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Substorm Triggering Processes During Different Phases of Geomagnetic Storms: A Case Study

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Abstract: Using observations from satellites and ground-based stations, we investigate the possible mechanisms triggering the expansion phases of two substorms that occurred during different phases of a geomagnetic storm. The main findings are summarized as follows. For the substorm occurring during the storm commencement and initial phase, the energy storage process is primarily modulated by enhanced solar wind speed and dynamic pressure, whereas a southward turning of the interplanetary magnetic field (IMF) appears to be a key trigger for the onset of the expansion phase. For the substorm occurring during the storm recovery phase, energy storage is primarily associated with the southward IMF, while the expansion phase begins after a time delay following the southward turning of the IMF. Detailed analysis of these two events suggests that the mechanisms triggering substorm expansion during geomagnetic storms may differ from those operating during isolated, non-storm substorms. In contrast, previous studies have identified northward turnings of the IMF as an important indicator of expansion-phase onset in substorms under non-storm conditions. These results provide new insight into the relationship between geomagnetic storm evolution and substorm development in Earth's magnetosphere.

Keywords: geomagnetic storm; substorm; magnetospheric compression; magnetic energy release; substorm triggering

1. Introduction

Earth's near-space environment, including the magnetosphere and ionosphere, is shaped by interactions among the solar wind, Earth's intrinsic magnetic field, and its upper atmosphere. Variations in solar activity and solar wind conditions can drive substantial disturbances in the geospace environment, including geomagnetic storms and magnetospheric substorms (Dungey, 1961; Tsurutani et al., 1988; Reeves et al., 1990; Gonzalez et al., 2002, 2011; Yue et al., 2009, 2010, 2011; Yue and Zong, 2011; Ambili et al., 2025; Zakharenkova et al., 2024; Zou et al., 2025; He et al., 2016; Shumko et al., 2025). These two major types of geospace disturbances can adversely affect spacecraft operations and space-based communication and navigation systems, with potentially significant consequences for technological infrastructure and human activities (Viljanen and Pirjola, 2017; Lakhina et al., 2021; Mac Manus et al., 2017; Despirak et al., 2024; Zhang et al., 2015) .

Geomagnetic storms are major large-scale space weather disturbances associated with enhanced

solar wind energy input into Earth's magnetosphere. Their development involves the transfer of energy, momentum, and mass through the coupled solar wind–magnetosphere–ionosphere system. The development of a geomagnetic storm is commonly associated with a strong and sustained southward component of the interplanetary magnetic field (IMF $B_z < 0$), often carried by coronal mass ejections (CMEs) or corotating interaction regions (CIRs). When enhanced solar wind dynamic pressure reaches Earth's magnetosphere, the magnetopause can be rapidly compressed, producing an increase in the horizontal geomagnetic field that is characteristic of a storm sudden commencement or sudden impulse (Chapman and Ferraro, 1931; Dessler and Parker, 1959; Shen et al., 1987). A southward IMF also favors magnetic reconnection with the geomagnetic field at the dayside magnetopause, facilitating the transfer of solar wind energy and plasma into the magnetosphere (Dungey, 1961; Maltsev and Lyatsky, 1975).

A substantial fraction of the transferred energy is subsequently stored in the magnetotail. During magnetotail reconnection, magnetic energy stored in the tail is released and plasma is transported earthward toward the inner magnetosphere. The resulting enhancement of the ring current contributes to the global decrease in the horizontal geomagnetic field that characterizes the main phase of a geomagnetic storm (Dessler and Parker, 1959; Akasofu, 1981; Nishida, 1968; Fu et al., 1999; Zong et al., 2001; Xiang et al., 2023). When the IMF turns northward, dayside reconnection and the associated solar wind energy input generally weaken. The ring current subsequently decays through processes such as charge exchange, Coulomb collisions, wave–particle interactions, and particle loss from the inner magnetosphere. Consequently, the depressed horizontal geomagnetic field gradually recovers, marking the recovery phase of the geomagnetic storm (Akasofu, 1981; Huang et al., 2006).

A magnetospheric substorm is a transient process during which energy transferred from the solar wind is stored in the magnetotail and subsequently released on a relatively short timescale. Two major paradigms have been proposed to explain the onset of the substorm expansion phase. These are the near-Earth neutral line (NENL) model (McPherron et al., 1973; Hones, 1977; Baker et al., 1996) and the current disruption model (Takahashi et al., 1987; Lui et al., 1988; Lui, 1996). The primary distinction between these two models concerns the sequence of processes leading to substorm onset: the NENL model emphasizes magnetic reconnection in the magnetotail, whereas the current disruption model emphasizes disruption of the near-Earth cross-tail current. Other studies have suggested that changes in the upstream solar wind may act as external triggers for substorm onset. Based on observational evidence, Lyons (1995) proposed that a northward turning of the interplanetary magnetic field (IMF) can trigger substorm onset, providing a basis for the external-triggering hypothesis. Using statistical analyses, Hsu and McPherron (2002) found a significant temporal association between IMF northward turnings and substorm expansion-phase onset, and argued that this relationship was unlikely to be coincidental. Their subsequent study suggested that approximately 60% of the substorms examined were associated with external perturbations, including IMF variations, whereas the remaining 40% may have been initiated by internal magnetospheric processes (Hsu and McPherron, 2003). However, the external-triggering hypothesis remains debated. For example, case studies by Henderson et al. (1996) showed that identifiable external triggering conditions are not observed for all substorm expansion-phase onsets. Morley and Freeman (2007) argued that, although solar wind energy input is required during the

substorm growth phase, internal magnetospheric instability can play the decisive role in initiating the expansion phase. Freeman and Morley (2009) further argued, based on their statistical analysis, that there was insufficient evidence to conclude that IMF northward turnings necessarily trigger substorm onset. Thus, the physical mechanisms responsible for substorm expansion-phase onset remain under debate.

Geomagnetic storms and magnetospheric substorms are closely coupled, although the physical processes linking their evolution remain complex. Whether storm-time substorms differ fundamentally from substorms occurring under nonstorm conditions remains unresolved. Baumjohann et al. (1996) performed a superposed epoch analysis of plasma and magnetic field observations in the near-Earth magnetotail at radial distances of approximately 10–20 R_E , revealing systematic differences between storm-time and nonstorm substorms. For nonstorm substorms, dipolarization was relatively gradual, with the maximum magnetic field elevation angle averaging approximately 15°. In contrast, storm-time substorms exhibited rapid post-onset dipolarization, with maximum elevation angles of up to 50°. Storm-time events were also associated with larger AE values and plasma sheet temperatures approximately twice those observed during nonstorm events. On the basis of these differences, Baumjohann et al. (1996) suggested that storm-time and nonstorm substorms might involve different expansion-phase onset mechanisms and could represent physically distinct regimes. In contrast, using a larger data set and an analysis similar to that of Baumjohann et al. (1996), McPherron and Hsu (2002) found substantial differences in magnetotail signatures between storm-time and nonstorm substorms but concluded that these differences were primarily quantitative rather than qualitative.

Observationally, substorm expansion-phase onset is commonly identified by an abrupt increase in auroral electrojet activity, such as a rapid increase in AE or a sharp decrease in SML. In auroral observations, the onset is typically associated with a sudden intensification and subsequent expansion of auroral emission. Nevertheless, whether the mechanisms governing expansion-phase onset differ fundamentally between storm-time and nonstorm substorms remains unresolved. Clarifying how expansion-phase onset mechanisms differ between storm-time and nonstorm substorms is therefore important for understanding the coupling between geomagnetic storms and substorm dynamics.

2. Event Selection and Data Sources

This study examines two substorms that occurred during geomagnetic storms on September 18, 2023, and October 12, 2024, respectively. The two substorms occurred during the storm commencement and early phase and during the recovery phase, respectively. In situ observations of magnetotail dynamics associated with the two substorms were obtained from the THEMIS-A (Time History of Events and Macroscale Interactions during Substorms) spacecraft and the Magnetospheric Multiscale (MMS) 1 spacecraft. Solar wind parameters and geomagnetic indices were obtained from the 1-min OMNI data set. The SuperMAG auroral electrojet indices (SME, SMU, and SML) and the ring-current index (SMR) were obtained from the SuperMAG data products.

3. Observations and Analysis

3.1 Substorm During the Storm Commencement and Early Phase: September 18, 2023

Figure 1 shows the OMNI solar wind observations from 12:00 to 21:00 UT on September 18, 2023. The three black vertical dashed lines, from left to right, mark three distinct changes in the solar wind and interplanetary magnetic field (IMF) conditions. At 13:35 UT (the first dashed line), the solar wind parameters changed abruptly. The solar wind speed, dynamic pressure, proton density, and total magnetic field strength all increased substantially. Specifically, the solar wind speed increased from approximately 410 to 550 km·s⁻¹, the dynamic pressure from 1.8 to 7.8 nPa, the total magnetic field strength from 10 to 22 nT, and the proton density from 4 to 12 cm⁻³. The sharp increase in solar wind dynamic pressure produced a strong compression of the magnetosphere, consistent with the storm sudden commencement discussed below. At 15:48 UT (the second dashed line), the IMF turned southward for approximately 25 min. At 16:32 UT (the third dashed line), the IMF turned southward again and remained predominantly southward for an extended interval. In contrast to the IMF variations, the solar wind plasma parameters showed no substantial changes during these two intervals.

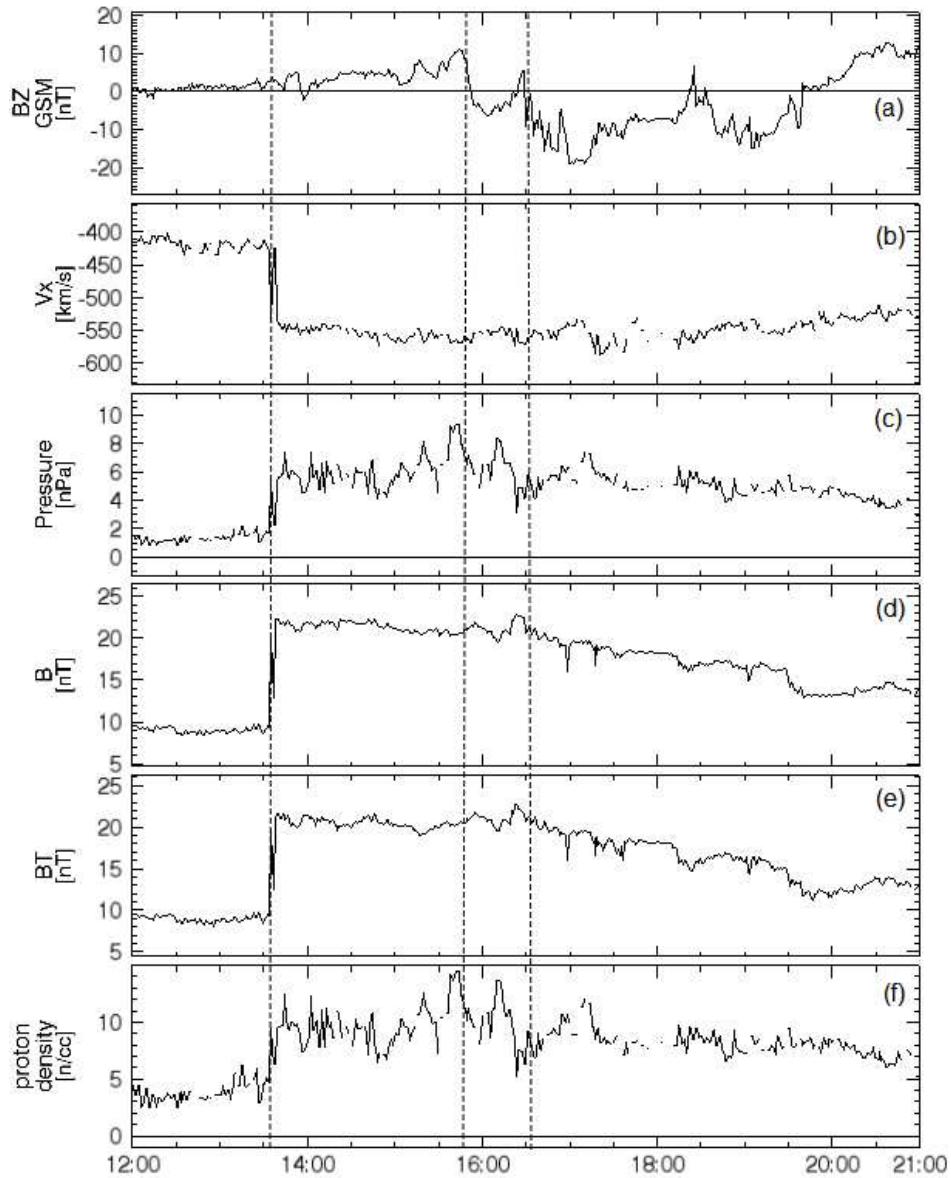


Figure 1: OMNI observations from 12:00 to 21:00 UT on September 18, 2023

From top to bottom, these are: (a) the Bz component of the interplanetary magnetic field; (b) the Vx component of the solar wind velocity; (c) the dynamic pressure of the solar wind; (d) the total interplanetary magnetic field strength B; (e) the BT component of the interplanetary magnetic field (excluding the Bx component); and (f) the proton density of the solar wind. The data on the horizontal axis represent time. The three vertical dashed lines in the figure represent 13:35 UT, 15:48 UT, and 16:32 UT, respectively.

The Newell coupling function (Newell et al., 2007) and the Akasofu ε parameter (Akasofu, 1981) are widely used to characterize solar wind–magnetosphere energy coupling. Figure 2 presents the SuperMAG indices and solar wind–magnetosphere coupling parameters from 13:00 to 21:00 UT. At 13:35 UT (the first dashed line), the abrupt enhancement in solar wind dynamic pressure strongly compressed the magnetosphere, and the SMR index increased from approximately 5 to 50 nT, consistent with a storm sudden commencement. Both coupling parameters increased modestly, with the Newell coupling function increasing from 4×10^3 Wb/s to 1.2×10^4 Wb/s and the Akasofu

parameter increasing from 0 to 1.3×10^{13} W. These enhancements indicate an increase in solar
 wind–magnetosphere coupling at this time. Meanwhile, the SML index showed a modest decrease.
 Notably, sharp decreases in SML occurred near the times of IMF southward turnings, suggesting
 the onset of substorm expansion phases. For example, at 15:48 UT (the second dashed line), a brief
 southward turning of the IMF was accompanied by a decrease in SML from approximately -180 to
 -550 nT. At 16:32 UT (the third dashed line), a more sustained southward turning of the IMF was
 followed by a further decrease in SML from approximately -300 to -1020 nT. These temporal
 correspondences suggest that the two IMF southward turnings were closely associated with the onset
 of two substorm expansion phases of different intensities. The two southward turnings are also
 evident in the IMF Clock-angle variations.

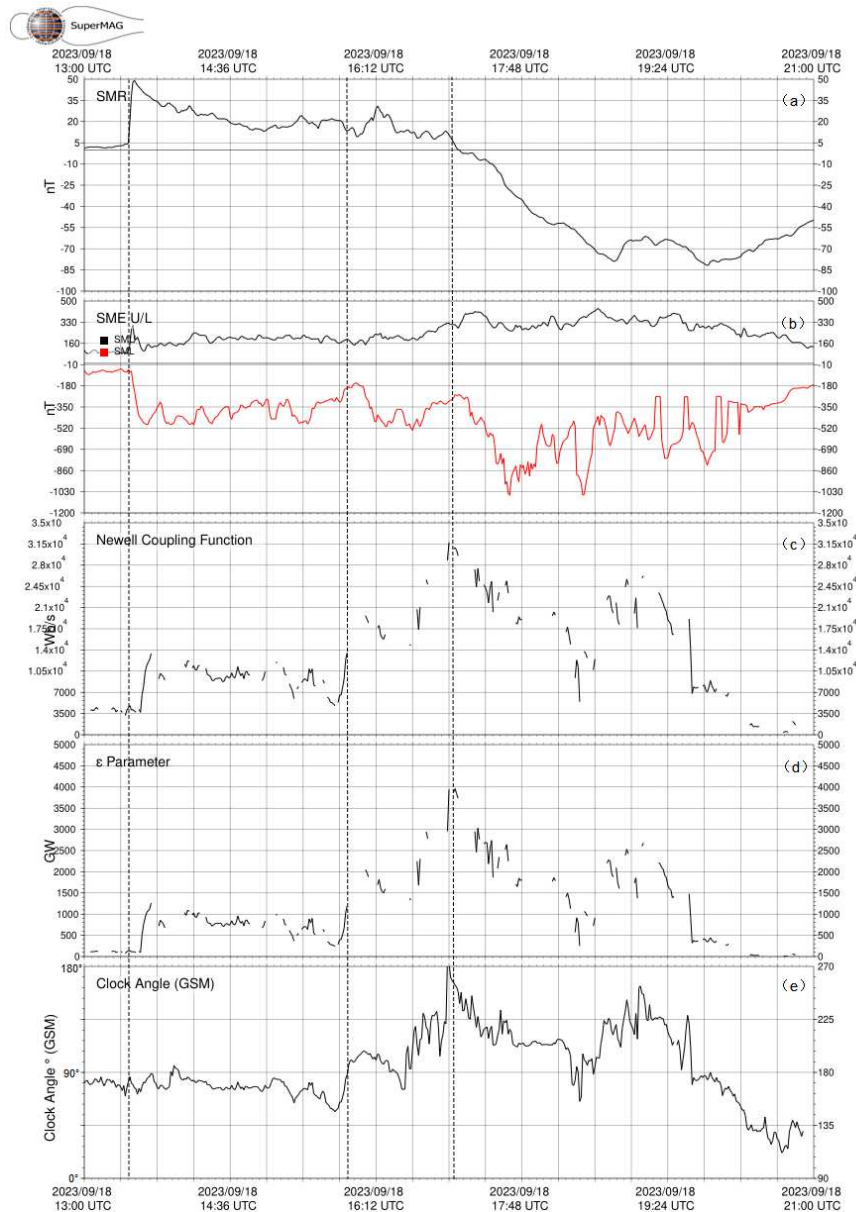


Figure 2: Data from the SUPERMAG website, September 18, 2023, 13:00–21:00 UT

From top to bottom: (a) SMR index, (b) SMU/L index, (c) NeWell function, (d) Akasofu ϵ parameter, (e) interplanetary magnetic
 field clock angle. The data on the x-axis represents time. The three vertical dashed lines in the figure correspond to 13:35 UT, 15:48 UT, and

We next examine in situ observations from the THEMIS-A and MMS1 spacecraft in the magnetotail to further characterize the evolution of this substorm. Figure 3 shows MMS1 observations in the magnetotail near $X_{\text{GSM}} = -13 R_E$ from 14:30 to 18:00 UT on September 18, 2023. Prior to expansion-phase onset, at approximately 15:35 UT (the first dashed line), MMS1 observed a distinct earthward high-speed flow with a speed of approximately $400 \text{ km}\cdot\text{s}^{-1}$. Concurrently, the magnetic field B_z component increased markedly, indicating enhanced dipolarization, while both the electron and ion number densities increased.

Following expansion-phase onset, several decreases in the total magnetic field magnitude were observed, each accompanied by a distinct earthward high-speed flow. These signatures may be associated with intermittent magnetic energy release in the magnetotail. For example, at 16:11 UT (the second dashed line), B_x changed from approximately -65 to -56 nT , while the total magnetic field magnitude decreased from approximately 64 to 57 nT . This variation was accompanied by an earthward high-speed flow with a speed of approximately $430 \text{ km}\cdot\text{s}^{-1}$. These observations are consistent with the conversion of magnetic energy into plasma bulk-flow and thermal energy. Similar signatures were also observed at approximately 16:56, 17:13, and 17:39 UT, suggesting repeated or intermittent energy-release episodes during the substorm.

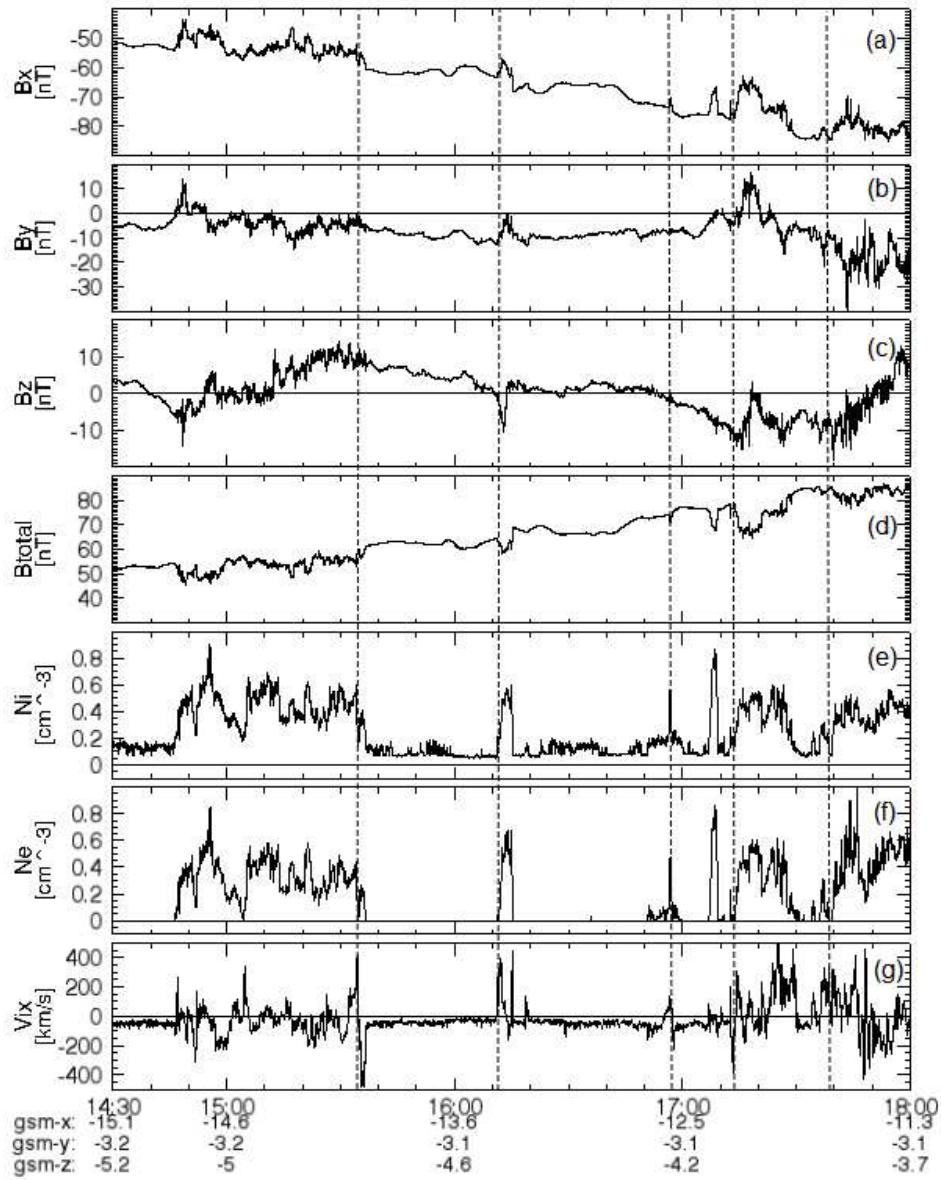


Figure 3: MMS 1 observations from 14:30 to 18:00 UT on September 18, 2023

From top to bottom: (a, b, c) the three components of the magnetic field in the GSM coordinate system; (d) total magnetic field strength; (e) ion number density; (f) electron number density; (g) the x-component of the ion velocity in the GSM coordinate system. The four rows of data at the bottom of the figure represent the time and the orbital position of the MMS 1 satellite in the GSM coordinate system. The black dashed lines in the figure correspond to the times 15:35 UT, 16:11 UT, 16:56 UT, 17:13 UT, 17:39 UT, and other times.

Figure 4 shows THEMIS-A observations in the magnetotail near $X_{\text{GSM}} = -12 R_E$ from 15:00 to 18:10 UT on September 18, 2023. Following expansion-phase onset, THEMIS-A observed several signatures characteristic of substorm evolution. For example, at 17:10 UT (the first dashed line), B_x decreased from approximately 64 to 40 nT, while the total magnetic field magnitude decreased from approximately 70 to 40 nT. Concurrently, both the electron and ion temperatures increased markedly. Because THEMIS-A was located near the plasma sheet boundary and tail lobe during this interval, no prominent earthward high-speed flows were detected, although weaker earthward ion flows were

observed. These signatures are consistent with magnetic energy release in the magnetotail during the substorm expansion phase.

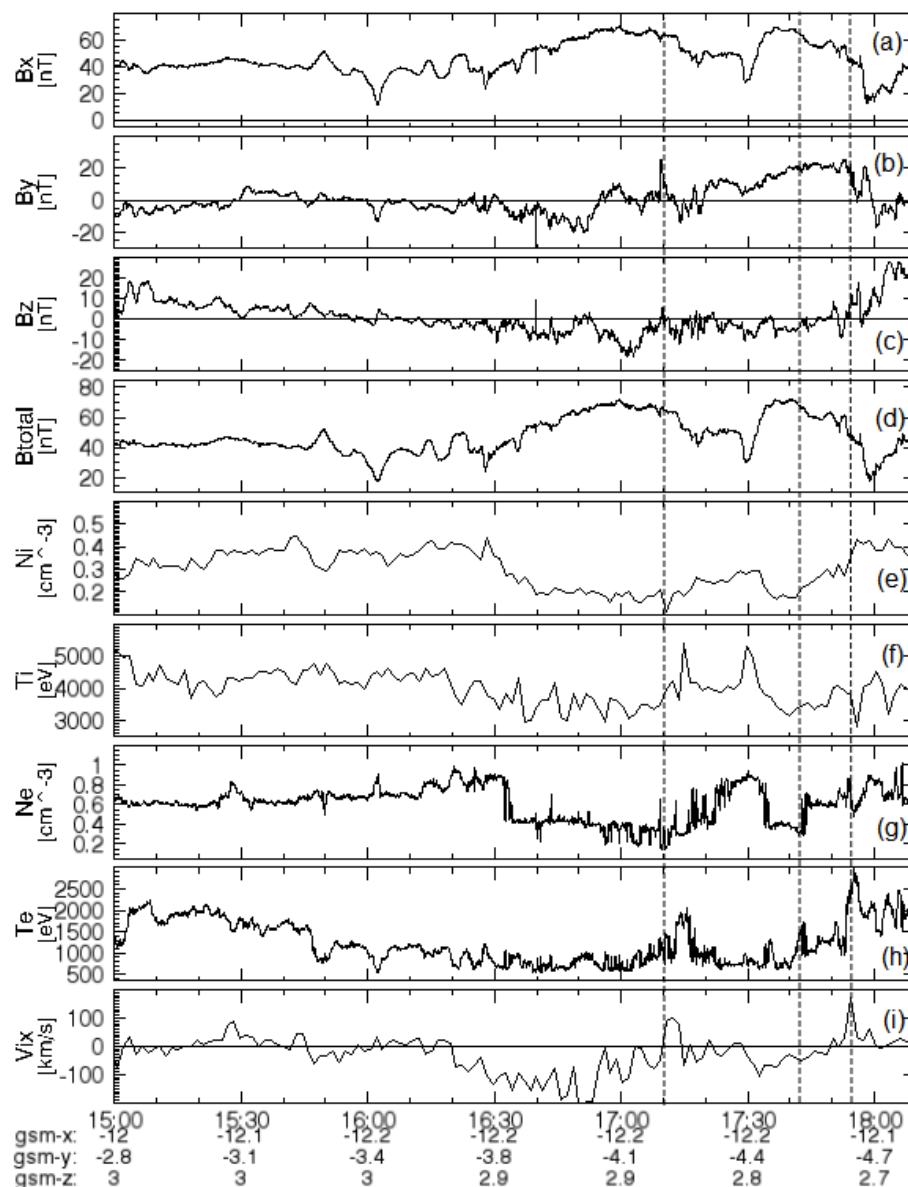


Figure 4: THEMIS A observations from 15:00 to 18:10 UT on September 18, 2023

From top to bottom: (a, b, c) the three components of the magnetic field in the GSM coordinate system; (d) total magnetic field strength; (e) ion number density; (f) ion temperature; (g) electron density; (h) electron temperature; (i) the x-component of the ion velocity in the GSM coordinate system. The four rows of data at the bottom of the figure represent the time points and the orbital positions of the THEMIS A satellite in the GSM coordinate system. The black dashed lines in the figure represent multiple time points, including 17:10 UT, 17:42 UT, and 17:53 UT.

Similar signatures of magnetic energy release were observed again at approximately 17:42 UT (the second dashed line). After approximately 17:53 UT (the third dashed line), the signatures of intense energy release weakened, while the SML index began to recover gradually. Meanwhile, B_z increased rapidly from approximately -3 to 29 nT. This strong increase in B_z indicates pronounced magnetic

field dipolarization, consistent with the transition toward the substorm recovery phase. Taken together, the MMS1 and THEMIS-A observations provide complementary evidence for the large-scale evolution of this substorm in the magnetotail.

3.2 Substorm During the Recovery Phase of a Geomagnetic Storm: October 12, 2024

Figure 5 shows OMNI solar wind observations from 08:00 to 12:00 UT on October 12, 2024. A major geomagnetic storm occurred on October 10, 2024, during which the SMR index reached a minimum of approximately -333 nT. By the interval of interest on October 12, the storm was in an extended recovery phase. We next examine the solar wind conditions associated with this event.

As shown in Figure 5c, the interplanetary magnetic field (IMF) turned southward at approximately 09:00 UT (the first dashed line), while the solar wind dynamic pressure remained nearly unchanged. The solar wind speed and total IMF magnitude increased modestly, with the speed rising from approximately 500 to 550 km·s⁻¹ and the total IMF magnitude increasing from approximately 4 to 7 nT. Unlike the September 18 event, this IMF southward turning was not accompanied by an immediate sharp decrease in SML. Instead, after the IMF had remained southward for approximately 53 min, SML began to decrease sharply at approximately 09:53 UT (the second dashed line), marking the onset of the substorm expansion phase.

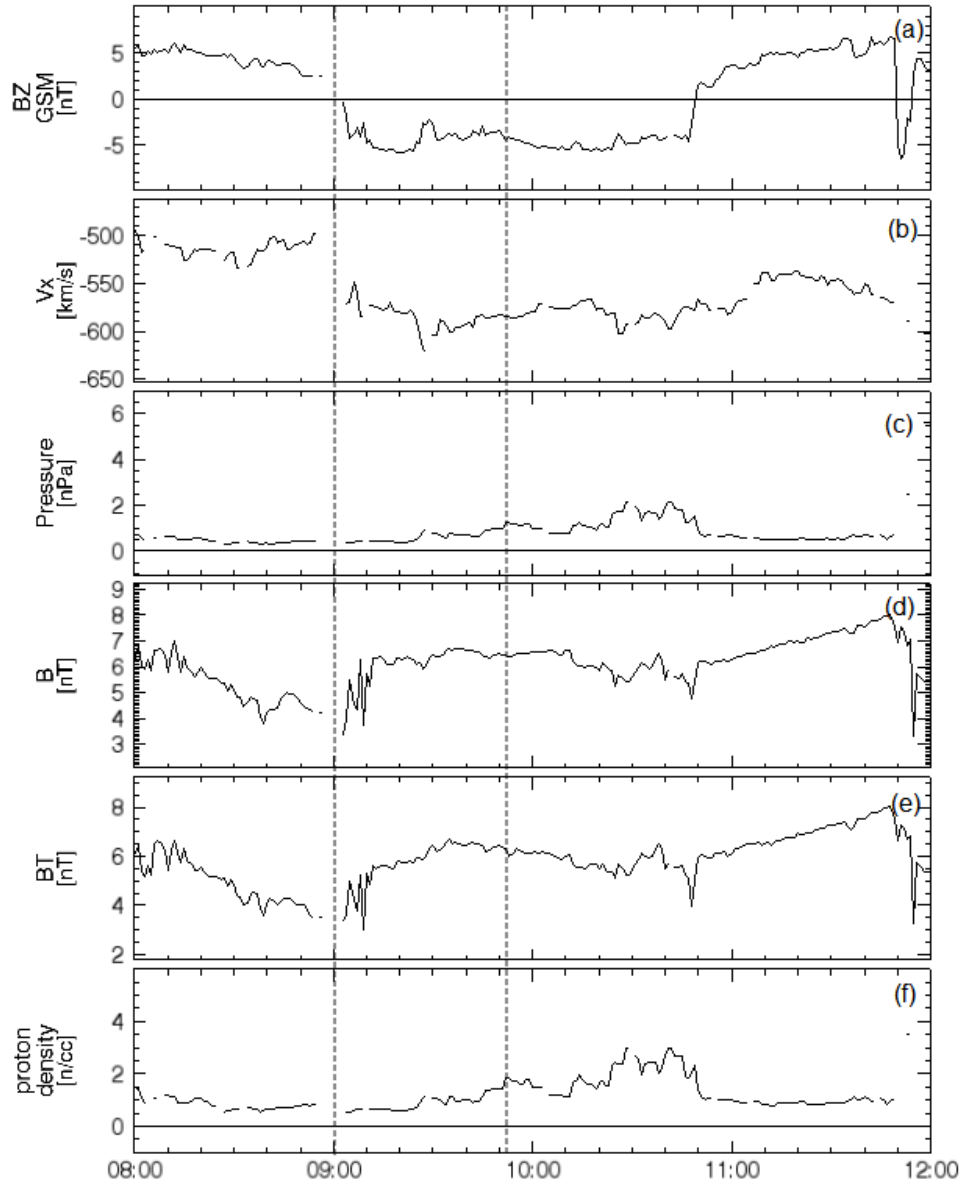


Figure 5: OMNI observations from 08:00 to 12:00 UT on October 12, 2024

From top to bottom, these are: (a) the B_z component of the interplanetary magnetic field, (b) the V_x component of the solar wind velocity, (c) the dynamic pressure of the solar wind, (d) the total interplanetary magnetic field strength B , (e) the BT component of the interplanetary magnetic field (excluding the B_x component), and (f) the proton density of the solar wind. The data on the horizontal axis represents time. The two vertical lines in the figure represent 09:00 UT and 09:53 UT, respectively.

Figure 6 presents the geomagnetic indices and solar wind–magnetosphere coupling parameters from 08:00 to 12:00 UT. Following the IMF southward turning at approximately 09:00 UT, both the Newell coupling function and the Akasofu ϵ parameter increased markedly. Specifically, the Newell coupling function increased from 0 to 1.6×10^4 Wb/s, while the Akasofu ϵ parameter increased from 0 to 4.6×10^{11} W. These enhancements indicate increased solar wind–magnetosphere coupling and enhanced energy input into the magnetosphere, favoring energy storage in the magnetotail. During this interval, the SMR index remained relatively stable. After approximately 53 min of sustained

southward IMF and enhanced solar wind–magnetosphere coupling, SML decreased sharply at approximately 09:53 UT, from about -100 to -1200 nT. This sharp SML decrease is identified as the onset of the substorm expansion phase.

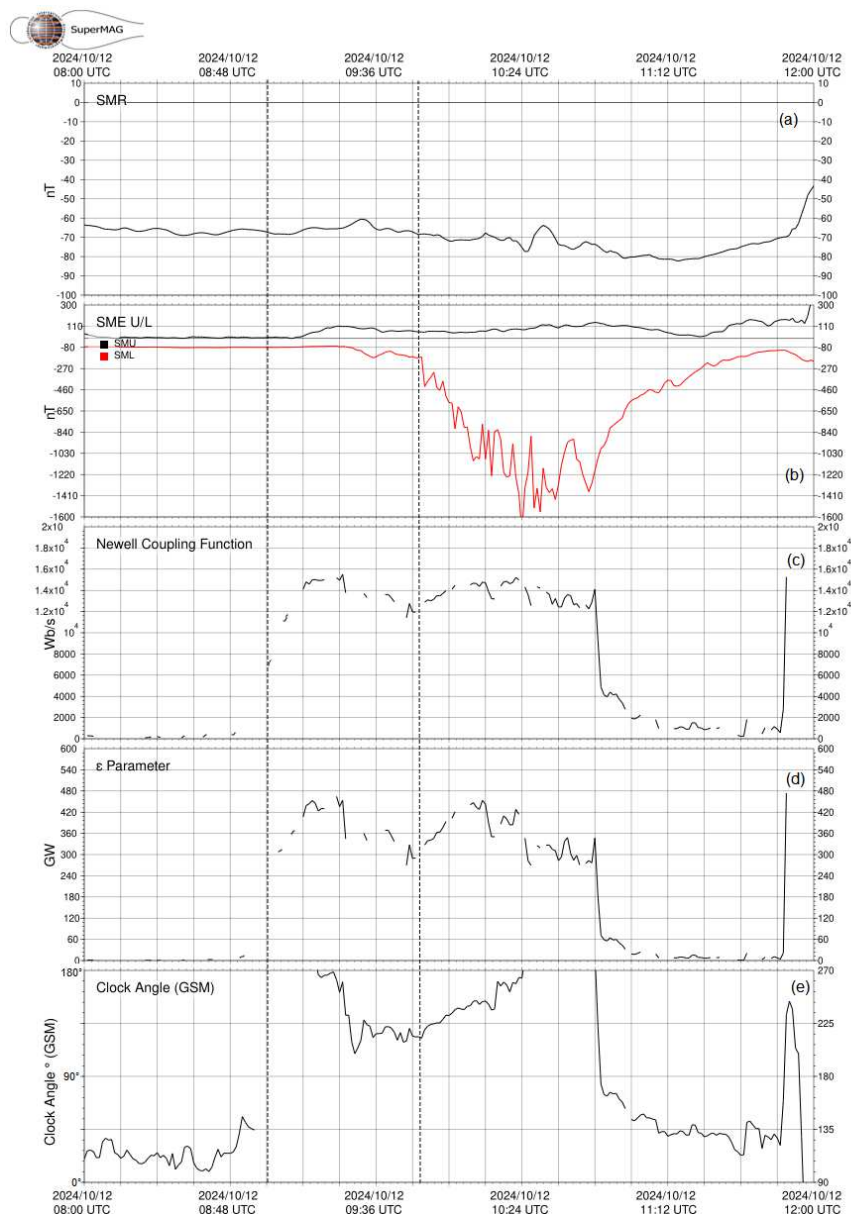


Figure 6: Data from the SUPERMAG website for October 12, 2024, 08:00–12:00 UT

From top to bottom: (a) SMR index, (b) SMU/L index, (c) NeWell function, (d) Akasofu ϵ parameter, (e) interplanetary magnetic field clock angle. The data on the x-axis represents time. The three vertical dashed lines in the figure correspond to 09:00 UT and 09:53 UT, respectively.

We further examine multipoint observations from the MMS1 and THEMIS-A spacecraft in the magnetotail to characterize the large-scale evolution of this substorm. Figure 7 shows MMS1 observations in the magnetotail near $X_{\text{GSM}} = -22 R_E$ from 09:00 to 11:30 UT on October 12, 2024. The spacecraft position shown at the bottom of Figure 7 indicates that MMS1 was located near the tail lobe in the distant magnetotail during this interval. Prior to expansion-phase onset, at

approximately 09:29 UT (the first dashed line), B_y increased markedly, while B_z turned southward and remained predominantly negative for an extended interval. These magnetic field variations were accompanied by a sustained high-speed tailward flow and increases in both B_x and the total magnetic field magnitude. The ion number density subsequently decreased markedly. Taken together, these signatures are consistent with a tailward-moving plasmoid-like structure or reconnection outflow. These observations suggest that magnetic reconnection may have occurred earthward of MMS1, that is, earthward of $X_{GSM} = -22 R_E$, before the substorm expansion-phase onset.

Figure 8 shows THEMIS-A observations in the near-Earth magnetotail near $X_{GSM} = -6 R_E$ from 09:00 to 11:30 UT on October 12, 2024. Prior to expansion-phase onset, from approximately 09:25 to 09:53 UT (the interval indicated by the black line), both B_x and the total magnetic field magnitude increased progressively, consistent with enhanced magnetic energy storage in the magnetotail. Following expansion-phase onset at approximately 09:53 UT, pronounced magnetic field dipolarization was observed, with B_z increasing from approximately 5 to 18 nT and accompanied by an earthward high-speed flow. Concurrent increases in the electron and ion energy fluxes were also observed, consistent with energetic particle injection toward the inner magnetosphere. At approximately 10:35 UT (the second dashed line), further dipolarization occurred, with B_z increasing from approximately 15 to 30 nT and subsequently remaining at an elevated level. Taken together, the MMS1 and THEMIS-A observations show coordinated responses in the distant and near-Earth magnetotail associated with the SML decrease, providing evidence for the large-scale evolution of the substorm.

Comparison of the two events, occurring during the storm commencement/early phase and recovery phase, respectively, shows that expansion-phase onset in both cases was associated with IMF southward turning. This association is also reflected in the variations of the Newell coupling function and the Akasofu ϵ parameter. Although solar wind speed and IMF magnitude also contribute to both coupling parameters, the IMF clock angle strongly modulates their response to the orientation of the IMF. As the IMF clock angle increases toward 180° , corresponding to an increasingly southward IMF, both coupling functions increase through their clock-angle dependence, indicating enhanced solar wind–magnetosphere coupling. In the two events examined here, this enhanced coupling preceded the onset of the substorm expansion phase, although the delay between IMF southward turning and substorm onset differed substantially between the two events.

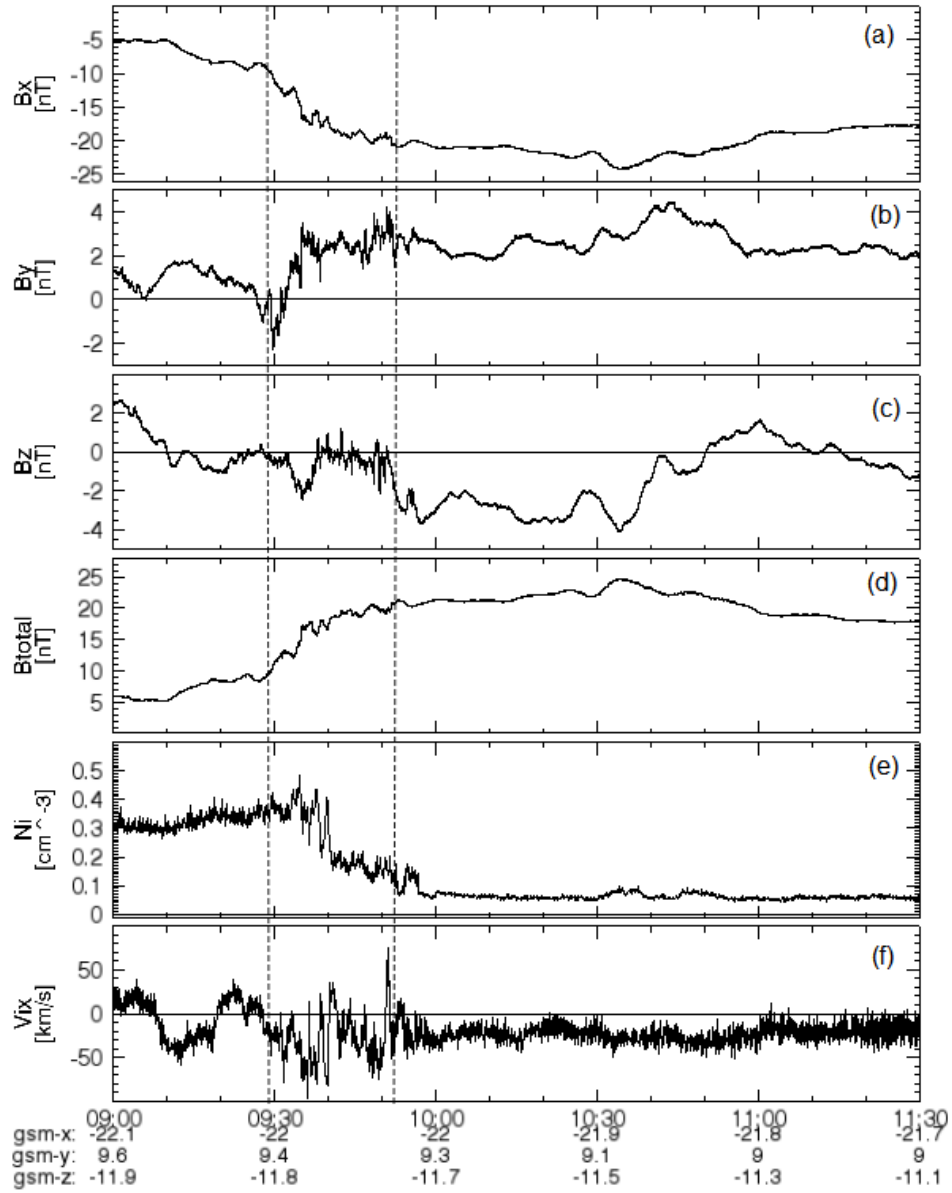


Figure 7: MMS 1 observations from 09:00 to 11:30 UT on October 12, 2024

From top to bottom: (a, b, c) the three components of the magnetic field in the GSM coordinate system; (d) total magnetic field strength; (e) ion number density; (f) the x-component of ion velocity in the GSM coordinate system. The four rows of data at the bottom of the figure represent the time and the orbital position of the MMS 1 satellite in the GSM coordinate system, respectively. The black dashed lines in the figure indicate 09:29 UT and 09:53 UT.

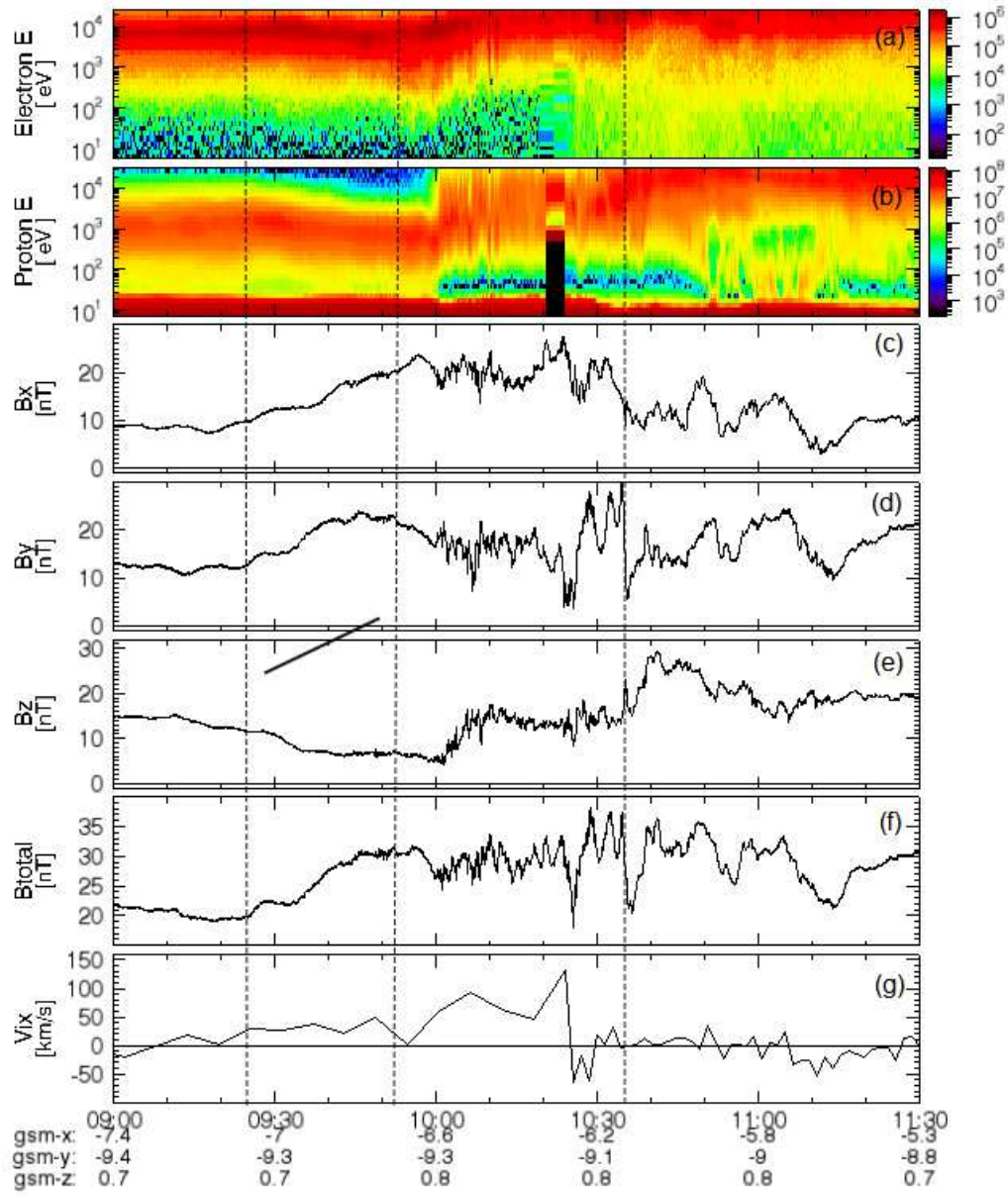


Figure 8: THEMIS A observations from 09:00 to 11:30 UT on October 12, 2024

From top to bottom, these are: (a) electron energy flux, (b) proton energy flux, (c, d, e) the three components of the magnetic field in the GSM coordinate system, (f) total magnetic field strength, and (g) the x-component of the ion velocity in the GSM coordinate system. The four rows of data at the bottom of the figure represent the time and the orbital position of the THEMIS A satellite in the GSM coordinate system, respectively. The black dashed lines in the figure indicate 09:25 UT, 09:53 UT, and 10:35 UT.

4. Discussion and Analysis

In the previous section, we presented the solar wind conditions and associated magnetotail responses for the September 18, 2023, and October 12, 2024 substorms, which occurred during different phases of geomagnetic storms. Here, we compare the two events and discuss the possible mechanisms controlling expansion-phase onset during different phases of geomagnetic storms.

4.1 Substorm During the Storm Commencement and Early Phase

At 13:35 UT on September 18, 2023, OMNI observations showed an abrupt enhancement in solar wind speed and dynamic pressure during the storm commencement and early phase. The enhanced solar wind dynamic pressure strongly compressed the magnetosphere, producing a rapid increase in the horizontal geomagnetic field consistent with a storm sudden commencement (Chapman and Ferraro, 1931; Ferraro, 1952; Siscoe et al., 1968; Russell et al., 1992; Araki and Shinbori, 2016; Shen, 2005). The enhanced solar wind forcing can increase magnetic energy storage in the magnetotail through large-scale convection and magnetospheric compression. Magnetospheric compression alone, however, does not necessarily lead to substorm expansion-phase onset and may instead produce transient responses without a fully developed substorm (Kokubun et al., 1977). One possible interpretation is that the compression placed the magnetosphere in a highly energized and susceptible state, while additional energy input associated with subsequent southward IMF was required before expansion-phase onset occurred.

In this event, the IMF turned southward before the expansion-phase onset. The southward IMF favored dayside magnetic reconnection, enabling continued transfer of solar wind energy into the magnetosphere and subsequent transport toward the magnetotail (Dungey, 1961). The enhanced energy input was followed within several minutes by expansion-phase onset, suggesting that the additional solar wind–magnetosphere coupling may have contributed to destabilizing the preconditioned magnetotail. Multipoint observations from MMS1 and THEMIS-A provide complementary evidence for the magnetotail evolution associated with the substorm onset and expansion phase. At approximately 15:35 UT, MMS1 observed an earthward flow exceeding 400 km·s⁻¹ in the plasma sheet, while the total magnetic field magnitude remained enhanced. This earthward fast flow suggests that magnetic reconnection may have occurred tailward of MMS1 before expansion-phase onset, because high-speed plasma flows are commonly associated with reconnection outflows in the magnetotail (Paschmann et al., 1979). This interpretation is consistent with previous studies reporting fast plasma flows associated with magnetotail reconnection prior to or near substorm expansion-phase onset (Hones et al., 1984; Moldwin and Hughes, 1993; Nagai et al., 1998; Miyashita et al., 2009; Machida et al., 2014).

Following expansion-phase onset, MMS1 observed a pronounced earthward bursty bulk flow (BBF) at approximately 16:11 UT, consistent with rapid plasma and energy transport toward the near-Earth magnetotail (Angelopoulos et al., 1996; Angelopoulos et al., 1994; Sergeev et al., 1995; Ma, 2006; Merkin et al., 2019; Pitkänen et al., 2011). The IMF remained predominantly southward during much of the event, indicating sustained favorable conditions for solar wind–magnetosphere energy coupling. Subsequently, at approximately 16:56, 17:13, and 17:39 UT, MMS1 observed repeated earthward high-speed flows accompanied by decreases in $|B_x|$ and the total magnetic field magnitude, together with increases in the electron and ion number densities. THEMIS-A also observed distinct earthward ion flows at approximately 17:10 and 17:55 UT, accompanied by decreases in $|B_x|$ and the total magnetic field magnitude and increases in plasma temperature and density. Taken together, these repeated flow and magnetic-field signatures are consistent with intermittent magnetic energy release and earthward transport during the substorm expansion phase.

Following several of these flow-related disturbances, $|B_x|$ and the total magnetic field magnitude

increased again, suggesting renewed magnetic energy accumulation in the magnetotail. These observations suggest that energy loading and unloading may alternate, or partially overlap, during storm-time substorm evolution, reflecting a highly dynamic magnetotail under sustained solar wind driving. After approximately 17:50 UT, the IMF briefly turned northward and SML began to recover, consistent with the transition into the substorm recovery phase. At approximately the same time, both MMS1 and THEMIS-A observed rapid increases in B_z from about -10 to 10 nT at MMS1 and from about 0 to 20 nT at THEMIS-A. These coordinated B_z enhancements indicate pronounced magnetic field dipolarization in the magnetotail (Runov et al., 2011; Fu et al., 2013). The characteristics of this event are broadly consistent with previous observational and theoretical studies of externally triggered substorms. Lyons et al. (1997) argued that external solar wind variations can play an important role in triggering a large fraction of substorms. McPherron and Hsu (2003) suggested that approximately 60% of the substorms in their sample were associated with IMF or solar wind dynamic pressure perturbations, whereas the remaining events showed no clear association with such external disturbances. These results suggest that some substorms may arise primarily from internal magnetospheric processes, while the onset of such internally driven events may still be modulated by external solar wind perturbations (McPherron and Hsu, 2003). More recently, McPherron (2023) discussed the feasibility of monitoring substorm occurrence using upstream solar wind observations.

Zhou and Tsurutani (2001) investigated nightside auroral responses to interplanetary shocks and solar wind dynamic pressure pulses. They found that the nature of the auroral response depended not simply on shock strength, but strongly on the duration of southward IMF preceding the shock arrival. In a subsequent study of more than 100 interplanetary shock events, Tsurutani and Zhou (2002) reported a similar dependence of the nightside response on the preceding IMF orientation. Under sustained southward IMF, prolonged solar wind–magnetosphere coupling can precondition the magnetotail by increasing its stored magnetic energy. If an interplanetary shock then compresses the magnetosphere, the resulting pressure pulse may provide an additional perturbation capable of initiating a full substorm expansion phase. In contrast, when the IMF is weak or predominantly northward, limited prior energy loading may restrict the response to localized, short-lived auroral intensifications or pseudobreakups, and in some cases little auroral response may occur. Global MHD simulations by Sun and Wang (2011, 2012) further examined the relationship between ground magnetic disturbances and nightside magnetospheric convection driven by interplanetary shocks during storm sudden commencements. Their simulations showed that interplanetary shocks can transiently enhance vortical flows and earthward plasma transport in the nightside magnetosphere. These flow enhancements can intensify large-scale magnetospheric currents and associated ionospheric currents, thereby producing measurable ground magnetic disturbances. The development of earthward flows can also produce localized magnetic field perturbations in the magnetotail and may contribute to conditions favorable for substorm onset. These results support the interpretation that, during storm sudden commencements, substorm expansion-phase onset can depend on the combined effects of solar wind compression and the preexisting IMF-controlled energy state of the magnetosphere (Sun and Wang, 2011, 2012).

4.2 Substorm During the Recovery Phase of the Geomagnetic Storm

The October 12, 2024 substorm occurred during the recovery phase of a major geomagnetic storm. OMNI observations show that the solar wind speed increased markedly at approximately 08:58 UT, whereas SML showed no corresponding abrupt response. One possible interpretation is that, because this event occurred during the storm recovery phase, the magnetotail was in a different preconditioning state from that during the storm commencement and early phase. Consequently, renewed energy loading may have been required before the magnetotail became sufficiently unstable for expansion-phase onset.

At approximately 09:00 UT, the IMF turned southward and remained predominantly southward. Approximately 53 min later, at 09:53 UT, SML began to decrease sharply and subsequently reached a minimum of approximately -1749 nT, marking the onset of the substorm expansion phase. Prior to expansion-phase onset, MMS1 observed signatures consistent with a tailward-moving plasmoid-like structure. At approximately 09:27 UT, MMS1 observed a sustained high-speed tailward flow. During this interval, B_z exhibited multiple polarity changes before remaining predominantly negative, B_x remained negative, and the ion number density first increased and then decreased (Lui, 2000). A spacecraft crossing an entire tailward-moving plasmoid may observe a bipolar B_z signature, whereas a partial crossing of its leading or trailing portion may sample only one polarity. Such structures contain plasma embedded within closed or reconnected magnetic-field configurations and propagate tailward following reconnection. These signatures suggest that magnetic reconnection may have occurred earthward of MMS1 before expansion-phase onset (Lui, 2000). THEMIS-A observations in the near-Earth magnetotail provide complementary evidence for the evolution of the system. Between approximately 09:25 and 09:53 UT, $|B_x|$ and the total magnetic field magnitude increased progressively, consistent with continued magnetic energy loading prior to substorm onset. Following expansion-phase onset at 09:53 UT, THEMIS-A observed a pronounced energetic particle injection accompanied by an earthward high-speed flow and decreases in $|B_x|$ and the total magnetic field magnitude. Approximately 10 min later, B_z began to increase markedly, indicating the development of magnetic field dipolarization. SML subsequently began to recover, consistent with the transition of the substorm toward its recovery phase. At approximately 10:35 UT, a further pronounced dipolarization was observed, with B_z increasing from approximately 14 to 32 nT and subsequently remaining at an elevated level.

For the event examined here, the observations suggest that the IMF southward turning initiated a period of enhanced solar wind–magnetosphere coupling and magnetotail energy loading rather than producing an immediate expansion-phase onset. The substorm onset occurred only after the IMF had remained southward for approximately 53 min, suggesting that sufficient preconditioning of the magnetotail may have been required before the stored magnetic energy could be released.

4.3 Substorms During the Main Phase of Geomagnetic Storms

Previous studies have investigated the characteristics of substorms occurring during the main phase of geomagnetic storms. Compared with isolated or nonstorm substorms, storm-main-phase substorms can exhibit distinct auroral morphologies. Based on optical auroral observations, Hoffman et al. (2010) reported that some substorms during the storm main phase lacked typical features such as auroral surges, bulges, and forks and exhibited shorter but more intense expansion

437 phases. These observations suggest that the classical substorm current wedge framework may not
438 fully describe the magnetosphere–ionosphere current system under storm-main-phase conditions
439 and that the associated energy-release and current-closure processes may differ from those of
440 isolated substorms.

441
442 High-intensity, long-duration, continuous AE activity (HILDCAA) represents another form of
443 prolonged auroral electrojet activity associated with sustained solar wind driving and is often linked
444 to high-speed streams and corotating interaction regions (CIRs). Tsurutani et al. (2004) examined
445 whether HILDCAA intervals could be interpreted simply as the superposition of multiple substorm-
446 like auroral activations. Using observations from the Ultraviolet Imager (UVI) on board the Polar
447 spacecraft, they examined auroral activity during two HILDCAA intervals in detail. They found that,
448 although substorm-like auroral activations occurred during the HILDCAA intervals, these
449 activations were not consistently associated with corresponding enhancements in the AE/AL indices.
450 Specifically, enhancements in AE were not always accompanied by the characteristic auroral
451 signatures of substorm expansion, and individual auroral activations did not necessarily correspond
452 to pronounced increases in AE. The enhanced AE/AL activity may instead reflect sustained
453 magnetospheric convection and associated ionospheric current intensification driven by solar wind–
454 magnetosphere coupling, rather than discrete substorm expansion phases alone. Thus, the extent to
455 which HILDCAA activity can be interpreted as a sequence of conventional substorms, rather than
456 as a distinct mode of sustained magnetospheric convection and energy dissipation, remains debated.
457 Sun et al. (2014) combined multispacecraft and ground-based observations to investigate an intense
458 substorm during the main phase of a severe geomagnetic storm, for which SYM-H reached a
459 minimum of approximately -179 nT. The event occurred during an interval of strong, short-
460 duration southward IMF and was accompanied by multiscale signatures including magnetic field
461 dipolarization, nondispersive plasma injections, and Pi2 pulsations. These observations highlight
462 the complex coupling among solar wind driving, magnetotail reconfiguration, particle injection, and
463 ionospheric responses during storm-main-phase substorms.

464
465 Akasofu and Chapman (1963) recognized that geomagnetic storm main-phase development and
466 auroral substorm activity can occur concurrently, emphasizing the close relationship between storm
467 and substorm dynamics. They also noted that the relationship between external solar wind forcing
468 and ring-current development cannot be described by a simple linear response. Previous studies
469 have further shown that substorm-associated particle injections can supply seed populations to the
470 inner magnetosphere and influence subsequent energetic-particle acceleration. Storm-time
471 substorms may therefore contribute not only to magnetotail energy release but also to ring-current
472 development and radiation-belt dynamics (Li et al., 2006; Sharma et al., 2003).

473
474 Overall, storm-main-phase substorms can differ substantially from isolated substorms in their
475 auroral morphology, intensity, and magnetospheric responses. Whether these differences reflect
476 quantitatively modified substorm dynamics or qualitatively different modes of magnetospheric
477 energy release remains unresolved. Further statistical studies combining coordinated
478 multispacecraft observations, ground-based measurements, and global MHD simulations are needed
479 to determine how storm-main-phase conditions modify substorm onset and evolution.

4.4 External Triggering of Substorms Under Nonstorm Conditions

Several mechanisms have been proposed to explain externally triggered substorm onset under nonstorm conditions. Among the proposed external triggers, northward turning of the interplanetary magnetic field (IMF) has received considerable attention. Based on observations linking many substorm onsets to IMF northward turnings, Lyons (1995) proposed an external-triggering framework in which expansion-phase onset is associated with a reduction in large-scale solar wind–magnetosphere convection. Within this framework, both IMF northward turnings and reductions in the IMF B_y component were proposed as possible external triggers of substorm onset. Lyons (1996) further argued that, when substorms are distinguished from intervals of enhanced magnetospheric convection, the onset of most substorms may be associated with changes in the IMF, particularly northward turnings and decreases in B_y . Lyons et al. (1997) presented additional observational evidence supporting an IMF-triggering interpretation.

Using statistical analyses, Hsu and McPherron (2002) found a strong temporal association between IMF northward turnings and substorm expansion-phase onset and argued that the association was unlikely to be coincidental. Hsu and McPherron (2003) subsequently analyzed events from March and April of 1978 and 1979. In their sample, 47% of substorms were associated with IMF northward turnings, 10% with decreases in B_y , and 3% with solar wind dynamic pressure variations, whereas approximately 40% showed no clear association with substantial changes in IMF B_z or B_y . This result differs from the stronger external-triggering interpretation proposed by Lyons (1996).

Russell (2000) proposed a physical interpretation for how an IMF northward turning could facilitate substorm expansion-phase onset. In this scenario, an IMF northward turning alters the large-scale magnetotail configuration such that distant-tail reconnection is reduced while near-Earth reconnection can persist, thereby favoring rapid reconfiguration of the magnetotail and substorm onset. These studies indicate that IMF northward turnings can play an important role in some externally triggered nonstorm substorms. In contrast, the two storm-time events examined in this study were associated with IMF southward turnings. Whether this contrast reflects fundamentally different triggering mechanisms requires further statistical investigation.

5. Conclusion

This study investigates two magnetospheric substorms that occurred during geomagnetic storms on September 18, 2023, and October 12, 2024. By combining solar wind measurements, ground-based geomagnetic indices, and multipoint magnetotail observations, we obtain the following main conclusions.

1. For the September 18, 2023 event, which occurred during the storm commencement and early phase, enhanced solar wind speed and dynamic pressure strongly compressed and preconditioned the magnetosphere. The pressure enhancement appears to have placed the magnetosphere in a highly energized state but did not immediately produce expansion-phase onset. The subsequent IMF southward turning favored dayside magnetic reconnection and enhanced energy transfer into the magnetosphere and toward the magnetotail. Expansion-phase onset followed within a short interval, suggesting that the additional energy input contributed to destabilizing the preconditioned magnetotail. Multipoint MMS1 and THEMIS-A observations further revealed repeated earthward

fast flows, magnetic-field reductions, and dipolarization signatures, consistent with intermittent magnetotail energy release and transport during the subsequent substorm evolution.

2. For the October 12, 2024 event, which occurred during the recovery phase of a major geomagnetic storm, the IMF turned southward at approximately 09:00 UT, but no immediate expansion-phase onset was observed. Instead, the IMF remained predominantly southward for approximately 53 min before SML decreased sharply at 09:53 UT. This delay suggests that sustained solar wind–magnetosphere coupling and renewed magnetotail energy loading were important for preconditioning the system before expansion-phase onset. MMS1 observations in the distant magnetotail indicated a tailward reconnection outflow or plasmoid-like structure before onset, whereas THEMIS-A observations in the near-Earth magnetotail revealed subsequent earthward flow, energetic particle injection, and magnetic field dipolarization.

Additional event studies and statistical analyses are needed to determine how IMF orientation and solar wind driving influence substorm onset during the main phase of geomagnetic storms. The relationship between conventional substorms and high-intensity, long-duration, continuous AE activity (HILDCAA) also remains debated, particularly regarding whether sustained AE activity represents a sequence of discrete substorms or a distinct mode of prolonged magnetospheric convection and energy dissipation.

The two storm-time events examined here exhibit onset characteristics that differ from those commonly reported for externally triggered substorms under nonstorm conditions. In both storm-time events studied here, expansion-phase onset was associated with IMF southward turning, whereas previous studies have often linked externally triggered nonstorm substorms to IMF northward turnings. Whether storm-time and nonstorm substorms involve fundamentally different onset mechanisms remains unresolved and requires analysis of a substantially larger event sample. Nevertheless, the contrasting onset signatures identified here provide a useful basis for future investigations of storm–substorm coupling.

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