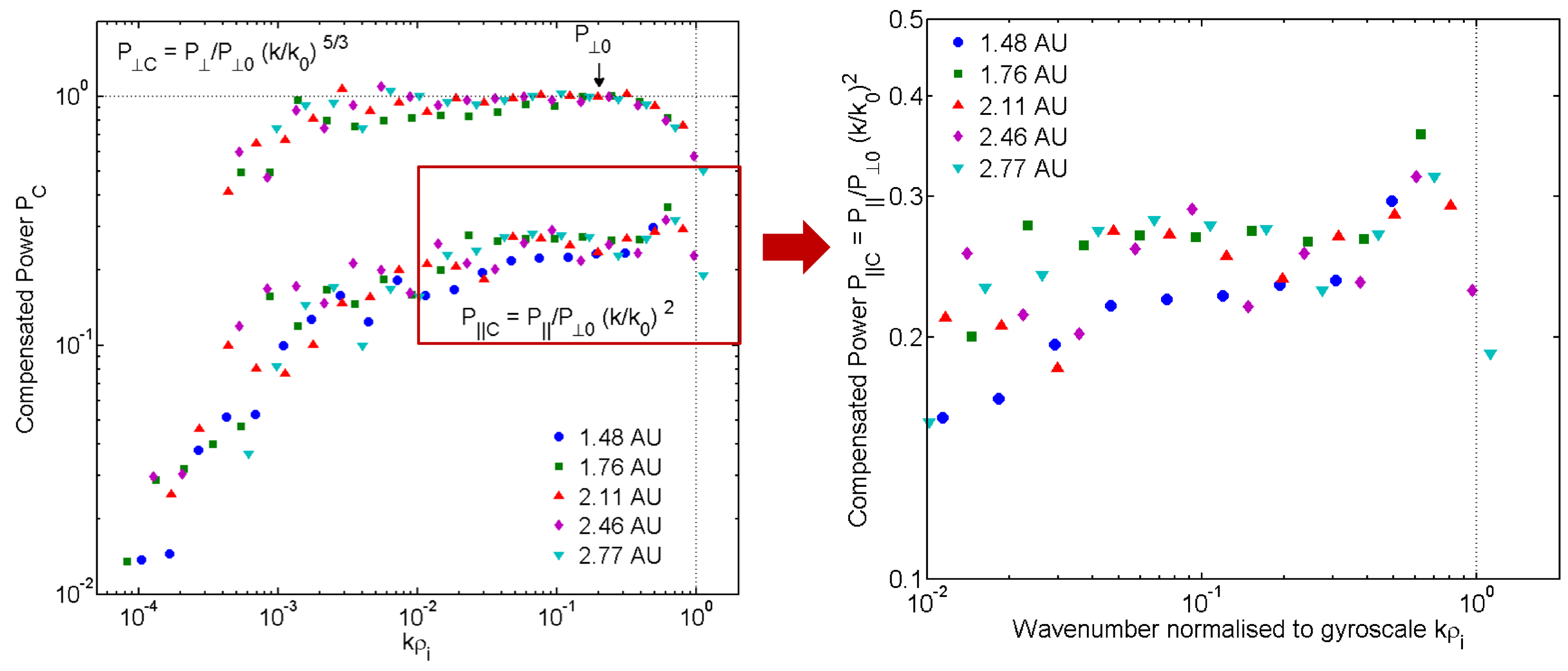
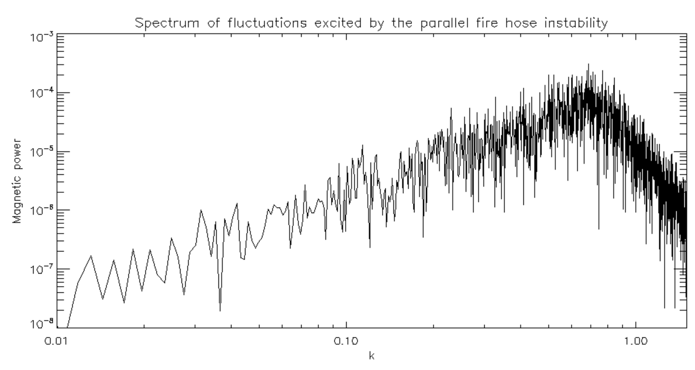


FIGURE 2

Compensated anisotropic power spectra from 5 different distances from the Sun [4]. The parallel power (top right) has a peak close to the ion gyroscale ($k\rho_i = 1$) at all distances from the Sun. This peak is at a scale similar to that in simulations by L. Matteini (bottom right) [6].



This shows that there is a very often a source of power in the fast polar solar wind at the ion gyroscale. The scale of injection is consistent with firehose instability simulations [6] and recent results [7, 8] that show the firehose threshold as a boundary for the phase space of temperature and plasma beta anisotropy in the solar wind and a source of magnetic fluctuations.

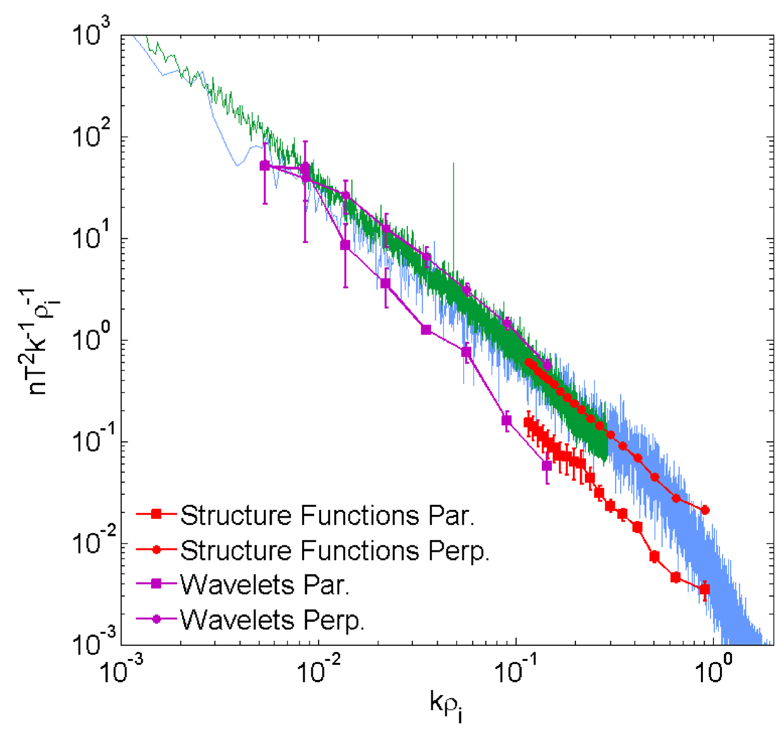
STRUCTURE FUNCTIONS AND SCALES SMALLER THAN ρ_i

Recent results have also used structure functions calculated form closely spaced spacecraft to access anisotropy at smaller scales than is possible with a single spacecraft alone [9]. Here we show that this technique and the wavelet technique produce similar results. To do this the structure functions (S(τ)) are normalised to have the same power and scale dependence as a Fourier transform (b(ω)) (5).

$$b(\omega) = \frac{\Gamma(p)\sin(\pi(p-1)/2)}{(2\pi)^{p+1}}\tau S(\tau) \quad (5)$$

FIGURE 3

The green Fourier power spectrum and purple wavelet power spectra are calculated from ACE magnetic field data from the same solar wind stream as the blue Fourier spectrum and red structure functions calculated from the Cluster spacecraft. The difference in parallel and perpendicular power calculated using the different techniques are similar,



CONCLUSIONS

Wavelet analysis of solar wind time series allows the investigation of anisotropy relative to the local magnetic field from single spacecraft data. Using long periods of Ulysses data we have shown that there is increased power in the parallel direction close to the ion gyroscale consistent with the parallel firehose instability.

We have also analysed WIND data and shown that imbalanced Elsasser variables do not have similar anisotropy and that anisotropy is associated with a decrease in cross helicity.

Finally we have shown that multi-spacecraft structure function results, capable of accessing much smaller scales than single spacecraft time series analysis, are consistent with results produced by wavelets..

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