SCALE-DEPENDENT ANISOTROPY OF MAGNETIC FLUCTUATIONS IN THE EARTH’S PLASMA SHEET

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Abstract. We use high resolution magnetic field data from the Cluster spacecraft to analyse the occurrence of specific anisotropy characteristics of magnetic fluctuations at two adjacent scales near the dissipation scale, during non-flow and bursty bulk flow (BBF) associated periods. The obtained anisotropy patterns show signatures of scale dependent anisotropy and can be explained by different physical processes. During non-flow periods the main source of the magnetic anisotropy are anisotropic ion populations within the plasma sheet boundary layer (PSBL). BBF-associated periods are characterized mainly by strong interaction of the plasma flow with the magnetic field. In both cases the local mean background magnetic field has a decisive role in the development of anisotropy in magnetic fluctuations.

Keywords. Magnetic turbulence, anisotropy, bursty bulk flows.

1. Introduction

Previous studies have confirmed that the flows in the Earth’s plasma sheet are bursty and transient [Baumjohann et al., 1990; Angelopoulos et al., 1993, 1994]. Most of the time (80-90% of all measurements) rapid plasma flows are absent. Nevertheless, the rarely occurring bursty bulk flows (BBFs) represent mesoscale carriers [Nakamura et al., 2004] of decisive amounts of mass, momentum and energy [Schödel et al., 2001], energetically influencing even the near-Earth auroral regions [Nakamura et al., 2001]. The analysis of associated flow fluctuations and magnetic field fluctuations [Baumjohann et al., 1990; Angelopoulos et al., 1993, 1994; Hoshino et al., 1994; Bauer et al., 1995; Chang, 1999; Consolini and Lui, 1999; Neagu et al., 2002; Lui, 2002; Volwerk et al., 2003; Vörös et al., 2003] led to the conjecture that the observed strong intermittent and multiscale variations in both temporal and spatial domains can be attributed to turbulence [Borovsky et al., 1997]. Eddy turbulence rather than Alfvénic turbulence seems to prevail and the most important dissipation mechanisms include a multiscale cascade of energy to non-magnetohydrodynamic (non-MHD) scales and an electrical coupling of the turbulent flows to the ionosphere [Borovsky and Funsten, 2003].

There are several difficulties, however, which make the experimental analysis of the plasma sheet turbulence iffy. First of all, a multiscale study of spatial variability in turbulence would require as many satellite pairs as there are scales. The lack of such information is usually handled...
through additional hypotheses which allow us to convert temporal fluctuations to spatial ones during rapid plasma flows [Horbury, 2000] or remnant flow intervals [Borovsky et al., 1997]. Then, the range of available MHD scales in the plasma sheet spans less than two decades [Borovsky and Funsten, 2003]. Also, non-steady physical conditions such as the motion of the plasma sheet boundary layer (PSBL) and the time evolution of driving and/or dissipation mechanisms strongly influence the estimation of the turbulence characteristics. All these effects, together with the shortness of quasi-steady data sets and the related restricted availability of statistical moments, can lead to spurious estimations of the scaling characteristics in turbulence [Vörös et al., 2004a].

In this paper we analyse anisotropy properties of 67 Hz resolution magnetic field data from the Cluster fluxgate magnetometer (FGM) [Balogh et al., 2001]. Spin-resolution (4s) velocity data from the Cluster ion spectrometry (CIS/CODIF) experiment [Rème et al., 2001] will also be used for comparison and interval selection. The high resolution magnetic field data allows an immersion into the scale or frequency ranges which are not available in velocity measurements. To avoid, at least partly, the difficulties mentioned, we restrict our analysis to second order statistics estimating the magnetic spectral power over small time-scales using the wavelet method of Abry et al. [2000]. Certainly the small-scale spectral power cannot characterize fully the observed fluctuations, but its estimation is less influenced by finite size effects, non-availability of statistical moments or non-stationarity of large-scale driving mechanisms or boundaries. It can still provide, however, important physical insight into the specific conditions of the evolution of BBF and non-BBF associated small-scale magnetic anisotropies.

2. The Wavelet Estimator for the Spectral Power

Abry et al. [2000] proposed a semi-parametric wavelet technique based on fast pyramidal filter bank algorithm for the estimation of scaling parameters $c$ and $\alpha$ in the relation $P(f) \sim c f^{-\alpha}$, where $c$ is a nonzero constant. The algorithm consists of several steps. First, a discrete wavelet transform of the data is performed over a dyadic grid $(\text{scale}, \text{time}) = (2^j, 2^j t)$. Then, at each octave $j = \log_22^j$, the variance $\mu_j$ of the discrete wavelet coefficients $d_j(j,t)$ is computed through:

$$
\mu_j = \frac{1}{n_j} \sum_{i=1}^{n_j} d_j^2(j_i,t) = 2^{\alpha_j} c,
$$

where $n_j$ is the number of coefficients at octave $j$. From Equation (2.1) $\alpha$ and $c$ can be estimated by constructing a plot of $y_j=\log_2 \mu_j$ versus $j$ (a so-called logscale diagram) and by using a weighted linear regression over the region $(j_{\text{min}}, j_{\text{max}})$ where $y_j$ is a straight line. In this paper we use the Daubechies wavelets for which finite data size effects are minimized and the number of vanishing moments can be changed [e.g. Mallat, 1999]. The latter allows cancelling or decreasing the effects of linear or polynomial trends and ensures that the wavelet details are well defined.

When the parameters $\alpha$ and $c$ are estimated from high resolution magnetic data over a frequency range $\geq 1$ Hz, the scaling parameter $\alpha$ is significantly underestimated because of the influence of the magnetometer noise on the linear regression in the log-scale diagram. The estimation of the power $c$ is less affected [Vörös et al., 2004b]. For this reason we will estimate only the power of fluctuations in this paper. Furthermore, to take care of transitory character of the plasma sheet fluctuations, we perform the estimation of the parameter $c$ within sliding overlapping windows of width 30 s with a time shift of 4 s. We also make $c$ dimensionless, by dividing it by the time-averaged level of magnetometer noise power $\langle c_n \rangle$. It has been shown that $\langle c_n \rangle$ is independent of the Cluster magnetometers and spacecraft positions. The dimensionless
power $c$ shows large deviations from the noise level during rapid perpendicular plasma flows [Vörös et al., 2004b].

3. Scale Dependent Power of Magnetic Fluctuations

Our goal is to investigate scale-dependent anisotropy features of magnetic fluctuations associated with BBFs and non-BBF intervals. Magnetic field fluctuations and bursty perpendicular flows are intimately associated. Figure 1 demonstrates this close relationship during the interval 17:50 - 20:00 UT on September 13, 2002, when the Cluster spacecraft were at [-7.5, 2.5, 2.5] R$_E$ in Geocentric Solar Magnetospheric (GSM) position (if not specified, throughout the paper we will use this coordinate system). Figure 1a shows the time series of $B_X$ magnetic component from s/c 1, 3 spacecraft, while the corresponding bursty perpendicular plasma flows are depicted in Figure 1b. Large perpendicular tailward and Earthward flows occur between 18:08 and 19:05 UT. Simple visual examination of $B_X$ reveals, that high frequency magnetic fluctuations are well correlated with the period of rapid plasma flows. Before 18:08 UT and after 19:05 UT, high frequency magnetic fluctuations are absent and longer period fluctuations dominate.

![Figure 1](image)

Figure 1. Event on 2002-09-13; a.) $B_X$ component of the magnetic field from s/c 1,3 spacecraft; b.) proton velocity $V_{\perp X}$ perpendicular to the magnetic field from s/c 1,3 spacecraft.

Both magnetic field and velocity fluctuations have 4s time resolution in Figure 1. From this one can get a feeling that the smallest time scales in magnetic field fluctuations, affected by rapid flows, are of the order of seconds. Indeed, this time scale can be related to the ion-gyroperiod time scale in the plasma sheet (~seconds), where strong dissipation of MHD turbulence structures stops the inertial range cascade of energy into smaller scales. One can envision either strong damping or even destruction of turbulence at these scales [Borovsky and Funsten, 2003]. It was shown, however, that BBF-associated magnetic turbulence also occurs on time scales less than 1 s [Vörös et al., 2003, 2004a,b]. Certainly, these fluctuations can already be affected by kinetic
effects, but we prefer to approach the problem of small scales in plasma sheet magnetic
turbulence experimentally. There exist several reasons supporting that approach. But the main
reason is related to the problem of the cascade picture, inertial range or the scales in turbulence.
An energy cascade in turbulent flows arises when a flow field is described in terms of exchange
of energy, momentum, etc. between scales. The exchange of a certain quantity between scales can
be described in terms of different representations, e.g. in Fourier space, using a wavelet
representation or large eddy simulations, etc. The energy transfer between scales should be
representation independent, but it is not [Tsinober, 2001]. It makes the definition of scales
difficult. The definition of small scales is, however common in all representations: the small
scales are always associated with the derivatives of suitable quantities, usually velocities.
Generally, the small scales contain a great deal of essential physics of turbulent flows, which is
poorly understood at present. These small scales are functionally as well as bi-directionally
related to large scales [Tsinober, 2001; Leubner and Vörös, 2004]. Therefore, we will concentrate
mainly on the small-scale description of fluctuations as is defined within the frame of the wavelet
representation.

There are no physical reasons to restrict the smallest scale of magnetic fluctuations to the
time scale equal or larger than the presumed MHD dissipation scale. In our study the small-scale
(denoted by subscript $s$) is 0.2 s and comes out only from the available resolution of the magnetic
data and from the requirement of the robust estimation of spectral power by the wavelet method.
In our experimental approach, we computed first the small-scale power of magnetic fluctuations
in a coordinate system with axes perpendicular and parallel to the local mean field. The local
mean field was always computed within an interval ten times longer than the actual time scale.
Then the estimation of the spectral power was repeated for gradually increased time scales. Our
goal was to find the nearest neighbour to 0.2 s time scale which exhibits anisotropy features
different from those at the smallest scale. The result is a two-scale wavelet study, which compares
anisotropy features of magnetic fluctuations at time scales 0.2 s and 2 s. The latter is by definition
our large scale (denoted by subscript $L$), though it is not the real large scale of the bursty flows.
We note that both scales are near the presumed dissipation scale.

Figure 2 shows that large deviations from the level of noise power ($c\sim 1$) occur during the
intervals of BBF-associated high frequency magnetic fluctuations. Magnetometer noise can be
identified through its characteristic scaling exponents. For the Cluster spacecraft these parameters
describing the noise component are approximately time- and position-independent. However,
they are slightly different for each spacecraft and magnetic component [Vörös et al., 2004b].
Therefore, in statistical studies comprising magnetic field components or data from different
spacecraft, the use of magnetic powers relative to the corresponding reference noise level is
preferable [Vörös et al., 2004b].

There are two main differences in the time evolution of the small-scale and large-scale
powers: (a.) the large-scale power relative to the reference noise level is more than an order of
magnitude larger than the small-scale power for the same interval (the corresponding absolute
powers are $\sim 1 \text{nT}^2$ and $\sim 0.01 \text{nT}^2$, respectively); (b.) on average during the BBF-associated
magnetic fluctuations $c_{\perp}/c_{||} > 1$ and $c_{\perp}/c_{||} \sim 1$.

The first observation indicates that spectral transfer of energy takes place from large scales to
small scales, confirmed also by a more extensive study of Vörös et al. [2004b]. Inverse cascades
of energy can occur, however, associated with current disruptions in the near-Earth regions [Lui,
1998]. The second observation indicates that magnetic fluctuations relative to the local mean
magnetic field are scale dependent. The anisotropy at larger time scales can be the opposite of
that observed at the small-scale. In fact, Figure 2c shows that the parallel power is stronger than
the perpendicular power after 19:00 UT. Since the occurrence of scale dependent anisotropy features can facilitate a construction of appropriate physical models related to the plasma sheet turbulence, the remaining part of this paper will be devoted to the statistical study of scale-dependent magnetic anisotropies. Previous case-studies [Vörös et al., 2004a,b] were devoted only to the analysis of specific events.

Figure 2. Event on 2002-09-13; a.) $B_X$ component of the magnetic field from s/c 1; b.) small-scale perpendicular ($c_{\perp s}$) and parallel ($c_{\parallel s}$) relative magnetic power; c.) large-scale perpendicular ($c_{\perp L}$) and parallel ($c_{\parallel L}$) relative magnetic power.

We note that by choosing larger scales within the presumed inertial range, our analysis might reveal significant variations of anisotropy features of magnetic fluctuations. In such a case wider analysing windows should be chosen. Therefore, an extension of the present study into larger scales, e.g. to 20 s scale, is possible only after a careful analysis of each individual case, assuring that the estimations are statistically significant. For reliable estimation of the power of fluctuations at the scale of 20 s analysing windows of several minutes would be required. At the same time the duration of rapid flows can be shorter. Therefore, in this paper we limit our preliminary statistical analysis to the dissipative scales.

4. Scale Dependent Anisotropy of Magnetic Fluctuations

We have used the high frequency magnetic field and the spin resolution velocity data from Cluster spacecraft s/c 1 and 3 taken in 2001 and 2002 to select and analyse intervals with $V_{\perp x} < 100$ km/s (non-flow or remnant flow intervals) and $V_{\perp x} > 150$ km/s (rapid flow associated intervals). The limits represent the maximum and minimum values of $V_{\perp x}$, respectively, and the condition $V_{\perp x} > 150$ km/s includes also flows with $V_{\perp x} \sim 1000$ km/s or larger. We have considered 6 periods of ~200 min long non-flow intervals and 6 periods of ~50 min long BBF-associated
intervals. The latter intervals are shorter and can contain also a short time period of transition from Earthward to tailward flow immersed in a predominant rapid flow. To avoid any influence of the low latitude boundary layer and the Earth’s magnetic field dipole effect the selected intervals fulfill the conditions $|Y_{GSM}| < 10 \text{ R}_E$ and $-20 \text{ R}_E < X_{GSM} < -14 \text{ R}_E$.

Figure 3. Non-flow associated statistics; a.) Large-scale scatter plot of magnetic anisotropy versus $B_X$; b.) Small-scale scatter plot of magnetic anisotropy versus $B_X$.

In our preliminary statistical analysis we considered scatter plots of the ratio of perpendicular to parallel power of magnetic fluctuations versus $B_X$. Figure 3a shows the scatter plot obtained at the large-scale and Figure 3b shows the same at the small-scale. In both cases, independent of $B_X$, the majority of points corresponds to isotropic fluctuations: $c_{\perp L}/c_{\parallel L} \sim c_{\perp s}/c_{\parallel s} \sim 1$. The main difference between the two scales is the appearance of significant populations of large-scale magnetic anisotropies, that is, points with $c_{\perp L}/c_{\parallel L} >> 1$. These points seem to be organized roughly into horizontal structures of approximately constant $B_X$. The observed magnetic anisotropy patterns can indirectly be related to the highly anisotropic particle distributions in the PSBL. Instabilities of ion beams were shown to contribute to the spectrum of broadband electrostatic noise in kHz range within the PSBL [Grabbe, 1989]. Ion-beam excited ion-cyclotron modes can convert to low-frequency Alfvén, fast or slow MHD mode waves [e.g. Treumann and Baumjohann, 1997]. It was shown that interactions and decay of MHD waves in the presence of a mean magnetic field can produce wave turbulence with wavevectors preferentially perpendicular to the mean magnetic field [Shebalin et al., 1983; Goldreich and Sridhar, 1995]. This can explain the increase of the perpendicular power of magnetic fluctuations and the appearance of magnetic anisotropy. Counter-streaming ion distributions occur also during quiet conditions within PSBL [Eastman et al., 1984]. In our preliminary study the largest non-flow associated large-scale magnetic anisotropies occur near $|B_X| \sim 30 \text{ nT}$. This particular value reflects the typical $X$-range of Cluster in the plasma sheet. Due to the spatial and temporal variability of the PSBL,
however, the Cluster spacecraft encounter and traverse PSBL at different values of $B_X$ in a relatively short time. Also ion beams can be transient (beamlets) or energetic conditions for the generation of electromagnetic waves would be not met. Short time enhancements of the ion-beam associated magnetic anisotropy at different values of $B_X$ can lead to the observed horizontal structures in the $c_{\perp L}/c_{\parallel L} - B_X$ scatter plot (Figure 3a).

Much less similar horizontal structures of enhanced $c_{\perp s}/c_{\parallel s}$ are present at the small-scale (Figure 3b). When $c_{\perp s}/c_{\parallel s} \sim 1$, one finds also that $c_{\perp s} \sim c_{\parallel s} \sim 1$, which means that the majority of points belongs to the fluctuations associated with magnetometer noise in Figure 3b. Therefore there is no significant spectral transfer of energy between the two adjacent scales during non-flow periods [see also Vörös et al., 2004b].

![Figure 4](image)

Figure 4. BBF-associated statistics; a.) Large-scale scatter plot of magnetic anisotropy versus $B_X$; b.) Small-scale scatter plot of magnetic anisotropy versus $B_X$.

Figures 4a and 4b show the two-scale anisotropy statistics for BBF-associated magnetic fluctuations. The scatter plots are non-symmetrical relative to $B_X = 0$ nT because of the smallness of our database. In comparison with non-flow statistics (Figure 3) the rapid flow associated intervals are shorter and the scatter plots contain less data points. Despite having fewer points the large scale horizontal patterns of anisotropy enhancements are less visible in Figure 4a than in Figure 3a. This indicates that besides the ion-beam instability source within the PSBL perpendicular magnetic fluctuations can be generated by other, BBF-associated mechanisms, related e.g. to large gradients of velocity, pressure or magnetic field which are not restricted to the PSBL. Transverse magnetic structures or velocity shears can redirect the initially parallel propagating waves to highly oblique waves [Ghosh et al., 1998]. In the plasma sheet BBF-associated dipolarization, an increase of $B_Z$, can represent such transverse magnetic structures.
Figure 4b shows a peak of enhanced small-scale anisotropy around $B_X = 0$ nT. It implies that the small-scale power of perpendicular magnetic fluctuations is increasing towards the neutral sheet. It can partly be explained by occurrence of decaying magnetic turbulence in a high-beta plasma, energized by BBFs. Since it is the result of the interaction of the plasma flow with the magnetic field, we can consider the enhanced level of magnetic anisotropy as a small-scale counterpart of BBF-associated magnetic field dipolarization. At the same time, the occurrence of the narrow maximum in Figure 3b at $B_X = 0$ nT indicates that at least a portion of the observed anisotropies is independent of the plasma flow, being a pure current sheet effect.

Near $B_X = 0$ nT and for $|B_X| \geq 20$ nT the anisotropy is scale dependent. In the first case the small-scale anisotropy (Figure 4b) is larger than the large scale anisotropy (Figure 4a). In the second case the opposite is true. In absence of rapid flows the occurrence of small-scale fluctuations near $B_X = 0$ nT is strongly reduced because of the lack of spectral transfer of energy to small scales (Figure 3b).

5. Conclusions

We used a wavelet method for the estimation of the perpendicular and parallel power of magnetic fluctuations relative to the local mean magnetic field. The magnetic power is estimated at two adjacent scales. Both scales were chosen close to the ion gyroperiod, where strong dissipation of MHD structures presumably stops the inertial range cascade of energy into smaller scales. Our goal was to find two neighbouring scales with different anisotropy characteristics of magnetic fluctuations. The two-scale study allowed us to identify characteristic anisotropy patterns associated with non-flow and rapid flow (BBF) periods. Physical mechanisms are proposed which could explain the observed anisotropy patterns and their sources. Non-flow associated magnetic anisotropies appear mainly within the PSBL due to the occurrence of anisotropic ion beams. BBF-associated magnetic anisotropies can be driven by the interaction of the rapid plasma flows with the background magnetic field and essentially are not restricted to the PSBL. BBFs can energize decaying magnetic fluctuations exhibiting scale dependent anisotropy features near the neutral sheet and close to the PSBL. These dissipative scale anisotropy patterns can be regarded as a counterpart of the BBF-associated dipolarizations of the magnetic field. During non-flow intervals magnetic fluctuations appear rarely near the neutral sheet and seem to be related to a pure current sheet effect.

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References


