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Severe Magnetic Fluctuations in the Near-Earth Magnetotail: Spectral Analysis and Dependence on Solar Activity

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Key Points:

- Occurrence rates of tail magnetic fluctuations show no clear dependence on the $F_{10.7}$ index in one solar cycle
- Spectra of magnetic fluctuations during dipolarizations change abruptly near the gyrofrequency of O^+ ions
- Under larger ambient magnetic field intensity, the spectral slope increases with increasing frequency in the range 0.05–1 Hz

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Abstract Magnetic fluctuations in the near-Earth magnetotail are an important signature of substorm onset. In a previous statistical study, we reported their occurrence rates, spatial distributions, and relationship with plasma flows. In the present study, we investigated their spectral properties using 11 years of measurements from the Time History of Events and Macroscale Interactions during Substorms mission for 2008–2018. We found 10,848 severe magnetic fluctuation events with $\sigma_B/\bar{B} > 0.5$, where σ_B and $\bar{B}$ are the standard deviation and average, respectively, of the magnetic field intensity for the local proton gyroperiod. The occurrence rates of severe magnetic fluctuations show no clear dependence on the $F_{10.7}$ index in one solar cycle. We extracted 36 dipolarization events with severe magnetic fluctuations. In the power spectral density (PSD) of the magnetic fluctuations during dipolarizations, the steepness of the spectral slope increased with increasing frequency in almost all the events. The average PSDs are shown sorted by (a) distance to the neutral sheet and (b) ambient magnetic field intensity. In all groups, the slopes of the average PSDs increased abruptly from below $\sim 10^{-1.3}$ Hz (0.05 Hz) to above $\sim 10^{-1.3}$ Hz, which is close to the gyrofrequency of O^+ ions. It is the first time that a change of slope near the proton gyrofrequency (frequency range: 0.05–1 Hz) was found in cases of larger ambient magnetic field intensity, implying that the magnetic fluctuations were relatively strong near the proton gyrofrequency. These results suggest that the magnetic fluctuations contribute to the nonmagnetohydrodynamic effect in the ion motion.

1. Introduction

First identified as auroral substorms by Akasofu (1964), substorms are elementary geomagnetic and auroral disturbances with timescales of 2–3 hr. Popular explanations for substorms include the inside-out (e.g., Lui, 1991a, 1991b, 2001), outside-in (e.g., Baker et al., 1991b; Shiokawa et al., 1998), and magnetosphere-ionosphere coupling (e.g., Kan, 1993; Kan et al., 2011) substorm models. Although the origin of substorm onset is under debate (Angelopoulos, 2008), magnetic fluctuations in the near-Earth magnetotail are an important signature at substorm onset and are involved in all the aforementioned models.

In the inside-out substorm model, these strong magnetic fluctuations at substorm onset can cause the current disruption and typically occur close to the neutral sheet in the magnetotail (Lui, 2001). In such current disruption, the magnetic fluctuations have a broad spectrum that covers timescales from below to above the ion gyroperiod (Lui & Najmi, 1997), meaning the collapse of the magnetohydrodynamic (MHD) condition. Therefore, these magnetic fluctuations are associated with the non-MHD processes of ions in the magnetotail, where the kinetic effect of ions is important (Consolini et al., 2005). In the outside-in substorm model, the magnetic fluctuations caused by earthward plasma flow are also involved in the substorm process (Shiokawa et al., 1998).

The timescales and amplitudes of these magnetic fluctuations have been studied (e.g., Ohtani et al., 1995, 1998; Ono et al., 2009; Takahashi et al., 1987). Takahashi et al. (1987) first reported such strong magnetic fluctuations at $|X| = 8\ R_E$ in the magnetotail, the amplitudes of which are $\sim$10–40 nT. Furthermore, Ohtani et al. (1995, 1998) showed that the typical timescales of these magnetic fluctuations are several times larger than the proton gyroperiod and concluded that these magnetic fluctuations are strongly related to current disruptions and plasma instabilities. Ono et al. (2009) showed that these magnetic fluctuations can induce an electric field that further accelerates ions nonadiabatically.

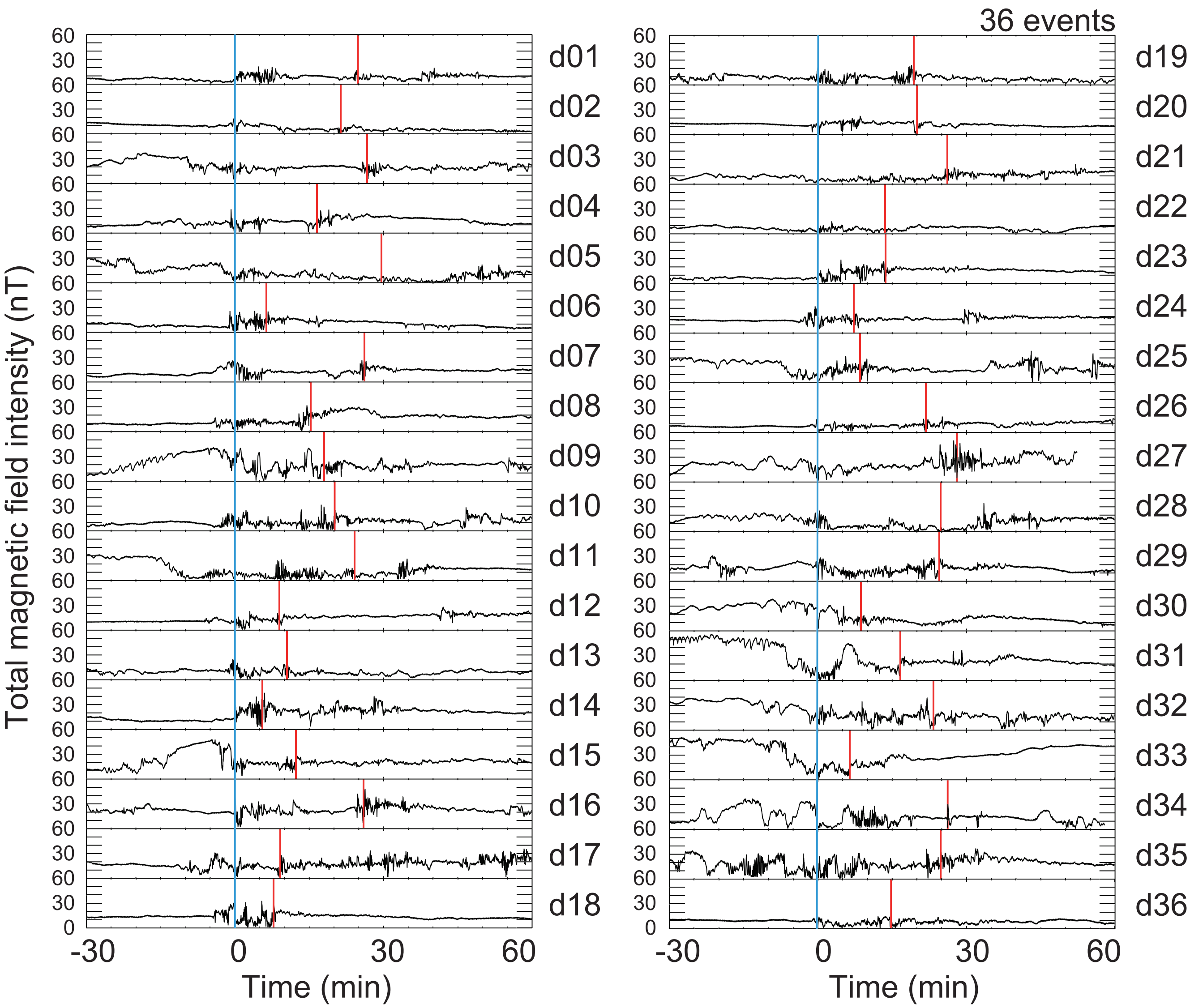

Figure 1. Variations of magnetic field intensity during selected 36 dipolarization events. The data are from −30 to +60 min relative to the first severe magnetic fluctuation. The first and last severe magnetic fluctuation events are indicated by the vertical blue line and the vertical red line, respectively.

Previous studies have also reported the spectral properties of these magnetic fluctuations (e.g., Kozak et al., 2018; Lui et al., 1992; Nishitani & Oguti, 1988; Ohtani et al., 1998; Shiokawa et al., 2005). The Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer (AMPTE/CCE), Spacecraft Charging at High Altitude (SCATHA), and GEOTAIL satellites used in those studies provided magnetic field measurements at ~8.8, ~7.8, and 8–11 R_E, respectively. Figure 7 of Nosé et al. (2014) summarizes some of these previous studies. In general, they all showed that the spectra of these magnetic fluctuations are broad. The power spectral density (PSD) decreases at larger frequency, and the spectra have a clear peak near the gyrofrequency of O^+ ions, which may explain the acceleration of O^+ ions (Nosé et al., 2014).

Despite the above studies, the spectral properties of magnetic fluctuations in the near-Earth magnetotail and their dependence on solar activity are still not well understood. Xu et al. (2017) conducted a statistical analysis of these magnetic fluctuations and reported their occurrence rates, spatial distributions, and relationship with earthward plasma flows using 2 years of data from the THEMIS E satellite. Using 11 years of data from the THEMIS D and THEMIS E satellites, the present study further investigates (a) the occurrence rates of severe magnetic fluctuations in one solar cycle, (b) the spectral properties of severe magnetic

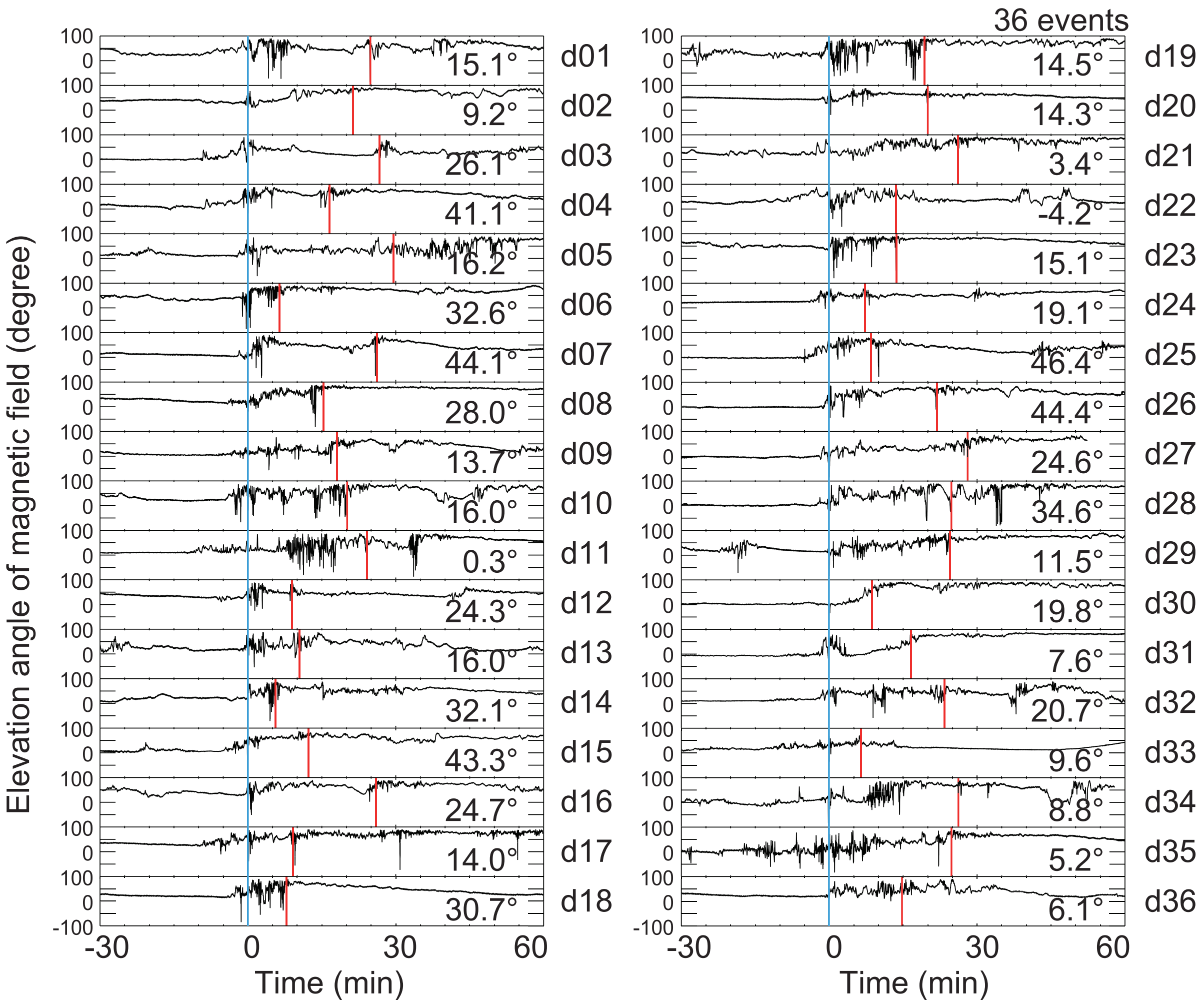

Figure 2. Variations of elevation angle of magnetic field during the 36 dipolarization events using the same format as in Figure 1. The increase of elevation angle indicates that the magnetic field becomes more dipole like.

fluctuations in multiple dipolarization events at 8–12 R_E, (c) the possible change of slope in the spectra near the proton gyrofrequency, and (d) the timing of earthward plasma flow during dipolarizations with severe magnetic fluctuations.

2. Data Set and Event Selection

We analyzed the 4-Hz sampled magnetic field intensity data obtained by the THEMIS D and THEMIS E probes for 2008–2018 using the method applied by Xu et al. (2017) in previous statistical analyses. A severe magnetic fluctuation event was defined as $\sigma_B/\bar{B} > 0.5$, where σ_B and $\bar{B}$ are the standard deviation and average, respectively, of the magnetic field intensity for the local proton gyroperiod. We focused on the variations of magnetic field intensity that may violate the gyromotion of ions. The details of this criterion can be found in Xu et al. (2017). In total, we found 10,848 severe magnetic fluctuation events.

The present study focused on the magnetic fluctuations at substorm onset. As an important signature of substorm onset, dipolarization is often accompanied by magnetic fluctuations (e.g., Jacquey et al., 1991). Dipolarization can be defined as an increase in the elevation angle ($= \arctan(B_z/B_{xy})$) of the magnetic field in geocentric solar magnetospheric (GSM) coordinates, where B_{xy} is the magnetic component in the GSM-XY plane. The criterion used by Xu et al. (2017) tends to select magnetic fluctuations at or near substorm onset. Therefore, to focus on those fluctuations related to substorm onset, from the already selected severe magnetic

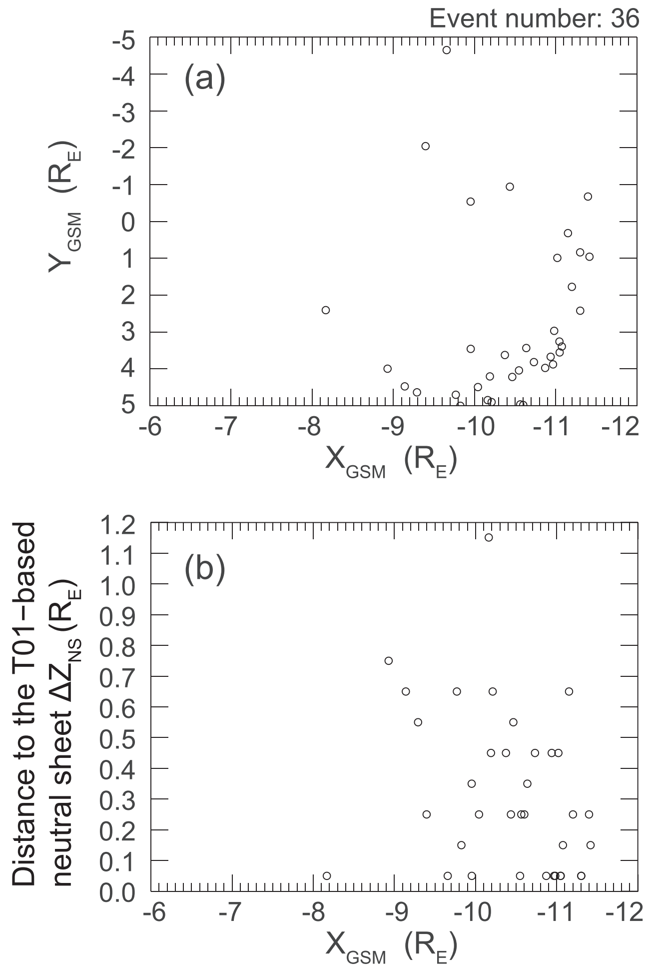

Figure 3. Spatial distributions of the 36 dipolarization events with severe magnetic fluctuations in the (a) GSM-*XY* and (b) X_{GSM}-ΔZ_{NS} planes, where ΔZ_{NS} indicates the distance to the neutral sheet using the T01 Tsyganenko model.

fluctuations, we selected clear isolated dipolarization events with reference to previous studies (Schmid et al., 2011, 2016). The criteria used to select the clear dipolarization events were as follows.

1. Location: Dipolarization events should be located at $(X_{GSM}, Y_{GSM}, Z_{GSM}) = (-9 \pm 3, \pm 5, \pm 3)\ R_E$ in GSM coordinates. This condition was used by Xu et al. (2017) for the initial selection of severe magnetic fluctuation events.
2. Duration: A dipolarization event contains three or more severe magnetic fluctuation events. The time between the first and last being 5–30 min, which is defined as the dipolarization window.
3. Elevation angle: At the times of minimum and maximum B_z in the dipolarization window, the differences in elevation angle and B_z exceed 10° and 4 nT, respectively. Within the dipolarization window, the elevation angle has at least one data point that exceeds 45°, and the maximum B_z occurs later than the minimum B_z.
4. Additional criteria: To exclude events with other dipolarization occurring before the dipolarization window or significant elevation angle change before the window, (i) the mean elevation angle during the dipolarization window must be 10° larger than that for 30 min before the window and (ii) the standard deviation of the elevation angle for 30 min before the dipolarization window must be less than 15°.

Based on the above criteria, we obtained 36 clear dipolarization events from the 10,848 severe magnetic fluctuation events that occurred in the studied 11-year period, and each clear depolarization event contained multiple severe magnetic fluctuation events. Figure 1 shows the variations of the magnetic field intensity during the 36 dipolarization events. The data are from −30 to +60 min relative to the first severe magnetic fluctuation event. The first and last severe magnetic fluctuation events are indicated by the vertical blue line

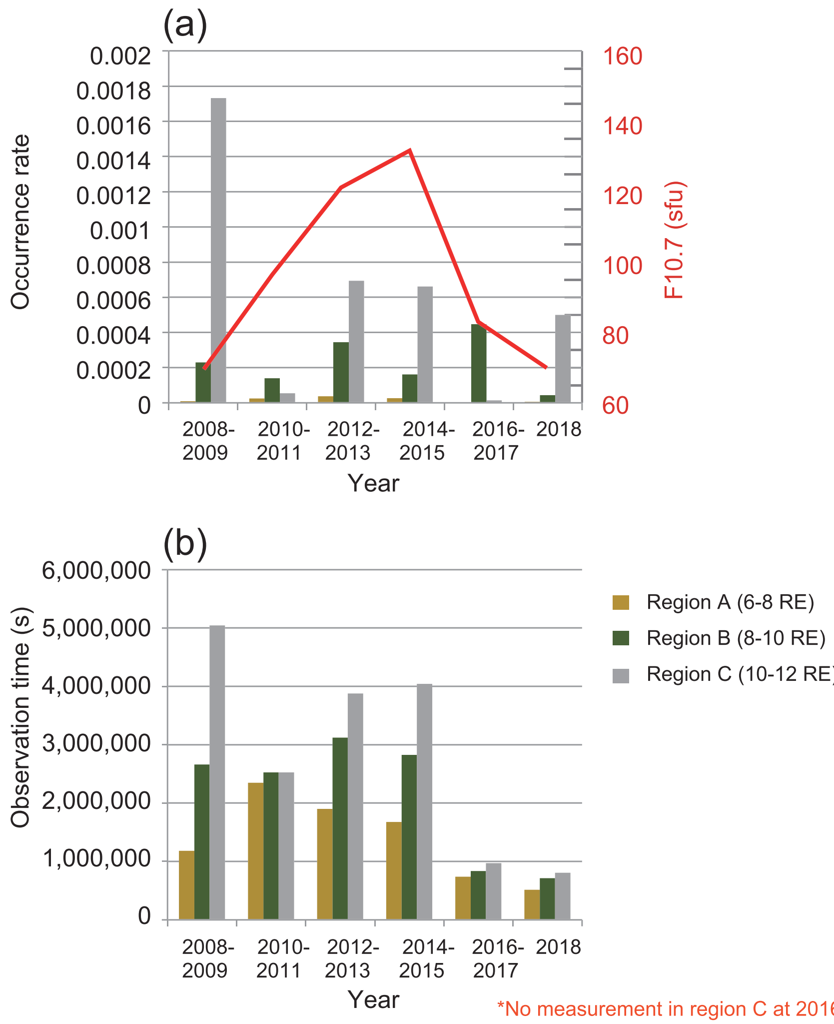

Figure 4. Comparison between occurrence rates of severe magnetic fluctuations and solar activity in a complete solar cycle: (a) occurrence rates in each subregion and $F_{10.7}$ index averaged over 2 years except for 2018; (b) total observation times in each subregion.

and the vertical red line, respectively. During each dipolarization window, the magnetic field exhibits strong and long-lasting variations.

Using the same format as in Figure 1, Figure 2 shows the variations of the elevation angle of the magnetic field during the dipolarization events. We calculated the 10-min averages of elevation angles before and after the vertical blue line. The subtraction between two averages indicates the increase of elevation angle before and after the dipolarizations, which is shown in each panel. The elevation angle exhibits a clear increase after the start of the dipolarization window (vertical blue line), indicating that the magnetic field became more dipole like. The features of both the dipolarizations and the severe magnetic fluctuations indicate the occurrence of substorm onset.

Figure 3 shows the locations of these dipolarization events in the GSM-XY and X_{GSM}–ΔZ_{NS} planes, where ΔZ_{NS} indicates the distance to the neutral sheet using the T01 model (Tsyganenko, 2002a, 2002b). The location marked for each dipolarization event is the average during the dipolarization window. Most of the events were located close to the neutral sheet within 1 R_E, which is consistent with the basic assumption of current disruptions as well as the statistical results of Xu et al. (2017).

3. Occurrence Rates of Severe Magnetic Fluctuations in a Solar Cycle

Because the analyzed times covered nearly a whole solar cycle, we compared the occurrence rates of the 10,848 severe magnetic fluctuation events with the averaged $F_{10.7}$ index. We checked the daily averaged $F_{10.7}$

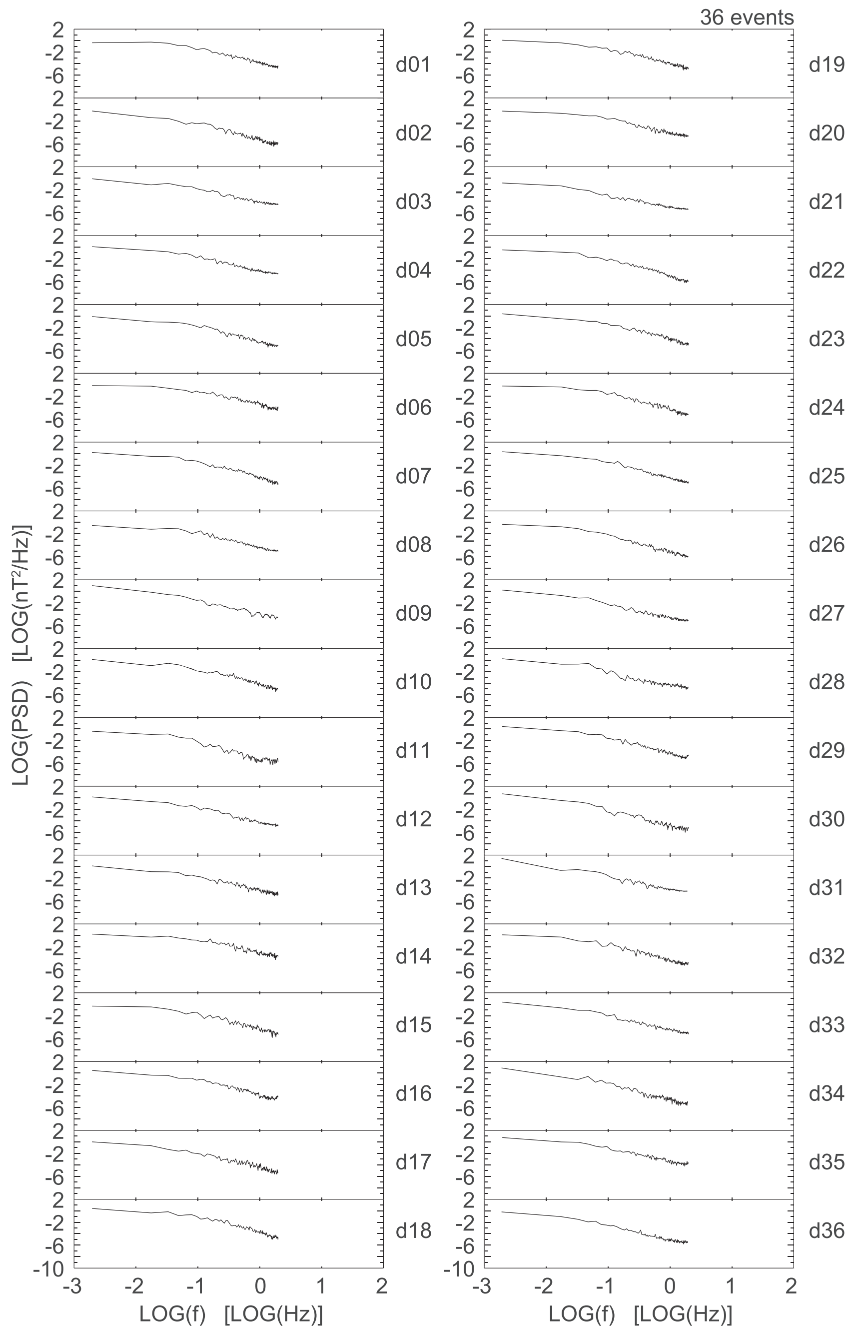

Figure 5. Power spectral densities (PSDs) of magnetic fluctuations during dipolarization events. In each event, the time segment for the fast Fourier transform analysis was chosen as the 512 s from the first severe magnetic fluctuation event.

index data and calculated their average every 1–2 years. This $F_{10.7}$ index is often used to indicate the solar activity. The $F_{10.7}$ index is the total solar radio emission at a wavelength of 10.7 cm measured by the solar disk within 1 hr and is given in solar flux units (sfu) (e.g., Tapping, 2013). We divided the analyzed region into three subregions according to the X_{GSM} coordinate. In Figure 4a, the bars indicate the occurrence rates of severe magnetic fluctuation events in each subregion, and the red curve shows the average $F_{10.7}$ index. Figure 4b shows the total observation times in each subregion. There is no clear relationship between solar activity and the occurrence rate of severe magnetic fluctuations.

Previous studies have investigated the dependence of substorm occurrence rate on the solar cycle or the solar wind conditions (e.g., Borovsky et al., 1993; Borovsky & Yakymenko, 2017; Chu et al., 2015;

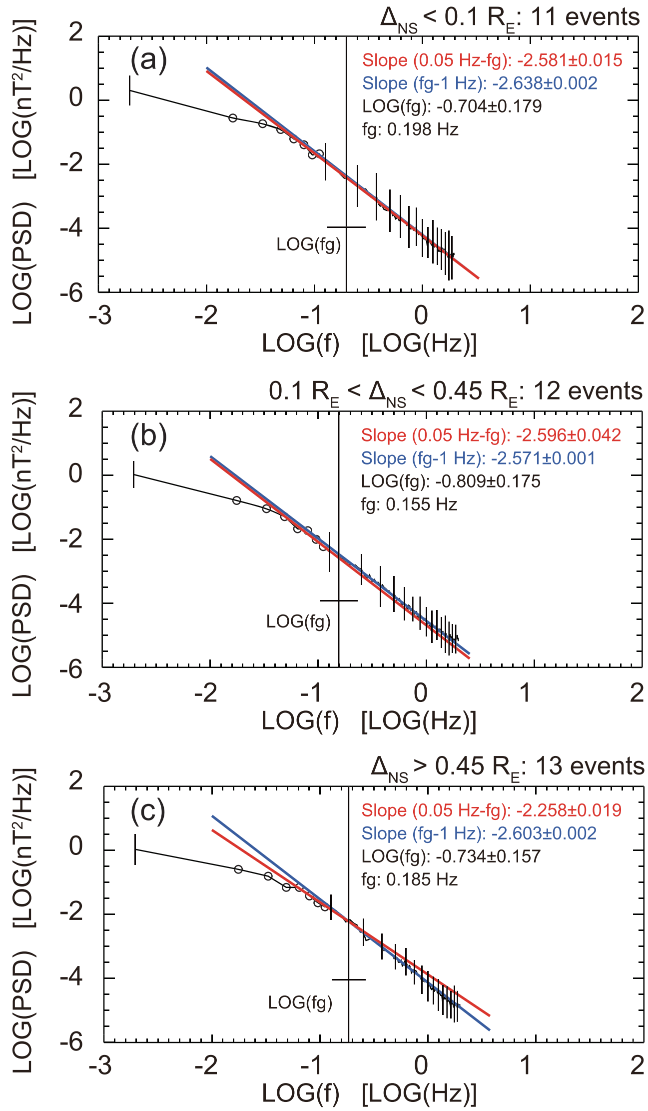

Figure 6. (a–c) Average PSDs of magnetic fluctuations during dipolarization events, where the events are divided by distance ΔZ_{NS} to the T01-based neutral sheet. The red and blue lines indicate the linear fitting results in the ranges 0.05 Hz to f_g and f_g to 1 Hz, respectively. We show all the data points between the leftmost two error bars using open circles.

Nevanlinna & Pulkkinen, 1998). Some studies have pointed out that substorm occurrence peaks in the declining phase of a solar cycle (e.g., Borovsky & Yakymenko, 2017; Tanskanen et al., 2011), because the equatorward extension of coronal holes on the Sun during the declining phase can result in long-lasting high-speed plasma at the Earth (McAllister et al., 1996). Figure 4 shows no clear peak in the occurrence rate of severe magnetic fluctuations in the declining phase of the solar cycle for 2016–2017, which is reasonable because magnetic fluctuation is only one of various mechanisms that triggers or is associated with substorms.

4. Spectral Analysis of Severe Magnetic Fluctuations During Dipolarizations

For each dipolarization event, we applied a fast Fourier transform (FFT) to the total magnetic field intensity and calculated the associated PSD. Instead of the dipolarization window, the time segment for the FFT analysis was chosen as the 512 s from the first severe magnetic fluctuation event. We smoothed the raw PSD by calculating the average value over every eight data points in the frequency domain, providing an equivalent degree of freedom of 16. Figure 5 shows the PSDs of the magnetic fluctuations for all 36 dipolarization events plotted on a logarithmic scale. In almost all events, the spectral slope increased with increasing frequency.

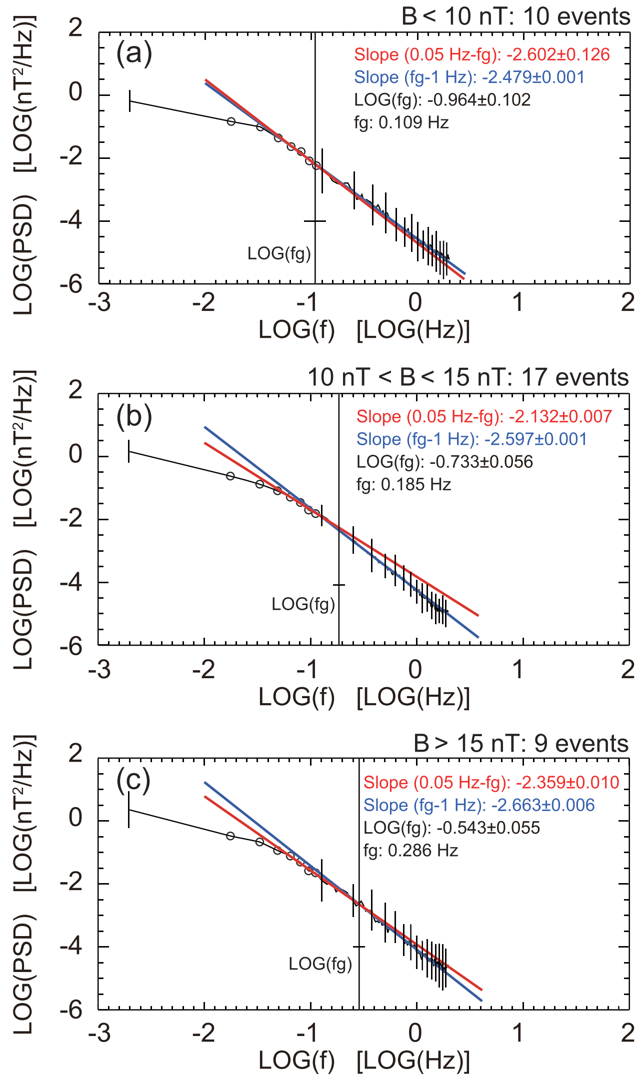

Figure 7. (a–c) Average PSDs of magnetic fluctuations during dipolarization events, where the events are divided by ambient magnetic field intensity. The red and blue lines indicate the linear fitting results in the ranges 0.05 Hz to f_g and f_g to 1 Hz, respectively.

We then divided the 36 dipolarization events into three groups sorted by (a) distance to the T01-based neutral sheet and (b) ambient magnetic field intensity. In each group, we calculated the average and standard deviation of the PSD values at each frequency point using all the PSD curves, because we seek to calculate the PSD slope (power law gradient).

Finally, we calculated the proton gyrofrequency in each dipolarization event using the average ambient magnetic field intensity during the 512 s of the FFT analysis. For each group in (a) and (b), we calculated the average proton gyrofrequency f_g for the corresponding dipolarization event. We then applied linear least squares fits in the frequency ranges of (i) 0.05 Hz to f_g and (ii) f_g to 1 Hz in the average PSD curve to obtain power law parameters. Previous studies have shown that the PSD power law has a kink at around 0.05–1 Hz (e.g., Shiokawa et al., 2005).

Figure 6 shows the average PSDs of the magnetic fluctuations during the dipolarization events, where the events are divided by distance ΔZ_{NS} to the T01-based neutral sheet. The red and blue lines indicate the linear regression lines for 0.05 Hz to f_g and f_g to 1 Hz, respectively. The error bars (shown every eight data points) are the standard deviations of the PSD values at the various frequency points using all the PSD curves. We show all the data points between the leftmost two error bars using open circles. In the group with $\Delta Z_{NS} < 0.1\ R_E$,

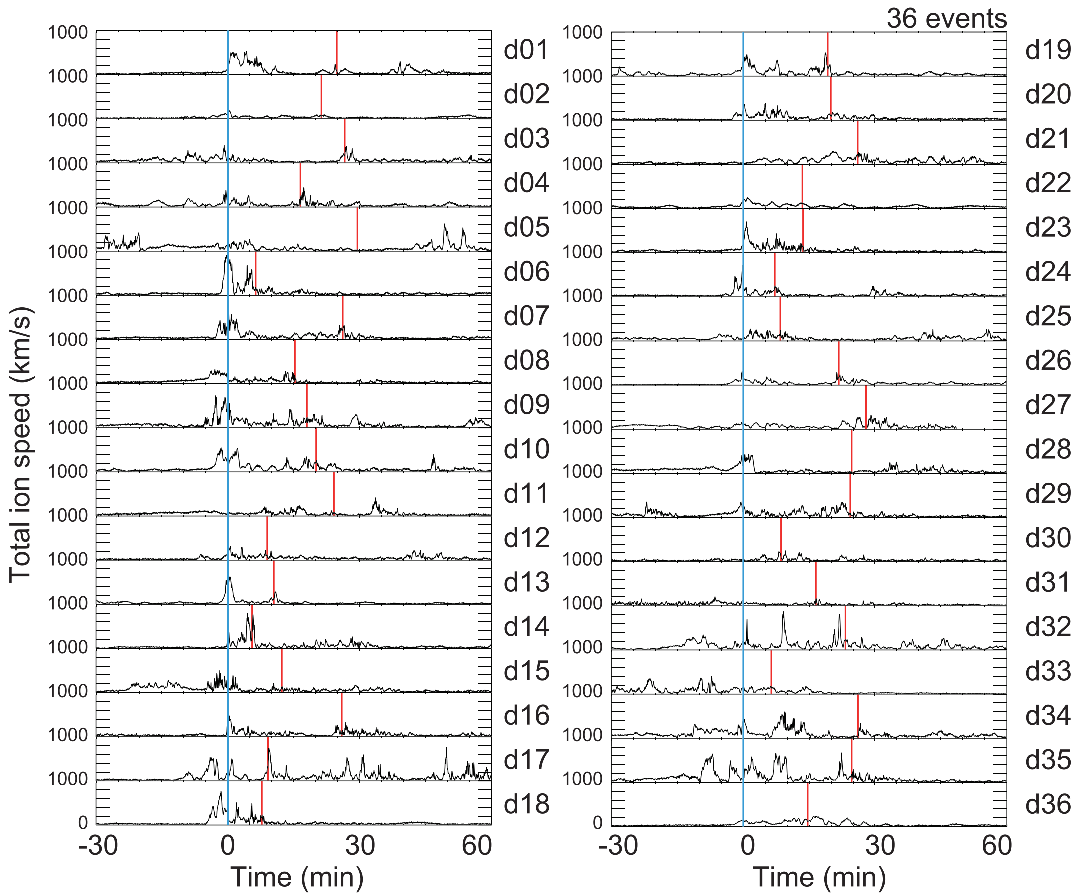

Figure 8. Total ion speed accompanying severe magnetic fluctuations during dipolarization events, using the same format as in Figure 1.

the two fitted lines exhibit no clear change in the average-PSD slope in the range 0.05–1 Hz, which differs from the results of Shiokawa et al. (2005) from the GEOTAIL satellite at $|X| = 8$–$11\ R_E$. In the group with $\Delta Z_{NS} > 0.45\ R_E$, the PSD slope is steeper in the higher-frequency range within 0.05–1 Hz, which is similar to the finding by Shiokawa et al. (2005) for events at small ambient magnetic field. For all three groups, the average PSD slope increases abruptly from below $\sim 10^{-1.3}$ Hz (0.05 Hz) to above $\sim 10^{-1.3}$ Hz. This suggests that the magnetic fluctuations were stronger near 0.05 Hz, which is lower than f_g. We discuss this abrupt PSD change in section 6.

Magnetic fluctuations at a frequency near the gyrofrequency of a particular ion species may strongly affect the motion of those ions and cause the non-MHD effect. The gyrofrequency of ions in the magnetotail depends on the ambient magnetic field intensity, which in turn is related to both the radial distance to the Earth and the distance to the neutral sheet. Using the same format as in Figure 6, Figure 7 shows the average PSDs of the magnetic fluctuations during the dipolarization events but with the events divided by ambient magnetic field intensity. The ambient magnetic field intensity of each dipolarization event is the average value over the 512 s of the FFT analysis. Figures 7a–7c show f_g increasing with increasing ambient magnetic field intensity. As in Figure 6, it seems that the slope of the average PSD increases abruptly from below $\sim 10^{-1.3}$ Hz (0.05 Hz) to above $\sim 10^{-1.3}$ Hz. We also see steepening in the range 0.05–1 Hz, as evident from the difference between the two fitted lines in Figures 7b and 7c. It seems that the intersection of the two fitted lines here is related to f_g, which may imply that the magnetic fluctuations near f_g are relatively strong and contribute to the non-MHD effect in proton motion.

5. Plasma Flow During Dipolarizations

Using the same format as in Figure 1, Figures 8 and 9 show the total ion speed and ion speed in the X_{GSM} direction associated with severe magnetic fluctuations during dipolarization events. In most cases, the total

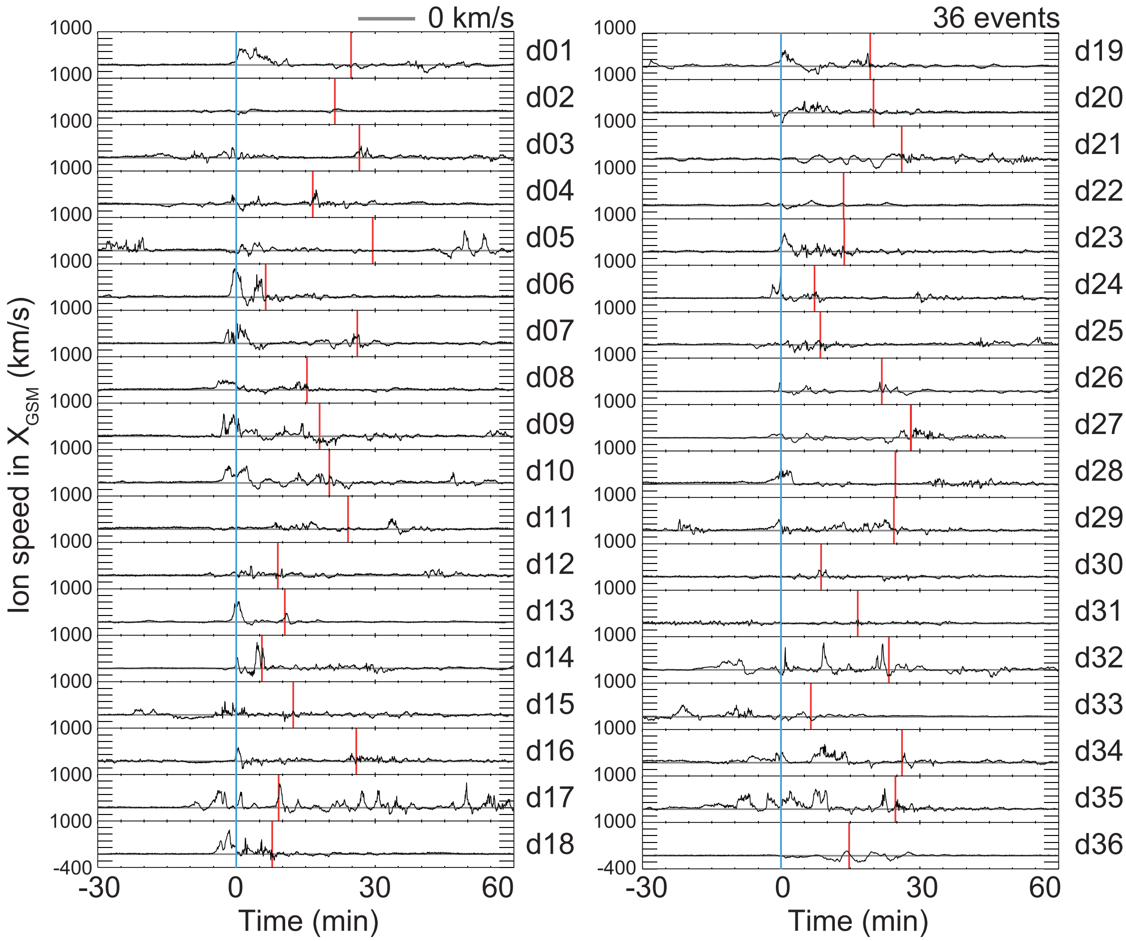

Figure 9. Ion speed in X_{GSM} direction accompanying severe magnetic fluctuations during dipolarization events, using the same format as in Figure 1.

ion speed increases clearly either during or near the dipolarization window. Of the 36 dipolarization events, 21 were accompanied by earthward high-speed ion flow with total ion speed V_{Total} > 200 km/s. For 30 of the dipolarization events, the total ion speed had already started to increase before the dipolarizations. These results are consistent with the statistical analysis by Xu et al. (2017) and are discussed in section 6.

6. Discussion

A main focus of this study is the spectral characteristics of severe magnetic fluctuations associated with field dipolarization in the near-Earth magnetotail. Compared with previous spectral studies (e.g., Kozak et al., 2018; Shiokawa et al., 2005) associated with field dipolarization, the present study was focused on severe magnetic fluctuations defined as $\sigma_B/\bar{B} > 0.5$. Then, as explained in section 2, the signature of dipolarization was used to clarify the timing of substorm onsets. The definition of dipolarization event in this study differed from that in previous studies. Here, a dipolarization event must contain multiple severe magnetic fluctuations in addition to an elevation angle increase. The present study also examined the solar cycle dependence of severe magnetic fluctuations, something not considered in previous studies.

Volwerk et al. (2003) and Shiokawa et al. (2005) have summarized and discussed the physical meaning of PSD slopes. In particular, (a) three-dimensional (3-D) magnetic turbulence exhibits a Kolmogorov slope of −5/3, which is comparable to the slope of −2.0 observed at lower frequencies in PSDs; (b) two-dimensional (2-D) magnetic turbulence exhibits a slope of −3.0 (Frisch, 1995), which is similar to the slope of −2.7 observed at higher frequencies in PSDs; (c) the abrupt increase and difference in slopes near f_g may indicate the turbulence changing from 3-D to 2-D. Herein, a similar change of magnetic turbulence from 3-D to 2-D from below f_g to above f_g is evident in Figures 7b and 7c. The slopes of the fitted lines (−2.663 to −2.132) are generally comparable with the values found in previous studies (e.g., Kozak et al., 2018; Shiokawa et al., 2005). Sahraoui et al. (2009) concluded that such change of slope near the proton gyrofrequency is related to the transition from low-frequency MHD turbulence to higher-frequency waves.

In this study, an abrupt change in slope at $\sim 10^{-1.3}$ Hz (0.05 Hz) was observed in the PSDs. In the linear fits of Figures 6 and 7, we have considered only the H^+ (proton) gyrofrequency. It is the first time that a change of slope near the gyrofrequency of proton (frequency range: 0.05–1 Hz) was found in cases of larger ambient magnetic field intensity. Figure 7 of Nosé et al. (2014) summarizes the dominant frequency of magnetic fluctuations in the near-Earth magnetotail as reported in several previous studies. It seems to be common for the magnetic fluctuations to have a dominant frequency less than f_g (the gyrofrequency of H^+ ions) but close to f_{gO^+} (the gyrofrequency of O^+ ions). Nosé et al. (2014) also concluded that the magnetic fluctuations during dipolarization can accelerate O^+ ions efficiently, while no clear acceleration of H^+ ions is observed. The 0.05 Hz found in the present study is also close to f_{gO^+} and is consistent with previous studies. These results and the discussion in section 4 suggest that magnetic fluctuations are relatively strong near the gyrofrequencies of O^+ and H^+ ions and contribute to the non-MHD effect in ion motion. In the signal analysis, a PSD with a peak at 0.05 Hz can represent intermittent pulses with a period of 20 s. We also checked the 512-s plots of magnetic field intensity in FFT analysis for all the dipolarization events. We found that it is hard to identify such burst signal with a period of ~20 s by visual inspection. We also have to note that the Doppler shift in magnetic field measurement caused by plasma flow may result in a possible ambiguity in the present study. One method to estimate such Doppler shift effect was reported by Narita et al. (2013).

In this study, severe magnetic fluctuations were analyzed during clear magnetic dipolarization events. The two observed characteristics of the magnetic fluctuations, namely, (i) proximity to the neutral sheet and (ii) a prior increase of earthward ion speed, are consistent with the previous statistical analysis by Xu et al. (2017), who also discussed the ambiguity of the relation between magnetic fluctuations and earthward plasma flow. A possible concern with that study is that selecting a large number of events (3,322) in a short observation time (2 years) might bias the results statistically. However, the results of the present multievent study support the conclusions of Xu et al. (2017) and suggest that in most cases the earthward plasma flows cause magnetic fluctuations in the near-Earth magnetotail.

7. Conclusions

In this paper, we focused on the solar cycle variation and spectral slope of severe magnetic fluctuations in the near-Earth magnetotail. We analyzed the 4-Hz magnetic field intensity data of the THEMIS D and THEMIS E probes for 2008–2018 at $|X| = 8 - 12\ R_E$ and found 10,848 severe magnetic fluctuation events with $\sigma_B/\bar{B} > 0.5$, where σ_B and $\bar{B}$ are the standard deviation and average, respectively, of the magnetic field intensity for the local proton gyroperiod. We then extracted 36 clear isolated dipolarization events based on the elevation angle of the magnetic field, and we investigated the spectral properties of the associated severe magnetic fluctuations. Our main results are summarized as follows.

1. We found no clear relationship between the occurrence rate of severe magnetic fluctuations and the solar activity in a complete solar cycle.
2. Most dipolarization events were located close to the neutral sheet within 1 R_E, which is consistent with a basic consideration of current disruptions.
3. We calculated the PSDs of the magnetic fluctuations during the clear isolated dipolarization events and found that the spectral slope increased with increasing frequency for almost all the events. We also showed the average PSDs of the magnetic fluctuations during the dipolarization events sorted by (a) distance to the neutral sheet and (b) ambient magnetic field intensity. In all groups, the slope of the average PSD increased abruptly from below $\sim 10^{-1.3}$ Hz (0.05 Hz) to above $\sim 10^{-1.3}$ Hz. This peak in PSD at 0.05 Hz is close to the gyrofrequency of O^+ ions. The slopes of the lines fitted to the PSDs in the range 0.05–1 Hz are from −2.663 to −2.132. The present results provide a wider radial distance coverage at 8–12 R_E and are generally consistent with those of previous studies of spectral slopes.
4. For the first time, a change of slope near the gyrofrequency of proton (frequency range: 0.05–1 Hz) in PSD was found in cases of larger ambient magnetic field intensity. These results suggest that magnetic fluctuations are relatively strong near the gyrofrequencies of O^+ and H^+ ions and contribute to the non-MHD effect in ion motion.

5. Of the identified 36 dipolarization events, 21 were accompanied by earthward high-speed ion flow with total speed $V_{Total} > 200$ km/s, and for 30 events the total ion speed had already started to increase before the dipolarization.
6. The two observed characteristics of severe magnetic fluctuations during dipolarizations, namely, (i) proximity to the neutral sheet and (ii) increase of earthward ion speed prior to magnetic fluctuations, were highly consistent with the previous statistical analysis by Xu et al. (2017). This suggests that in most cases, the earthward plasma flows cause magnetic fluctuations in the near-Earth magnetotail.

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