Observations of turbulence within reconnection jet in the presence of guide field


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We present the first comprehensive observations of turbulence properties within high speed reconnection jet in the plasma sheet with moderate guide field. The power spectral density index is about $-1.73$ in the inertial range, and follows the value of $-2.86$ in the ion dissipation range. The turbulence is strongly anisotropic in the wave-vector space with the major power having its wave-vector highly oblique to the ambient magnetic field, suggesting that the turbulence is quasi-2D. The measured “dispersion relations” obtained using the k-filtering technique are compared with theory and are found to be consistent with the Alfvén-Whistler mode. In addition, both Probability Distribution Functions and flatness results show that the turbulence in the reconnection jet is intermittent (multifractal) at scales less than the proton gyroradius/inertial lengths. The estimated electric field provided by anomalous resistivity caused by turbulence is about 3 mV/m, which is close to the typical reconnection electric field in the magnetotail. Citation: Huang, S. Y., et al. (2012), Observations of turbulence within reconnection jet in the presence of guide field, Geophys. Res. Lett., 39, L11104, doi:10.1029/2012GL052210.

1. Introduction

[2] Turbulence, as an inherently nonlinear phenomenon, is observed in most space plasmas such as the solar wind, the Earth’s magnetosheath, the magnetotail, the polar cusp region and the high latitude ionosphere (see a comprehensive review in Zimbardo et al. [2010]). Turbulence is believed to play an important role in controlling and affecting plasma process within the plasma sheet. Turbulence in the plasma sheet of the Earth’s magnetosphere has been studied intensively in the past decades [e.g., Borovsky and Funsten, 2003; Vörös et al., 2004; Weygand et al., 2005].

Recently, it was found that magnetic fluctuations in the plasma sheet have multi-scale features [Vörös et al., 2004] and that the plasma sheet turbulence is intermittent [Weygand et al., 2005].

[3] Magnetic reconnection is a fundamental dissipative process that enables reconfiguration of magnetic field topology and converts magnetic energy into plasma kinetic and thermal energies. There is often a close relation between magnetic reconnection and turbulence. Recently, three-dimensional (3D) kinetic simulations showed that magnetic reconnection evolves into turbulence in a later phase and shows spontaneously formation of new flux ropes [Daughton et al., 2011] or complex web of current filaments [Che et al., 2011]. Turbulence within a magnetic reconnection ion diffusion region has been studied [Eastwood et al., 2009]. Reconnection-associated multi-scale fluctuations have been also reported [Vörös et al., 2008]. In-situ evidence of reconnection in the turbulence plasma has been observed downstream of the Earth’s bow shock [Retinò et al., 2007] and Sundkvist et al. [2007] studied magnetic energy dissipation in turbulent plasma due to reconnection in the downstream of bow shock. In addition, global magnetohydrodynamic simulation showed the importance of strong localized reconnection regions in driving turbulence in the plasma sheet [El-Alaoui et al., 2010]. Therefore, the observations and analysis of turbulence associated with reconnection in space are crucial for improving our understanding of both turbulence and reconnection. In this letter, we investigate properties of turbulence within high speed reconnection jet in the plasma sheet with moderate guide field measured by the Cluster spacecraft. We used the magnetic field and the plasma moments data from FGM, CIS and STAFF instruments [Escoubet et al., 1997].

2. Observation and Analysis

[4] The earthward reconnection jet analyzed here was observed on 17 August 2003, when the Cluster spacecraft were located at around (~16.8, 5.6, 3.2) R$_E$ (the Earth’s radius) in the Geocentric Solar Magnetospheric (GSM) coordinates with spacecraft separations of about 220 km. Figure 1 shows an overview of the Cluster-4 observations between 16:54 UT and 17:06 UT. The Cluster spacecraft are first in the lobe region where $|B_x|$ is very large and the plasma $\beta$ is low (before 16:55 UT), typically $\beta < 0.05$, where $\beta = V_b^2/nm^2$. Later on the Cluster spacecraft enter the plasma sheet where $|B_x|$ becomes smaller and $\beta$ is higher (~1). In the plasma sheet, the spacecraft detect high speed earthward flow ($V_x$ up to 1300 km/s, see Figure 1b). The Cluster spacecraft enter into the central plasma sheet after 17:03 UT.
Before detecting the earthward flow, the Cluster spacecraft detect a tailward flow between 16:33 UT and 16:52 UT (not shown). Associated with the tailward flow, $B_z$ is mostly negative, while $B_z$ is positive in the earthward flow. The correlated change of the plasma flow $V_x$ and the magnetic field $B_z$ suggests that a tailward retreating X-line has passed the spacecraft and that the observed earthward flow is close to X-line. This fast earthward flow lasts about 8 minutes (from 16:55:10 UT to 17:02:40 UT), where $\beta \sim 1$ (typical value in the plasma sheet) and $N \sim 0.25 \text{ cm}^{-3}$. The proton temperature (Figure 1d) in the earthward flow is much higher than the temperature in other regions, such as the central plasma sheet, which implies that protons have been heated by reconnection. Actually, the average value of $B_y$ is $\sim -15 \text{ nT}$ (60% of the asymptotic magnetic field of about 25 nT) during the earthward flow. The negative
magnetic field $B_z$ agrees with the expected polarity of Hall magnetic field in the southern hemisphere of the earthward of the X-line (positive $V_z$ and negative $B_z$), suggesting the spacecraft may have observed an ion diffusion region with moderate guide field. Summarizing, the Cluster detect a high speed earthward reconnection jet in the plasma sheet with moderate guide field.

[6] There are large fluctuations in $B_z$ and $B_y$ associated with this earthward reconnection jet. Figure 1f shows the Fourier power spectra of magnetic field measured by the four Cluster spacecraft during the reconnection jet (the dashed grey line is the power spectra of lobe data that reflects the sensitivity level of the FGM instrument). There is a clear breakpoint around the proton cyclotron frequency. Assuming that we observed spatial fluctuations Doppler-shifted by jet velocity, the breakpoint is also around the proton gyro-radius or the inertial length scale ($\beta \sim 1$) [Sahraoui et al., 2009]. The power spectrum in the low frequency range follows a power law with a slope of about $-1.73$ close to $-5/3$, the scaling of the so-called Kolmogorov spectrum [Kolmogorov, 1941], and similar to other observations in the reconnection diffusion region [Eastwood et al., 2009; Huang et al., 2010]. This slope falls also in the range reported by, e.g., Weygand et al. [2005]. Above the spectral break, i.e., in the ion dissipation (or the dispersive) range, the power spectrum steepens to $f^{-2.86}$.

[7] To determine the wave vectors of turbulence, we apply the $k$-filtering technique to the magnetic field measured by the four Cluster spacecraft. This technique allows one to estimate the magnetic field energy distribution in the frequency and wave vector domain ($\omega$, $k$), using data measured simultaneously in different points in space without any assumption about the linear or nonlinear nature of the underlying physics [Pincon and Lefeuvre, 1991; Sahraoui et al., 2003, 2010a]. The parameters of the Cluster tetrahedron, namely the elongation ($E \sim 0.2$) and the planarity ($P \sim 0.25$), guarantee a good 3D spatial coverage of the magnetic field variations [Robert et al., 1998]. We divided the whole time interval into four sub-intervals denoted in Figure 1 in order to eliminate as much as possible the influence of rotations in the magnetic field and/or reversal of the plasma flow (to guarantee a good estimation of the Doppler-shift). Figure 2a shows the angles ($\theta_{kB}$) between wave-vectors estimated from the $k$-filtering method and the ambient magnetic field (obtained by averaging over each sub-interval) for each frequency of the interval denoted in Figure 1f. The angles ($\theta_{kB}$) vary between 75° and 120°, with an average value around 95°. These results show clearly that the wave vectors are highly oblique to the ambient magnetic field and that turbulence is strongly anisotropic in the wave-vector space.

[8] To identify the nature of the plasma modes in our observations we compare the wave vector $k$ and the frequency $\omega$ obtained from the $k$-filtering in the plasma rest frame to linear solutions of the Maxwell-Vlasov kinetic theory obtained using WHAMP [Rönntmark, 1982] for the observed plasma parameters in each time interval. As stated above, the $k$-filtering does not assume any linear physics to be at work. The comparison to linear theory aims only at testing whether one can still recognize any linear dispersion relation in the data. Although linear properties of plasmas modes have been reported in several space observations and numerical simulations of fully developed turbulence [Sahraoui et al., 2010b; Howes et al., 2011], a debate still exist as to how relevant is (quasi-)linear approach to understand strong plasma turbulence [e.g., Dmitruk and Matthaeus, 2009].

[9] The result of the comparison to linear kinetic theory is displayed in Figure 2b. We find only three undamped modes in kinetic theory, i.e., fast, Bernstein, and Alfven-Whistler modes (the slow magnetosonic mode, being strongly damped by kinetic effects, is not presented here). To estimate the error bars in the figure we considered 5% uncertainty of flow velocity and empirical estimation of the uncertainty in the wave vectors given in Sahraoui et al. [2010a]. We can see that the observed dispersion relations are generally consistent with the kinetic Alfven mode (KAW) ($\omega \leq \omega_{ci}$) and with its extension at high frequency ($\omega > \omega_{ci}$) on the whistler branch (when $\beta_1 \geq 2$) [Sahraoui et al., 2012]. This mode is referred to, in both frequency ranges, as the Alfven-whistler mode [Huang et al., 2010; Sahraoui et al., 2012]. Note however that in interval 1 and 2 we observe some frequencies higher than $f_{sw}$, while the KAW mode does not extend to those high frequencies (due to damping by cyclotron resonances). Figure 2b also shows the curve of the Doppler shift $\omega_{sc} = k \cdot V_t$ that indicates how valid is the Taylor assumption (when $\omega \ll k \cdot V_t$) [e.g., Vörös et al., 2006b] which allows to infer spatial variations from the observed temporal ones. The observed dispersion dots that are “far” below the Doppler shift curves (black dashed lines) would satisfy the Taylor assumption, while the dots lying near (or above) that curve would violate that assumption (this is particularly true for interval 2).

[10] An earlier study has found that the observed turbulence in the reconnection diffusion region without obvious guide field satisfies the dispersion relation of the fast-whistler mode having the wave vectors almost parallel to the ambient magnetic field [Eastwood et al., 2009]. This contrasts with our finding that the wave vectors are highly oblique to the ambient magnetic field. One possible explanation for the difference can be that in our case the Cluster spacecraft observed a high speed earthward reconnection jet in the plasma sheet with moderate guide field while the earlier study has dealt with the case of reconnection without a guide field. Possible interaction of parallel Alfvénic fluctuations with local perpendicular 2D structures has been suggested to exist in the high-speed flow [e.g., Vörös et al., 2006a]. More detailed studies are required to distinguish the cause of the difference in the orientation of the turbulence wave vectors.

[11] To analyze the turbulence in more details, we calculate the probability distribution functions (PDFs) and their normalized fourth order moment, known as the flatness, of the increments of magnetic field component $B_z$ which is usually considered as the reconnection component. We calculated the PDFs using the function: $\delta b(t) = (B_z(t + \tau) - B_z(t))$, where $B_z(t)$ is magnetic field component $B_z$ at time $t$ and $\tau$ is the time lag [Weygand et al., 2005]. Figure 3a shows the PDFs of the increments of $B_z$ for different values of $\tau$. The black line in the figure is the theoretical result for a random Gaussian process. Before estimating the PDFs, we removed a running average of 1000 s from the magnetic field time series [Weygand et al., 2005]. If the fluctuations are random, their PDFs should be nearly Gaussian. We can see that the PDFs of the increments of $B_z$ are nearly Gaussian at large scales (i.e., large time
lags $\tau$, typically $\tau > 11$ s) and depart from Gaussianity by developing significant wings at smaller values of $\tau$.

The corresponding flatness is given in Figure 3b. For a Gaussian process, the value of flatness is equal to 3. We can see that the flatness is about 3 for time lags larger than 10 s, which means that the increments of $B_z$ in this scale range is close to Gaussian process. For smaller time lags the flatness increases monotonically, which indicates that the increments of $B_z$ are not globally scale invariant, or equivalently, that turbulence is intermittent (or multifractal) [Frisch, 1995]. The intermittent turbulence within reconnection jet is consistent with the previous observations of plasma sheet turbulence [Weygand et al., 2005]. Our results are also similar to previous results reported in the turbulent plasma due to reconnection downstream of the Earth’s bow shock [Sundkvist et al., 2007].

3. Summary and Discussion

There are many possible sources of turbulence in the plasma sheet, such as the solar wind variations, shear flow instabilities, MHD instabilities, or reconnection itself. One
In-situ evidence of reconnection in the turbulent plasma sheet [e.g., Büchner et al., 2006] has found that the reconnection rate $C_0/C_24$ Daughton et al. [2011] have found that the reconnection rate $C_0/C_24$ Eastwood et al. [2004] in the ion dissipation/dispersive turbulent plasma sheet [e.g., Huang et al., 2010], we can estimate the role that turbulence in the reconnection jet are close to the diffusion region or X-line. Assuming that the turbulence properties in the reconnection jet are close to the diffusion region or X-line. It has been suggested that the fluctuations in reconnection with guide field can give rise to much higher anomalous resistivity than the case without guide field [Zeiler et al., 2002]. In addition, Che et al. [2011] have found that the reconnection rate increases abruptly when the current layers spread into a complex web of filaments which manifests as electromagnetic turbulence.

In summary, we have comprehensively investigated turbulence within a reconnection jet in the plasma sheet measured by the Cluster spacecraft during the reconnection event in the presence of moderate guide field. The power spectrum of the magnetic fluctuations at low frequency follows a power law close to the Kolmogorov spectrum $f^{-5/3}$, and then steepens to $f^{-2.5}$ in the ion dissipation/dispersive range. The turbulence is intermittent within the reconnection jet at scales smaller than the proton gyroradius or inertial lengths. Using the $k$-filtering method, we found that the wave vectors are highly oblique to the ambient magnetic field, which suggests that the turbulence is quasi-2D in the reconnection jet. The black curve represents a Gaussian distribution. The flatness is deduced from FGM data when $\tau > 1$, and from STAFF waveform data when $\tau < 1$. The horizontal red and blue lines show temporal signatures of proton gyroradius and inertial length scales as the same in Figure 1. The black dashed horizontal lines is one that flatness $=3$.

**Figure 3.** (a) Probability distribution functions of $B_\perp$ at indicated time lags $\tau$. The black curve represents a Gaussian distribution. (b) Flatness ($K = \langle (B_2 - \langle B_2 \rangle)^4/\langle (B_2 - \langle B_2 \rangle)^2 \rangle^2 \rangle$) of the magnetic field component $B_\perp$ as a function of the temporal lag $\tau$. The flatness is deduced from FGM data when $\tau > 1$, and from STAFF waveform data when $\tau < 1$. The horizontal red and blue lines show temporal signatures of proton gyroradius and inertial length scales as the same in Figure 1. The black dashed horizontal lines is one that flatness $=3$.Important source of turbulence is the rapid variations associated with localized reconnection. The existence of strong localized reconnection regions with high speed jets were considered as the main process driving turbulence in the plasma sheet [El-Alaoui et al., 2010]. In our case, the solar wind conditions are relatively quiet, and thus the external sources could not have driven the turbulence observed here. The magnetic field of the plasma sheet, detected after the reconnection jet was relatively stable, indicating that there are no obvious instabilities. Therefore, we suggest that the turbulence is driven by high speed reconnection jet, and this turbulence is much more strongly driven than the one in an ordinary plasma sheet.

Turbulence, while being driven by magnetic reconnection of the associated bursty reconnection outflow, might be able to feedback the plasma and to produce favorable conditions for magnetic reconnection, or to enhance the reconnection rate [Vörös et al., 2008; Servidio et al., 2010]. Recent kinetic simulations showed the 3D reconnection develops into a turbulent phase [Che et al., 2011; Daughton et al., 2011]. In-situ evidence of reconnection in the turbulence plasma sheet has been observed downstream of the Earth’s bow shock [Retinò et al., 2007]. Therefore, there may be a possible repeating cycle, “reconnection→bursty bulk flow→turbulence→reconnection” [Chapman et al., 1998]. Anomalous resistivity is thought to be very important for the initiation of magnetic reconnection when sufficiently thin current sheets are formed [e.g., Büchner, 2006]. Magnetic reconnection laboratory experiments showed evidence for a positive correlation between the magnitude of electromagnetic fluctuations and resistivity enhancement [Ji et al., 2004]. In our case, as discussed above, we believe that the observed reconnection jet should be close to the diffusion region or X-line. Assuming that the turbulence properties in the reconnection jet are close to the ones in the diffusion region [Huang et al., 2010], we can estimate the role that turbulence may play in enhancing the anomalous resistivity. Applying the quasi-linear theory of anomalous resistivity [Yoon and Lui, 2006], we estimate the electric field due to anomalous resistivity provided by turbulence as about 3 mV/m, which is close to the typical reconnection electric field ~4 mV/m in the magnetotail. Moreover, if we apply the same method used by Ji et al. [2004] to estimate electric field due to magnetic fluctuations, we get the value of ~2.9 ± 0.9 mV/m, which is consistent with the above estimations. Eastwood et al. [2009] also have estimated the electric field associated with magnetic fluctuations in reconnection diffusion region without guide field, and have found that the value is much smaller than the observed reconnection electric field. This discrepancy is probably due to the presence of guide field in our case. It has been suggested that the fluctuations in reconnection with guide field can give rise to much higher anomalous resistivity than the case without guide field [Zeiler et al., 2002]. Our estimates seem to be consistent with recent 3D kinetic simulation results, which show that the evolution of magnetic reconnection develops into turbulent phase in the presence of large guide field [Che et al., 2011; Daughton et al., 2011] and has very low level of fluctuations near X-line in the case without guide field [Zeiler et al., 2002]. In addition, Che et al. [2011] have found that the reconnection rate increases abruptly when the current layers spread into a complex web of filaments which manifests as electromagnetic turbulence.
wave-vector space. The measured “dispersion relations” agree with the Alfven-Whistler mode calculated using the Vlasov kinetic theory. The electric field due to anomalous resistivity provide by turbulence is close to the typical reconnection electric field in the magnetotail, which is much larger than the case without guide field.

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References


