Processes in the Current Disruption Region: From Turbulence to Dispersion Relation

Key Points:
- Spectral breaks of both the magnetic field magnitude and $B_z$-component at frequencies less or equal to the proton gyrofrequency are observed.
- The spectral indices for the magnetic field magnitude and its $z$-component are similar, features of the turbulent processes depend on scale.
- The pulsations, inverse cascades, and dispersion relations indicate the presence of nonlinear processes in the current disruption region.

Abstract Using measurements from Cluster-II space mission, we compared the characteristics of the fluctuations of the magnetic field magnitude and the $B_z$ component in the current disruption (CD) regions. We used fast Fourier transform, statistical, and wavelet analysis, and wave surveyor technique on the multispacecraft measurements. Among the obtained results one can note the presence of spectral breaks in both the magnetic field magnitude and the $B_z$ component at frequencies smaller or equal to the proton gyrofrequency. The numerical values of the spectral index for the magnetic field magnitude and for the $B_z$ component are similar, and the nature of the turbulent processes is close to that of the homogeneous magnetohydrodynamic (MHD) (the spectral index varies from $-2.00$ to $-1.31$) on the large time scale and resembles Hall-MHD (the spectral index varies from $-2.33$ to $-2.99$) on the smaller time scales. The kurtosis results are consistent with those of the spectral analysis. From wavelet technique, we detected powerful Pc4 and Pi1 pulsations, along with cascade features both for the magnetic field magnitude and for its $z$-component. The dispersion ratios also indicate the presence of nonlinear energy cascade processes in CD regions. We have found that the pulsations observed for magnetic pressure are also present in thermal proton and electron pressures although their powers differ considerably. For the dynamic helium and oxygen pressures, and also for the thermal pressures of these components, only pulsations in the high-frequency region are revealed.

1. Introduction

In the early days of magnetospheric research, the simplified single-fluid description known as magnetohydrodynamic (MHD) approach to magnetospheric dynamics was employed. It provided an averaged description of the magnetospheric configuration very well, namely how antisunward extension forms an extended magnetotail (Zelenyi & Veselovskiy, 2008). Embedded within the magnetotail are a plasma sheet and a strong current sheet that separate the relatively empty tail lobe regions with oppositely directed magnetic field lines. The magnetotail of Earth’s magnetosphere is a self-consistent large-scale current structure, the parameters of which are determined by both plasma of the solar wind and internal processes. Current systems provide a connection between the Earth’s magnetotail and ionosphere (via field-aligned currents [Birkeland & Muir, 1908; Ganushkina et al., 2018]).

Complex structures in the magnetotail were found early on. These features are beyond the MHD description unless some nonMHD elements are invoked. For example, magnetic loops were revealed by Bowling (1975) and Hruška and Hrušková (1970). Also magnetic fluctuations were described as transient turbulence using magnetic measurements alone (Bowling, 1975). Detail studies with more comprehensive measurements, plasmoid-like structures were later made by Hones (1979); Hones et al. (1984); Moldwin and Hughes (1992); Zong (2004); and Zong et al. (1997). Magnetic loops can substantially deform the magnetotail field configuration and are detected as traveling compression regions by satellites in the magnetotail lobe (Slavin et al., 2003).

In our work, we consider plasma turbulence that occurs during the cross-current disruptions. These have sustained dipolarization with the typical duration of many minutes. This is distinct from dipolarization fronts that last typically only tens of seconds. The cross-current disruption turbulence has a key difference from works on general turbulence in the geomagnetic tail. In particular, in Vörös et al. (2004), the authors studied magnetic turbulence in the plasma sheet of the geomagnetic tail during bursty bulk flows and...
at quiet intervals, analyzing the nonstationarity of scaling laws and multiscale power. The turbulence we report here is quite different from the general turbulence of the plasma sheet because Borovsky and Funsten (2003) showed that the primary turbulence in the plasma sheet does not consist of wave modes, but is consisted of eddies with a characteristic size of 1.6 $R_E$ due to flow shear. On the other hand, cross-current disruption turbulence is a manifestation of a structural catastrophe of topological origin in the current sheet. As such, the associated turbulence exhibits a second-order transition (Chang, 1999; Ohtani et al., 2000; Sharma et al., 2001). This characteristic is not identified in the studies such as Vörös et al. (2004) and Borovsky and Funsten (2003). In order to reveal the wave content of magnetic field fluctuations, we have performed dispersion analysis which can show the self-organized nature of turbulence (i.e., formation of web-like current structures) studied by Milovanov et al. (2001). Estimates of the spectral index of current and magnetic field fluctuations are used in Milovanov et al. (2001) in the consideration for the applicability of fractal topology to current sheet turbulence.

A magnetospheric substorm is a high priority topic in space investigations. During the growth phase of a substorm (Caan et al., 1978; McPherron et al., 1973), a gradual decrease in the vertical component of the magnetic field ($B_z$) and an increase in the horizontal component ($B_x$) occur, resulting in a tailward stretch of the magnetic field lines associated with intensification of the current across the magnetotail. During the expansion phase, from few minutes to few tens of minutes, a sharp relaxation of the stretched magnetic field lines to a more dipolar configuration occurs (Baumjohann et al., 1999). Such magnetic reconfiguration is called dipolarization. It has been interpreted as a signature of a decrease of the cross-tail current, also called current disruption (CD), in the plasma sheet (Lui et al., 1988). These CD events have been identified by the occurrence of large magnetic field changes predominantly around the neutral sheet of the magnetotail in which $B_z \gg B_x, B_y$ (the dawn-dusk component). During CD, magnetic field changes reach the level in which $dB_z dB_x$ is of the order one or larger, where $B_0$ is the $B_z$ value before CD onset. During CD, the $B_z$ component can change the sign (Lui et al., 1988; Takahashi et al., 1987). This interpretation of current decrease during CD has been confirmed with multiple coordinated satellite measurements (Lui, 2011) and auroral observations (Rae et al., 2009). Furthermore, propagation of spatial structures such as leading edges of dipolarization (LED) does not characterize the CD progression. Short summary about spatial development in geomagnetic tail of this predominantly temporal phenomenon could be found in (Lui, 2014).

Wavelet analyses conducted on CD events show a wide spectrum of waves and nonMHD behaviors (Cao et al., 2013; Chen et al., 2003; Cheng & Lui, 1998; Hwang et al., 2014; L. Kozak, Petrenko, Kronberg, Porokhorenkov, et al., 2018; L. Kozak, et al., 2018a, 2018b; Le Contel et al., 2009; Lui, 2013, 2015; Lui et al., 1988; Lui et al., 1999; Lui & Najmi, 1997; Lui et al., 2008). These disturbances are associated with a whole chain of unsteady processes and emergence of anomalous resistivity, forming a turbulent region characterized by intermittency (Consolini, 2005; L. V. Kozak, et al., 2018). The type of turbulent motions depends on the scale of the processes under consideration (L. V. Kozak et al., 2018). The formation of inverse cascade also points to the presence of self-organization (L. V. Kozak et al., 2018).

The phenomenon of dipolarization could be accompanied by the earthward transfer of flux tubes with enhanced value of $B_z$ called dipolarizing flux bundles (DFBs) (Liu et al., 2014). The leading edges of such structures are plasma discontinuities represented as dipolarization fronts (Lui, 2013; Nakamura et al., 2002; Runov et al., 2009). Grigorenko et al. (2016) showed statistically that electrostatic and electromagnetic wave activity during dipolarization leads to additional heating of electrons.

In the simplest case, conversion of magnetic energy to particle acceleration during substorm activity implies involving the concept of magnetic reconnection of oppositely oriented lines from the northern and southern lobes of the magnetotail (Dungey, 1961). The abrupt onset of these dynamic activities has been attributed to plasma instabilities such as the ion-tearing instability (Schindler, 1974), the ballooning instability (Cheng & Lui, 1998; Henderson, 2012; Liu, 1997; Samson, 1998), Kelvin-Helmholze instability (Rostoker, 1996; Rostoker, 2007; Samson, 1998). Further awareness of the shortcomings of the single-fluid approach also leads to the consideration of kinetic instabilities such as the cross-field current instability (Lui et al., 1991) and shear-flow instability (Ganguli et al., 2014, 2018).

The study of such disturbances helps to identify several scales both in time and space. Scaling studies become another valuable avenue gain deeper understanding and extract insights on the underlying physical
processes (Quattrociocchi et al., 2019; Sorriso-Valvo et al., 2019). The recent NASA mission called Magnetospheric MultiScale proves the importance of multiple scaling in magnetospheric dynamics (Burch et al., 2015).

In this article, we focus on the scaling analysis of disturbances of the magnetic field magnitude and the $B_z$ component in the Earth’s magnetotail. This allows us to identify the difference between magnitude and almost parallel fluctuations along the mean magnetic field vector. We conduct fast Fourier transform (FFT), statistical and wavelet analysis in the current disruption region of the magnetic field. Furthermore, using the wave survey method and multi spacecraft measurements we have found dispersion relations for the magnetic field magnitude and the $B_z$ component. A comparison between thermal, dynamic and magnetic pressures is made in order to estimate the contribution of the magnetic field changes to the dynamical and thermal processes in the current disruption regions.

2. Measurements and Calculated Characteristics of the Dipolarization Fronts

This study analyzes magnetic field measurements obtained using fluxgate magnetometers placed on a Cluster-II mission satellite (Balogh et al., 2001) in the magnetic field dipolarization region during three CD events: September 9, 2014, September 11, 2014, and July 24, 2015. Figure 1 shows the magnetic field magnitude as well as its components from satellites closest to the current sheet in the geocentric solar magnetospheric (GSM) coordinate system. Measurement resolution is 22.4 Hz. This resolution allows for investigating plasma characteristics in the Earth’s magnetotail at different time scales. By the term turbulence we mean and consider it as a result of the current sheet filamentation and as the presence of multiple wave disturbances that accompany this process.

During the events September 9, 2014, September 11, 2014, and July 24, 2015 the satellites were in the antisunward direction in the range: 11.7–12.6 $R_E$, 13.7–14.5 $R_E$ and 10.9–11.4 $R_E$ respectively (Table 1, Figure 2).

Since the current disruption region is subtended by four spacecraft, we have been able to estimate the velocity, direction of the LED motion with its normal. The results are also listed in Figure 1. For the estimation we used the method of minimum variance and timing analyzes method (Paschmann & Daly, 2000; Sonnerup & Scheible, 1998). For the considered events, the LED moves earthward (the minimum velocity is 180 km/s, and the maximum value is 700 km/s). The calculated LED velocities are consistent with the estimates obtained by (Schmid et al., 2016) (57% structures are characterized by such velocity values).

The relative standard deviations of the magnetic field magnitude and $B_z$ component are from 0.5 to 2.5 for the events under consideration.

To quantify plasma population reactions from the magnetic field changes that occur during the current disruption, fluctuations of dynamic pressure $p_{dyn,a} = \frac{1}{2} \rho_a v_a^2$ and thermal pressure $p_{t,a} = n_a k_B T_a$ (separately

![Figure 2. Spacecraft localization during CD events with LEDs. CD, current disruption; LED, leading edges of dipolarization.](image-url)
Figure 1. Analyzed values of magnetic field magnitude (a). Example of magnetic field fluctuations for the satellites closest to the current sheet in GSM (b). The CD occurrences are shown in white. CD, current disruption, GSM, geocentric solar magnetospheric.
for each plasma species $\alpha$ were taken into consideration. Pressure data for protons and ions taken according to the CIS-CODIF sensor measurements (Rème et al., 2001), and for electrons from the PEACE sensor measurements (Johnstone et al., 1997) were analyzed. Figure 3 shows calculated values of different pressure types for electron and ion composition from SC C4. Time resolution of data is 4–8 s. It can be noted that during CD for all three events, the thermal pressure of the protons has the highest value, followed by the thermal pressure for the electrons, the magnetic pressure and the dynamic pressure in the descending order. The estimated averaged values of plasma characteristics in the region of dipolarization are summarized in Table 2.

### 3. Results of the Research

#### 3.1. FFT Analysis

By studying the power spectral density (PSD) obtained through FFT, it is possible to establish the presence of a turbulent cascade. This feature is manifested by the existence of the power-law dependence $\text{PSD}(f) \propto f^{-\alpha}$ of the spectrum of magnetic field fluctuations. The first spectra of the low-frequency magnetic fluctuations in the magnetotail were obtained from the OGO-5 data with law $f^{-2} - f^{-2.5}$ (Russell, 1972), although there was no spectral kink near the proton gyrofrequency. In Bauer et al. (1995), a substantive study of magnetic spectra was performed depending on various characteristics of the plasma in the geomagnetic tail. To find the PSD of the signal under study, we used the following expression (Eriksson, 1998; Paschmann & Daly, 2000):

$$\text{PSD} = \frac{2N}{f_i} \left| \frac{1}{N} \sum_{m=0}^{N-1} X_m \exp \left( \frac{2\pi imn}{N} \right) \right|^2$$  \hspace{1cm} (1)

where, $m = 0, 1 \ldots N - 1$, $n = 0, 1 \ldots N/2$.

To find the spectral index and the scale of the turbulent regime change in the frequency domain in the spacecraft frame, we performed a two-piece linear approximation of $\log(\text{PSD})$ from $\log(f)$ in the range of $\sim 0.005 \sim 5.0$ Hz. The PSD results for the magnetic field magnitude and $B_z$ component are presented in Figure 4 and Table 3.
Figure 3. Fluctuations of pressures for considered events. The CD occurrences are shown in white.
For all spectra, both for the magnetic field magnitude and for $B_z$, a kink is observed ($f^*$) at frequencies lower than the proton Larmor frequency (Table 2). This feature may indicate the effect of heavy ions. At the same time, the analysis of the power law fits of the PSD versus frequency allows us to determine a suitable model for describing the observed turbulence. In particular, for a homogeneous isotropic 3D model of Kolmogorov, $E_k \propto k^{-5/3}$ (Kolmogorov, 1941), for a magnetized two-dimensional medium $E_k \propto k^{-3/2}$ (Iroshnikov Kraichnan model) (Kraichnan, 1959, 1970), and for Hall-MHD model $E_k \propto k^{-7/3} - k^{-11/3}$ (Biskamp et al., 1996; Chen et al., 2017). Hall-MHD model contains the Hall effect term in the generalized Ohm’s law. This term becomes significant for the small-scale plasma dynamics, considering ions as stationary background in comparison with electrons (Galtier & Buchlin, 2007). In this framework, Galtier and Buchlin (2007) found a number of spectral indexes, which vary from $-7/3$ when the magnetic energy exceeds the kinetic energy, and $-11/3$ when the kinetic processes is significant. At the same time, in the Kraichnan model, when

| Parameter                             | September 09, 2014 | September 11, 2014 | July 24, 2015 |
|---------------------------------------|--------------------|--------------------|--------------|
| Electron gyrofrequency                | $f_{ce}$, Hz       | 486                | 382          | 442          |
| Proton gyrofrequency                  | $f_{ci}$, Hz       | 0.265              | 0.208        | 0.241        |
| Proton plasma frequency               | $f_{pe}$, Hz       | 3,640              | 4,980        | 3,060        |
| Electron plasma frequency             | $f_{pe}$, Hz       | 84.9               | 116          | 71.3         |
| Electron inertial length              | $d_e$, km          | 13.1               | 9.58         | 15.6         |
| Ion inertial length                   | $d_i$, km          | 562                | 411          | 669          |
| Electron density $n_e$, cm$^{-3}$     | 0.336 ± 0.126      | 0.581 ± 0.082      | 0.0339 ± 0.059 |
| Proton density $n_H^+$, cm$^{-3}$     | 0.164 ± 0.142      | 0.3017 ± 0.151     | 0.116 ± 0.035 |
| Helium ion density $n_{He^+}$, cm$^{-3}$ | 0.008 ± 0.007     | 0.019 ± 0.019      | 0.010 ± 0.018 |
| Oxygen ion density $n_{O^+}$, cm$^{-3}$ | 0.010 ± 0.021     | 0.019 ± 0.031      | 0.013 ± 0.040 |
| Electron mass density $\rho_e$, 10$^{-31}$ g cm$^{-3}$ | 3.06 ± 1.15       | 5.29 ± 0.75        | 3.09 ± 0.54  |
| Proton mass density $\rho_{H^+}$, 10$^{-28}$ g cm$^{-3}$ | 2.74 ± 2.38       | 5.13 ± 2.53        | 1.94 ± 0.59  |
| Helium ion mass density $\rho_{He^+}$, 10$^{-28}$ g cm$^{-3}$ | 0.53 ± 0.47       | 1.26 ± 1.26        | 0.67 ± 1.20  |
| Oxygen ion mass density $\rho_{O^+}$, 10$^{-28}$ g cm$^{-3}$ | 2.66 ± 5.58       | 5.05 ± 8.24        | 3.45 ± 10.6  |
| Ion mass density $\rho_{ions}$, 10$^{-28}$ g cm$^{-3}$ | 5.93 ± 6.09       | 11.44 ± 8.71       | 6.06 ± 10.68 |
| Alfvén velocity $v_A$, km/s           | 635.9              | 360.3              | 571.8        |
| Electron thermal pressure $p_{e\theta}$, nPa | 0.103 ± 0.018     | 0.176 ± 0.023      | 0.184 ± 0.025 |
| Proton thermal pressure $p_{p\theta}$, nPa | 0.155 ± 0.039     | 0.335 ± 0.056      | 0.183 ± 0.043 |
| Helium ion thermal pressure $p_{He\theta}$, nPa | 0.009 ± 0.011   | 0.023 ± 0.022      | 0.009 ± 0.012 |
| Oxygen ion thermal pressure $p_{O\theta}$, nPa | 0.009 ± 0.008    | 0.026 ± 0.018      | 0.004 ± 0.004 |
| Plasma pressure $p_{total}$, nPa      | 0.276 ± 0.045      | 0.560 ± 0.067      | 0.380 ± 0.051 |
| Magnetic pressure $p_{magnetic}$, nPa | 0.124 ± 0.044      | 0.083 ± 0.047      | 0.109 ± 0.054 |
| Beta parameter $\beta$                | 2.23               | 6.75               | 3.49         |
| Mean vector of bulk velocity in GSM   | $v$, km/s          | [47.31, −34.02, 26.22] | [89.60, 50.98, 38.42] | [34.44, −9.82, −55.83] |
| AL index                              | $AL$, nT           | From −16 to −24    | From −237 to −212 | From −137 to −210 |

**Table 2**

*Plasma Characteristics During CDs*

Abbreviation: CD, current disruption; GSM, geocentric solar magnetospheric.
Figure 4. Results of FFT analysis comparison for the magnetic field magnitude and the $B_z$ component. The spectral break ranges are displayed by the gray vertical band.
compared to the Kolmogorov spectrum, the level of energy transfer on a small scale significantly decreases, while the time of energy transfer increases; and the EMHD theory describes a situation where most of the plasma dynamics is regulated by electrons.

Among the results obtained, it can be noted that for the large time scales, $\omega \leq f^*$ the spectral index varies from $-2.0$ to $-1.31$, whereas at the smaller time scales the value lies in the range from $-2.99$ to $-2.33$. At the same time, the difference of spectral index values for different scales, and for the magnetic field magnitude and its $z$-component are similar in the limits of error. The use of shorter datasets does not improve the spectral index estimates, as this significantly narrows the turbulence features from general to local consideration. Since the flatter spectrum implies a lower rate of energy transfer through turbulent scales, we suggest that along the field (close to $B_z$ component) energy is transformed faster. Meanwhile, for the September 11, 2014 event, the greatest differences are observed between exponents at scales smaller and larger than the kink time scale. On event September 11, 2014, such a clear difference between the spectrum indices below and after break frequency. It means a more striking change in the energy transformation mechanism through spatial-temporal scales.

### 3.2. Statistical Analysis

Within the framework of the FFT analysis, different scales of turbulent processes in the CD regions were found. The intermittency scales were studied within the framework of the statistical approach. The

| Event             | Field component | SC  | $f^*$ | Slope before | Slope after |
|-------------------|-----------------|-----|------|--------------|-------------|
| September 9, 2014 | B               | C1  | 0.1  | $-1.5066 \pm 0.1312$ | $-2.9127 \pm 0.1792$ |
|                   |                 | C2  | 0.1  | $-1.3622 \pm 0.1180$ | $-2.8291 \pm 0.1980$ |
|                   |                 | C3  | 0.1  | $-1.6976 \pm 0.1472$ | $-2.6883 \pm 0.1723$ |
|                   |                 | C4  | 0.1  | $-1.7017 \pm 0.1711$ | $-2.7861 \pm 0.1811$ |
| September 9, 2014 | $B_z$           | C1  | 0.1  | $-1.3086 \pm 0.1852$ | $-2.4933 \pm 0.1110$ |
|                   |                 | C2  | 0.1  | $-1.1355 \pm 0.1811$ | $-2.7930 \pm 0.1421$ |
|                   |                 | C3  | 0.07 | $-1.4381 \pm 0.1872$ | $-2.6406 \pm 0.1107$ |
|                   |                 | C4  | 0.07 | $-1.5812 \pm 0.1899$ | $-2.6201 \pm 0.1398$ |
| September 11, 2014| B               | C1  | 0.1  | $-1.4041 \pm 0.1507$ | $-2.7074 \pm 0.0907$ |
|                   |                 | C2  | 0.1  | $-1.4616 \pm 0.1436$ | $-2.9912 \pm 0.1138$ |
|                   |                 | C3  | 0.1  | $-1.4931 \pm 0.1839$ | $-2.7569 \pm 0.0915$ |
|                   |                 | C4  | 0.1  | $-1.5811 \pm 0.1614$ | $-2.8331 \pm 0.1142$ |
| September 11, 2014| $B_z$           | C1  | 0.1  | $-1.4118 \pm 0.1621$ | $-2.8416 \pm 0.1614$ |
|                   |                 | C2  | 0.1  | $-1.3183 \pm 0.1403$ | $-2.9948 \pm 0.1391$ |
|                   |                 | C3  | 0.1  | $-1.4672 \pm 0.1812$ | $-2.7620 \pm 0.1906$ |
|                   |                 | C4  | 0.1  | $-1.4769 \pm 0.1595$ | $-2.8334 \pm 0.1999$ |
| July 24, 2015     | B               | C1  | 0.24 | $-2.0051 \pm 0.1687$ | $-2.9395 \pm 0.1961$ |
|                   |                 | C2  | 0.24 | $-1.8554 \pm 0.1634$ | $-2.7155 \pm 0.1973$ |
|                   |                 | C3  | 0.24 | $-1.8404 \pm 0.1812$ | $-2.9286 \pm 0.1914$ |
|                   |                 | C4  | 0.2  | $-1.8290 \pm 0.1699$ | $-2.8794 \pm 0.1999$ |
| July 24, 2015     | $B_z$           | C1  | 0.2  | $-1.9851 \pm 0.0997$ | $-2.7895 \pm 0.1499$ |
|                   |                 | C2  | 0.2  | $-1.7942 \pm 0.1124$ | $-2.5306 \pm 0.1704$ |
|                   |                 | C3  | 0.2  | $-1.8053 \pm 0.1156$ | $-2.7733 \pm 0.1607$ |
|                   |                 | C4  | 0.2  | $-1.6532 \pm 0.1012$ | $-2.8737 \pm 0.1755$ |

Abbreviation: CD, current disruption.
turbulence intermittency is a phenomenon consisting of the interchange of regions with a high intensity level of the magnetic field gradient pulsations with regions of reduced one. This feature indicates the presence of nonuniform and nonlinear energy transfer between different structures, which leads to the concentration of energy in limited space regions (Frisch, 1995; L. V. Kozak, Petrenko, Lui, et al., 2018; Zimbardo et al., 2010). All these phenomena are important from the viewpoint of energy transformation through scales.

To determine the intermittency, a kurtosis was found in the distribution of fluctuations of the magnetic field magnitude $K(\tau)$ depending on the scale of the processes $\tau$. The kurtosis value was determined by the formula (Zaks, 1976):

$$K(\tau) = \frac{\langle (B(t+\tau) - B(t) f^\perp) \rangle^2}{\langle (B(t+\tau) - B(t) f^\perp) \rangle^4}.$$  

(2)

Kurtosis values for different spacecraft and three considered events are presented in Figure 5. It can be noted that for all satellites on the $\omega \leq f^*$ scale, $K(\tau)$ values fluctuate around 3, which corresponds to the normal distribution, and on the small time scales they vary from 73 (C1, September 9, 2014) to 22 (C2, SC4, July 24, 2015). Sharp changes in the kurtosis are observed on the scales of the Larmor frequency for the analyzed events (Table 2). The larger the $K(\tau)$, the greater is the intermittency. The fluctuation distribution function has a sharper peak and wider tails than the normal distribution. Thus, we observe very strong intermittency at small scales (smaller than the proton gyroperiod). On the large scales, the intermittency reduces.

The decreases in the kurtosis values at small $\tau$ are due to instrumental errors.

3.3. Wavelet Analysis

We performed this type of analysis using the Morlet wavelet function $\Psi_0$ (Torrence & Compo, 1998):

$$\Psi_0(\eta) = \frac{1}{\pi} \exp(i\omega_0\eta)\exp(-\eta^2/2).$$  

(3)

where, $\omega_0$ is the dimensionless frequency, $\eta$ is the dimensionless time.

The continuous wavelet transforms of the data points $x_n$ are constructed as follows (Farge, 1992; Grinsted et al., 2004; Jevrejeva et al., 2003):

$$W_n(s) = \sum_{n'=1}^{N-s} x_{n'}^\Psi \left[ (n' - n)s \delta \right].$$  

(4)
where * is the complex conjugate, \( W_n(s) \) is the wavelet transform, \( s \) is the scale.

### 3.3.1. Wavelet Analysis for the Magnetic Field

The wavelet analysis helps to track the change in frequency composition of the signal over time domain. The largest power in the wavelet spectrum makes it possible to establish the time scale at which the formation of the most intense structures takes place. Figure 6 shows the results of the continuous wavelet transform of the magnetic field magnitude and the \( B_z \)-component for the spacecraft closest to the neutral sheet in the process of cross-tail current disruption. Direct and inverse cascade features are indicated by the green and red rectangles, respectively. The term cascade refers to the nature of energy transfer over a spectrum of turbulent pulsations. The direct cascade is a phenomenon in which small-scale pulsations receive energy as a result of fragmentation of large-scale pulsations, forming a so-called inertial range. The inverse cascade is the merging of small-scale structures into larger-scale ones. Such processes are identified as a change in wavelet power spectra in frequency domain during time. Mixed third-order structure function could also be used defining whether direct or inverse cascade takes place. This is shown in work (Sorriso-Valvo et al., 2007). For the September 9, 2014 event, there is a group of direct and inverse cascades at the beginning and at the end of the high fluctuation intervals. The highest wavelet power values are observed at frequencies of 0.08 and 0.05 Hz with duration being less than half a minute. The event September 11, 2014 is interesting in terms of simultaneous existence of two crossing cascades: a direct and an inverse one. They mutually intersect at 04:08 UT. Each of these cascades lasts no longer than 2 minutes. Its coverage frequency is from 0.02 to 0.1 Hz. The inverse cascade feature is more apparent for the \( B_z \). For the July 24, 2015 event, the short-lived maximum wavelet powers are at frequencies of 0.025 and 0.4 Hz. Moreover, for \( B_z \), the magnetic field component of the second maximum (near 21:01:40 UT) is weaker in comparison with the same for \(|B|\) because of the more distinctly inverse cascade in \( B_z \).

During CDs, signals with periods of 100, 50, and 25 s are clearly recorded, which correspond to Pc4 and Pi1 pulsations, as well as direct and inverse cascades. The Pc4 and Pi1 pulsations are continuous and irregular ultra-low-frequency waves (with a range of periods of 45–150 s and 1–45 s), respectively (McPherron, 2005). At the same time, pulsations and inverse cascades, which indicate the processes of self-organization, are observed both for the magnetic field magnitude and for its \( z \)-component and detected on all satellites in the spatial range of 10.8–14.7 \( R_E \).

### 3.3.2. Wavelet Analysis for the Pressures

We present the following results to characterize the response of ion and electron populations during the current disruption, despite the fact that this is a self-consistent process. The results of wavelet analysis of magnetic, dynamic and thermal pressures for protons and electrons by measurements of spacecraft C4 are shown in Figure 7.

For the September 9, 2014 event, the pulsation at 0.008 Hz is repeated for all pressures other than the dynamic one. The spectrum power for electron pressure is approximately four times smaller than the magnetic and proton thermal pressure. Moreover, in the latter case, the frequency increases from 0.005 to 0.01 Hz, and, starting at approximately 0.02 Hz, higher-frequency fluctuations are observed. For the dynamic pressure at the time of passing of the LED, a brief burst is observed, with duration of more than 10 s. The relatively low power for electron population may be caused by insufficient temporal resolution of the PEACE instrument on board the Cluster spacecraft.

For the events of September 11, 2014 and July 24, 2015, the number of frequencies observed during the CD is significantly higher.

The CD onset (04:03-04:04 UT) for the September 11, 2014 event is observed as a jump in magnetic pressure with a duration of 15–20 s long at the frequency of 0.06 Hz. At the beginning of the CD, the proton thermal pressure oscillates at the frequency of 0.04 Hz. Furthermore, some lower-frequency fluctuations are present with 0.015, 0.01 Hz. On the graphs for dynamic pressure, we have a 5-min-long pulsation with a low wavelet power value (0.004 nPa²) and a short, powerful burst of 0.04 Hz in the middle thereof.
For the July 24, 2015 event, the CD for the spacecraft C4 starts at 20:55:32 UT. In this period, the pulsations of magnetic pressure are seen at frequencies 0.015 and 0.006 Hz, the first of which being at least twice as powerful than the other one. It should be noted that the pulsation at 0.008 Hz occurs before the CD begins. The dip of the thermal proton pressure (the upper panel) is accompanied by a peak in spectrum at
a frequency of 0.006 Hz, which also holds true for the magnetic pressure. At the beginning of the CD, the proton dynamic pressure shows a splash of about 20 s at a frequency of 0.035–0.04 Hz. After the CD onset, there are fluctuations in the frequency range of 0.01–0.1 Hz (see 21:00 UT). For the electron pressure, perturbation is also observed before the CD onset, and at the onset the fluctuations are observed at 0.025 Hz for 40 s. The graph of electron pressure demonstrates vivid perturbations at a frequency of 0.004 Hz, along with the inverse cascades.

Thus, the pulsations observed for magnetic pressure are observed for thermal proton and electron pressures. Although the signal strength varies considerably. The pulsations at high-frequencies, similar to those
observed for thermal proton pressure in the range of more than 0.07 Hz, occur only for dynamic parameters of helium and oxygen pressure, and also for thermal data of these parameters.

### 3.4. Dispersion Relation from the Wave Survey Method

Simultaneous measurements of the plasma characteristics with several spacecraft (multipoint measurements) allow us to obtain a dispersion diagram. The wave surveyor technique is used in this study, whose algorithm is described in detail in Narita (2012) and Vogt et al. (2008), while the technique identifying a single dominant wave mode for scalar or vector data is not limited to a certain number of sensors. Significant advantages of this method are the direct computation of the dispersion relation and the absence of the effect of isotropic white noise on the result. Input parameters are the time series of the investigated values, the coordinates of the sensors and the mean bulk flow velocity vector.

To find the dispersion relations, the following expression is used by Vogt et al. (2008):

$$
k(\omega_{sc}) = \left(\sum_{\sigma=1}^{S} r_{\sigma} r_{\sigma}^T\right)^{-1} \sum_{\sigma=1}^{S} \theta_{\sigma}(\omega_{sc}) r_{\sigma}
$$

where, $\omega_{sc}$ is the frequencies in spacecraft rest frame, $r_{\sigma}$ is the centered coordinates of the spacecraft position, $S$ is the number of spacecraft, $T$ is the transposition of the column into row; $\theta_{\sigma}(\omega_{sc})$ is the phase of complex-valued eigenvector of the covariance matrix in the Fourier representation for the largest values from the set of all eigenvalues. The main goal of this algorithm is to find the covariance matrix in the Fourier representation ($C(\omega_{sc})$) through the matrix averaging of the products of Fourier transforms on the ensemble:

$$
C(\omega_{sc}) = \langle b(\omega_{sc}) b^\dagger(\omega_{sc}) \rangle
$$

where, $^\dagger$ is the Hermit conjugation, and $b$ is a Fourier transform vector of dimension $S$:

$$
b = \begin{pmatrix}
b_{\sigma=1}(\omega_{sc}) \\
n_{\sigma=2}(\omega_{sc}) \\
\vdots \\
n_{\sigma=S}(\omega_{sc})
\end{pmatrix}
$$

In the Cluster-II mission, the third and fourth spacecraft are very close relative to each other compared to the distances between the other SC (the distance varies from 290 to 635 km for the considered events). Therefore, the upper limit of estimated wave numbers ranges from 0.0099 to 0.0217 rad/km to avoid spatial aliasing. The dispersion pictures were obtained from the analysis of measurements of two C3 and C4 spacecraft.

Figure 8 shows the dispersion relations found for the magnetic field magnitude and the $B_z$ component. In this case, in the plasma rest frame ($\omega_{re}$) the frequency dependencies are plotted from the wave vector modulus. The transition from spacecraft frame into plasma rest frame is determined by the Doppler relation $\omega_{re}(\omega_{sc}) = \omega_{sc} - k(\omega_{sc})v$, where, $v$ is the mean bulk flow velocity.

The results of wave survey method for the component of the magnetic field $B_z$ and the total magnetic field are shown in Figure 8. The regions with gray color filling represent a set of two branches of the dispersion equation at different wave propagation angles $\theta$:

$$
(\omega^2 - v_A^2 k^2)(\omega^2 - v_A^2 k^2 \cos^2 \theta) - \frac{\sigma^2 k^4 v_A^2}{\omega_{ci}^2} = 0
$$

where $v_A$ is the Alfvén speed, $\omega_{ci}$ is a proton gyrofrequency. The upper region corresponds to the magneto-sonic, and the lower one is the Alfvén waves.

The propagation angle of the waves was determined by fitting the dispersion diagram in the lower branch (the points are black), satisfying the conditions $\omega < kv_A$, $\omega < \omega_{ci}$ (below the dashed blue lines). In this case, the Alfvénian velocities and proton gyrofrequencies evaluated in this work (Table 2) were used. The
Figure 8. Dispersion relations for $B_z$ component and the magnetic field magnitude from measurements of the SC C3 and C4. The symbols are the values calculated from the wave survey method. Black crosses are used for the fitting procedure. The blue dotted lines indicate $k v_A$ and the values of the proton gyrofrequency $\omega_{ci}$. The gray areas indicate the set of dispersion curves of magnetosonic and Alfvén waves at any angle of propagation to the mean magnetic field.
obtained propagation angles for the $B_z$ components are $32.8° \pm 4.9°$ and $24.6° \pm 9.8°$, while for the total magnetic field the values are $20.2° \pm 7.2°$ and $15.1° \pm 12.8°$ for the events of September 9, 2014 and September 11, 2014, respectively. For the total magnetic field, the values for the propagation angles are smaller than those for the $B_z$ component.

For the July 24, 2015 event, the number of points was insufficient for fitting.

The signatures of oblique Alfvén waves are observed. For example, the distribution of the Alfvén velocities in the $\omega$–$k$ plane changes its slope. The variability of bulk velocity contributes to the translation along the frequency domain (Doppler shift). Also, the spread of points in the dispersion patterns can be associated with the presence of a nonlinear energy cascade, as well as the rapid variability of the characteristics of the plasma environment. Narita (2016) came to similar conclusions regarding the small-amplitude fluctuations in the plasma sheet boundary layer. The results obtained are consistent with the FFT and statistical analysis presented above.

4. Conclusion

In this investigation we obtained the leading edge of dipolarization at $-14.5R_E < X_{GSM} < -10.9R_E$ moving toward the Earth at velocity of $182.8 \pm 37.0$ km/s (September 9, 2014), $511.6 \pm 19.0$ km/s (September 11, 2014), $705.3 \pm 77.1$ km/s (July 24, 2015). The calculated velocities are consistent with the estimates obtained by Schmid et al. (2016).

Analysis of the kurtosis points to the presence of intermittency in the turbulent processes on short time scales i.e. less than the proton gyroperiod. The variance of magnetic field, and $B_z$ component, normalized to the current mean value, changes from 0.5 to 2.5. The positive value of the kurtosis (more than 3) points to the energy surplus of great large-scale disturbances being created by a source, and can serve as an evidence of an increase in the range of interaction and correlation (Consolini, 2005).

An interesting result is that the change of power spectral index which is clearly observed during current disruption for the magnetic field magnitude is also observed for the $B_z$-component. At the same time the difference of spectral index values for different scales, and for the magnetic field magnitude and its $z$-component are similar in the limits of error. Also, it was obtained that the specific changes of turbulent processes occurring on spatial scales less than the Larmor proton radius or the inertial ion length ($\sim 500$ km) are in good agreement with Electron-MHD theory. (The spectral index for EMHD-model is $\sim -7/3$). There is correlation between spectral indices for $B_z$ on small time scales and $\beta$ parameter values. With the increase of $\beta$ parameter the spectral index value increases as well, demonstrating that kinetic effects become more significant in this regime. According to Galtier and Buchlin (2007), the spectral index can reach a value of 11/3 (Hall-MHD) when the kinetic parameters have the dominant influence.

There is a correlation between the statistical and FFT studies: a larger value of kurtosis corresponds to a larger value of the spectral index, and its sharp changes correspond to the gyrofrequency of protons; for large time scales both the spectral index (value vary in the range of 2.0–1.31) and kurtosis value points to homogeneous turbulence.

The use of wavelet analysis clearly demonstrates Pc4 and Pi1 pulsations in fluctuations of the magnetic field magnitude and its $B_z$-component. The presence of such pulsations indicates the injection of highly energetic particles, and also the presence of instabilities (namely Kelvin-Helmholtz instability, flow instability etc.) (e.g., Samson, 1998).

The geomagnetic pulsations, which are observed for magnetic pressure, clearly appear also in the analysis of the thermal proton and electron pressure, fluctuation amplitudes for them, however, differ significantly. For the dynamic pressure of helium and oxygen, and also for the thermal pressure of these parameters only pulsations at high frequencies are observed. Power peaks for dynamic pressure identify the onset of CD or plasma discontinuities (which is clearly visible for the events September 9, 2014 and September 11, 2014). And pressure changes occur at approximately the same time scales with the presence of inverse cascades. That is, the process of self-organization occurs for both magnetic structures and the plasma population.
In the CD region, both direct and inverse cascade processes are clearly observed. A presence of the cascades, especially the inverse cascades (a passage to the lower wave numbers/larger vortexes), points to a spontaneous generation of the large-scale coherent structures (self-organization) associated with energy transfer (Biskamp et al., 1996).

The point scattering in the dispersion relations obtained with the wave survey method demonstrates the presence of nonlinear energetic cascade (Narita, 2012), and a fast changeability of characteristics of plasma environment in the region of magnetic field dipolarization.

The results obtained through various methods and approaches, namely FFT analysis, wavelet analysis, kurtosis analysis and wave survey method, are consistent with each other and indicate a complex chain of processes in cross-tail current disruption events that may not be common in MHD turbulence.

Data Availability Statement

The Cluster data used in this study were downloaded from the Cluster Science Archive version 2.1 at https://csa.esac.esa.int/csa-web/.

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