TURBULENCE-GENERATED PROTON-SCALE STRUCTURES IN THE TERRESTRIAL MAGNETOSHEATH

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ABSTRACT

Recent results of numerical magnetohydrodynamic simulations suggest that in collisionless plasma, turbulence can spontaneously generate thin current sheets. These coherent structures can partially explain the intermittency and the non-homogenous distribution of localized plasma heating in turbulence. In this Letter, Cluster multi-point observations are used to investigate the distribution of magnetic field discontinuities and the associated small-scale current sheets in the terrestrial magnetosheath downstream of a quasi-parallel bow shock. It is shown experimentally, for the first time, that the strongest turbulence-generated current sheets occupy the long tails of probability distribution functions associated with extremal values of magnetic field partial derivatives. During the analyzed one-hour time interval, about a hundred strong discontinuities, possibly proton-scale current sheets, were observed.

Key words: magnetic fields – magnetic reconnection – plasmas – turbulence

1. INTRODUCTION

Downstream of the terrestrial bow shock (BS), the supersonic and super-Alfvénic solar wind flow slows down and gets compressed and heated. The solar wind is diverted by the strong geomagnetic field at the magnetopause (MP). The magnetosheath (MS) is the region between the BS and the MP, where the field and plasma fluctuations are rather strong. Numerical simulations (Karimabadi et al. 2014; Omidi et al. 2014) demonstrate the complexity of this region—being populated by various interacting multi-scale structures, such as filaments, vortices, current sheets, plasma jets, and flows. In situ measurements from different missions also revealed the existence of nonlinear structures in upstream and downstream BS regions, for example, shocklets (Hoppe et al. 1981), short-duration large-amplitude magnetic structures (Lucek et al. 2004), and hot-flow anomalies (Facskó et al. 2009) embedded in the highly turbulent MS. Some of these nonlinear structures are also associated with enhanced levels of wave and fluctuation activity (Kovács et al. 2014). The fluctuations and structures are more pronounced in the quasi-parallel BS configuration when the angle between the interplanetary magnetic field and the nominal BS normal is smaller than 45°. In such a case, the upstream (solar wind, foreshock) and downstream MS regions are magnetically connected and the resulting turbulence becomes increasingly intermittent away from the BS (Yordanova et al. 2008).

In turbulent space plasmas, thin magnetic structures, current sheets, and reconnection can be generated spontaneously through complex interactions (Chang et al. 2004; Servidio et al. 2009; Mattheus et al. 2015). Furthermore, recent studies on the statistics of velocity gradient tensor invariants revealed that approaching the non-MHD scales, vortex stretching may play a relevant role in generating small-scale dissipative structures (Consolini et al. 2015). These structures observed as discontinuities in the solar wind (Greco et al. 2009) are associated with local dissipation/heating (Osman et al. 2012, 2014) and introduce intermittency to plasma turbulence. The occurrence frequency of discontinuities in the solar wind agrees rather well with the statistics of turbulence-generated current sheets in numerical simulations (Greco et al. 2008, 2009; Servidio et al. 2011). Cluster observations in MS downstream quasi-parallel BS also confirmed the occurrence of reconnecting thin current sheets (Retinó et al. 2007; Sundkvist et al. 2007) and the current sheet associated electron heating (Chasapis et al. 2015).

Numerical simulations have shown that the strongest discontinuities and current sheets generated by turbulence populate the tails of non-Gaussian probability distribution functions (PDFs) of the normalized current density (Greco et al. 2009; Mattheus et al. 2015). However, this has not been shown directly from the data. Although it is tempting to assume that the fat tails of the PDFs are completely determined by turbulence-generated strong current sheets, one should not forget that there might exist other intermittent structures of different origin. As a matter of fact, the high Reynolds number simulations of MHD turbulence (Greco et al. 2009; Servidio et al. 2011) cannot reproduce the rich ensemble of intermittent nonlinear structures mentioned above. In this Letter, using Cluster data in the MS downstream of quasi-parallel BSs, we show that the strongest observed current sheets de facto occupy the tails of histograms. We also estimate the occurrence frequency of the strongest current sheets along the trajectory of the Clusters spacecraft. The paper is organized as follows. Section 2 explains the data and instrumentation and Section 3 introduces the structure detection tools. Section 4 demonstrates how the structure detection tools work for a thin current sheet. In Section 5, discontinuity and current sheet statistics is presented. Section 6 contains the summary and conclusions.

2. DATA AND INSTRUMENTATION

In this Letter we consider the data interval between 9.6 and 10.6 UT (decimal hours) on 2002 March 27 when the Cluster
spacecraft probed the magnetosheath downstream of a quasi-
parallel BS. OMNI 1 minute data have been used to obtain the
model BS (Farris & Russell 1994) and magnetopause (Shue
et al. 1998) boundaries as well as the normal vector to the BS.
The Cluster fleet was initially at the GSE coordinate system
position (10, −8.2, −8) RE, moving ~1RE toward the
magnetopause in a nearly perfect tetrahedron configuration
with inter-probe separations of about 100 km. The relative
positions of the spacecraft are shown in Figure 1. The upstream
plasma and field conditions in the solar wind were quasi-
stationary with average parameters—magnetic field ∼3.4 nT,
velocity ∼446 km s⁻¹, and density ∼3 cm⁻³.

During the selected interval, the magnetic field measure-
ments were available from the FGM instrument (Balogh
et al. 1997) with sampling frequency f₁ = 67 Hz, and from the
STAFF instrument (Cornilleau-Wehrlin et al. 1997) with
f₂ = 450 Hz. Using a finite impulse response filter at ~1 Hz,
the magnetic data from both instruments were merged into one
time series with extended frequency coverage up to 450 Hz in
burst mode. The electric field data were available from the
EFW instrument (Gustafsson et al. 1997).

3. STRUCTURE DETECTION TOOLS

Current sheets associated with large-scale boundaries such as
the magnetopause or the magnetotail current sheet can be easily
identified. Even if the boundaries are moving or the structures
are flapping, the same current sheet can be observed multiple
times. On the other hand, turbulence-generated boundaries and
the associated current sheets are small-scale and transient in the
spacecraft frame. Their identification requires special methods.
To detect discontinuities and current sheets in the magne-
tosheath, three types of parameters will be estimated from
Cluster spacecraft pairs (Ci – Cj, i, j = 1, 2, 3, 4) in time t: (1)
the Partial Variance of Increments (PVIₖ(t)); (2) the angle
between magnetic field vectors θ_k(t); and (3) the magnetic field
derivatives ∂_j(t).

The method using PVIs was first introduced to identify
discontinuities within the intermittent solar wind turbulence
from a single point measurement. The results have also been
supported by numerical simulations (Greco et al. 2009). The
PVIs here are calculated on the basis of the normalized
variance of the absolute value of magnetic field spatial
increments between two spacecraft δB_j(t) = B_i(t) − B_j(t):

\[
PVI_j(t) = \sqrt{\frac{\langle |\Delta B_j(t)|^2 \rangle}{\langle |\Delta B_j(t)|^2 \rangle}},
\]

where the average ⟨⟩ is taken over the whole interval. The
mean PVI_m(t) = \sum_j PVI_j(t)/6 is also calculated. In contrary
to the standard one-directional PVI (Greco et al. 2008), PVIₘ
comprises information on increments along all Ci–Cj pairs in the
Cluster tetrahedron. In recent 3D simulations of MHD
turbulence, a similar multi-directional PVI was used, arguably
providing an unbiased information about the spatial structure of
discontinuities (Zhang et al. 2015).

The rotation of the magnetic field vector between spacecraft
pairs is estimated through

\[
\theta_k(t) = \cos^{-1} \frac{\mathbf{B}_i(t) \cdot \mathbf{B}_j(t)}{|\mathbf{B}_i(t)| \cdot |\mathbf{B}_j(t)|}
\]

The partial derivatives of the magnetic field are obtained from

\[
\partial_j(t) \equiv \frac{\Delta B_j(t)}{\Delta r_j(t)}
\]

where δr_j(t) is the spatial separation between Ci, Cj pairs and
∂_j stands for the partial derivatives ∂B_x/∂X, ∂B_y/∂Y,
∂B_z/∂Z, etc. These form the orthogonal components of
(∇ × B)xyz and (∇ · B)xyz. For supposedly time-independent
short events with roughly constant (∇ × B)xyz and for linearly
changing magnitudes of magnetic components over the
tetrahedron, the current density \( j = (\nabla \times \mathbf{B})/\mu_0 \) (\( \mu_0 \) is the magnetic constant) can be
calculated.

It has already been shown that the parameters PVI and θ are
correlated. Discontinuities with high values of PVI are
associated with large magnetic rotations θ > 90° (Chasapis
et al. 2015b). The joint occurrence of strong magnetic shear
and high PVI indicates that the corresponding discontinuity is a
current sheet. More about structure detection tools in
turbulence can be found in Chasapis (2015a). For the studied
interval, the correlations are demonstrated in Figure 2. The left
panels 2(a)–(d) show the magnetic field intensity for C1, the
PVI magnitude for the spacecraft pair C1–C4, the magnetic
field rotation angle for the same pair of probes, and the partial
derivatives for the B_z components of the magnetic field. The
parameters from the other spacecraft or spacecraft pairs look
similar (not shown). The right panels 2(e)–(h) show the PDFs
corresponding to the time series on the left. The maxima of the
PDFs are normalized to one. Gaussians with the same standard
deviations are inserted as well. Although the PDF of B(C1) is
the closest to the Gaussian distribution, there are significant
deviations from it near the peak value. It indicates that various
physical processes with different magnetic PDFs can form the
summary histogram within the analyzed interval. The large
deviations from the Gaussians for the other parameters are
evident near the maxima and at the tails of PDFs. Since the
strongest discontinuities or (reconnecting) current sheets are
expected to form the tail of PDFs (Greco et al. 2009), we are
interested in correlations between the extremal values of PVI_j,
θ_j and ∂_j. The green boxes in panels 2(a)–(d) show a few sub-
intervals of the data when the threshold PVI(C1–C4) = 4
selects intervals of large deviations of θ_j and ∂_j as well.

4. AN EXAMPLE CURRENT SHEET

Figure 3 shows a crossing of a thin proton-scale (~0.5 s)
current sheet by the Cluster fleet, for which Chasapis et al.
(2015b) found electron heating signatures. For this event the
Figure 2. Left panels (a)–(d): magnetic field intensity for C1; PVI magnitude for C1–C4 with threshold 4 (dashed green line); magnetic field rotation angle for C1–C4; and partial derivatives of the magnetic field $B_Z$ component. The boxes outlined in green show examples of detected discontinuities above the given threshold PVI = 4. Right panels (e)–(h): PDFs (histograms) corresponding to the data on the left. Gaussian distributions are shown in blue.

Figure 3. Example of a current sheet. This event and the current associated electron heating have already been studied by Chasapis et al. (2015b). (a) Normal electric field $E_x$; (b) $B_Z$ components of the magnetic field; (c) partial variances of increments: $PVI(C_i-C_j, t) \equiv PVI_{ij}(t)$ and $PVI_{im}(t)$; (d) magnetic field rotational angles $\theta(C_i-C_j, t) \equiv \theta_{ij}(t)$; (e)–(g) partial derivatives of magnetic field components.
GSE coordinate system was shown to be very close to the current sheet system. The panels show the bipolar change of the electric field $E_X(C2)$ (a), the $B_Z(C1, C2, C3, C4)$ components of the magnetic field (b), PVI for spacecraft pairs and the mean PVI magnitude with three levels of threshold (horizontal lines in red, blue, and black) and their respective current sheets (colored dots). The five strongest discontinuities are color coded in red, magenta, blue, green, and brown. The arrows mark the positions of the two selected events (1 and 4) in (a)–(c) (previously studied by Chasapis et al. (2015b)) and (d)–(f) (previously studied by Retinò et al. (2007)); (h) and (i) show the discontinuity thickness and number vs. PVI, respectively.

5. CURRENT SHEET AND DISCONTINUITY STATISTICS

The potential discontinuities in the data can be found using the mean PVI. In any case, however, the PVI thresholds should not be considered as unique parameters identifying the thin current sheets. For the selected cases here we considered all the parameters shown in Figure 3 and visually checked the events. The usefulness of PVI is demonstrated in Figure 4(g), where three different thresholds (red, blue, and black horizontal lines) and the corresponding time instants—points—are shown. The red, blue, and black populations of points correspond to the PVI thresholds of the same color. The first five discontinuities are numbered and color coded by red, magenta, blue, green, and brown. This color code is also used in Figure 5 to indicate the location of discontinuities in a histogram. The first discontinuity (magnetic components are depicted in Figures 4(d)–(f)) is a magnetic reconnection event described thoroughly by Retinò et al. (2007). The second discontinuity is a current sheet with $B_y$ sign changes, and the third discontinuity is a more complicated event comprising crossings of two neighboring current sheets. The fourth discontinuity (Figures 4(a)–(c)) was identified as a current sheet associated with electron heating by Chasapis et al. (2015b). For these current sheets, the maxima of $\theta_y$ are close to 180°. The fifth discontinuity is a current sheet where the maxima of $\theta_y$ are less than 120°, which is still a very high magnetic shear angle (Chasapis et al. 2015b).
Figure 5. PDF calculated from extremal values of magnetic field partial derivatives. The first five strongest discontinuities from Figure 4(g) are color-coded points at the tail of the PDF. Black points show the data, and green lines correspond to Gaussian distributions.

Figure 4(h) shows the largest thickness of discontinuities in seconds for changing thresholds PVIm. It is calculated as a local duration of a discontinuity in time, with PVIm ≥ threshold. Since for a given threshold a discontinuity may be represented by one PVIm ≥ threshold value only, the smallest thicknesses are often close to 0 s. Therefore, the mean discontinuity thickness has no meaning. However, the largest thickness (Figure 4(h)) together with the total number of detected discontinuities (Figure 4(i)) for a given PVIm threshold provides information about the minimum number of discontinuities with thicknesses equal to or smaller than the largest thickness. The comparison of Figure 4(h) with Figure 4(i) shows that for very thin structures, for example with a duration of less than one second (possibly current sheets), there exist almost one hundred discontinuities during the analyzed magnetosheath interval. Nevertheless, Figure 4(g) demonstrates that the strongest discontinuities represent a tiny part of the time series only. In order to show that the intermittently occurring rare current sheets belong to the tails of PDFs, as is expected from 2D MHD simulations of current density distributions (Greco et al. 2009), the PDF(j) should be obtained directly from the data. Although non-Gaussian skewed distributions are typical for space plasmas (Burlaga & Ness 1998; Vörös et al. 2015), the direct estimation of j from in situ data is difficult. The curlometer technique provides an estimate of \( \nabla \times B \), but it is loaded by several known sources of errors (Vallat et al. 2005). The curlometer works satisfactorily for well selected, short, and stationary events with a linear variation of B inside the tetrahedron. This is not the case for the entire one-hour interval analyzed here. To reconstruct the whole PDF(j), the localized strong currents (PDF tail), the nearly current-free flux tube regions, and the random transient currents (central part of the PDF) should all be involved in a histogram. However, the quality of the current density estimation for the considered time interval is low. This can be deduced from the ratio \( \text{div} B / |\nabla \times B| \), which has values \( \gg 1 \) for large parts of the data. For good quality (j) estimations, it should be \( \ll 1 \) (Grimald et al. 2012). This is why instead of the derived quantity \( \nabla \times B \), which can also be burdened with additional errors, we use the partial derivatives \( \partial_{ij} \) for further statistical investigations. However, as Figures 3(e)–(g) show, some of the \( \partial_{ij} \)s are close to zero even during current sheet crossing. On the other hand, there exist nonzero \( \partial_{ij} \) values which are not associated with the current sheet. The simplest way to obtain PDF(\( \partial_{ij} \)) is to take the extreme value of \( \partial_{ij}(\text{extr}, t) = \max(\partial_{ij}(t)) \) or \( =\min(\partial_{ij}(t)) \) at times t. Physically, we select structures that are associated with the largest magnetic gradient between spacecraft pairs in the tetrahedron volume at times t. The result is shown in Figure 5. The black points correspond to the histogram of the entire time series of \( \partial_{ij}(\text{extr}, t) \). The left (negative values) and the right (positive values) of PDF(\( \partial_{ij}(\text{extr}) \)) are obtained independently. Since the extreme value distribution has very low occurrence frequencies for small values of derivatives, the central noisy part of the histogram for \(-0.05 < \partial_{ij}(\text{extr}) < 0.05 \) (nT km\(^{-1}\)) is cut off. The color-coded points on the PDF curve, according to their \( \partial_{ij} \)(extr), correspond to the five current sheets for different thresholds PVIm shown in Figure 4(g). We note that the boxes in histograms near a given value of \( \partial_{ij} \)(extr) contain contributions from many other time intervals. Nevertheless, for
the purposes of this study, it was enough to show that the strong discontinuities belong to the histogram boxes at the tails of PDFs. The green curves in Figure 5 correspond to Gaussian distributions. The smallest values are normally distributed, while at the non-Gaussian tail the strongest discontinuities are observed, as is expected from numerical simulations (Greco et al. 2009; Servidio et al. 2009; Matthaeus et al. 2015). The wider Gaussian in Figure 5 has the same mean and standard deviation as the data. The narrower Gaussian represents a fit to the central part of the histogram, shown to indicate the strong deviation of the tails from the normal PDF. The PDF values between the two Gaussian curves are expected to correspond to magnetic structures, possibly flux tubes (Greco et al. 2009).

6. SUMMARY AND CONCLUSIONS

The main aim of this study was to show that the thin current sheets identified by simple structure detection tools populate the fat tails of PDFs. This has already been shown for the histograms of the normalized current density in MHD turbulence simulations (Greco et al. 2009; Matthaeus et al. 2015). However, in simulations the identification of current and magnetic structures forming the non-Gaussian PDF \( j \) is straightforward. Although the four-point curlometer technique is an excellent tool for estimating \( j(t) \) from four-spacecraft data, it works well for selected short events only. The two-point magnetic field differences have already been used previously in turbulence studies to obtain the long tail PDFs (Vörös et al. 2006) and to identify the intermittency effects (Yordanova et al. 2015). The extremal values of magnetic field partial derivatives calculated between spacecraft pairs are also associated with thin current sheets. We found that the strongest current sheets associated with \( \partial_\phi j(\text{extr}) \) belong to the tails of PDF(\( \partial_\phi j(\text{extr}) \)), confirming the results of MHD turbulence simulations on the generation of intermittent structures (Greco et al. 2009; Matthaeus et al. 2015). It was also found that over one hour Cluster observed about a hundred thin magnetic structures in the MS downstream of a quasi-parallel BS that might be associated with non-homogenous localized heating of plasma. This conjecture has to be confirmed by a thorough analysis of similar events using high-resolution field, particle, and plasma data from the MMS mission. Our results also demonstrate that a conditional selection of structures and their identification in histograms (PDFs) represents a powerful tool for better understanding of the role of rare but intense events (in our case strong discontinuities or reconnection sites), which can determine the basic physical properties of plasma systems.

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