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Key Points:

- An abrupt and intense auroral electrojet enhancement occurred during the storm of 24 April 2023
- This extreme event differs from typical geomagnetic disturbances in terms of magnitude, spatiotemporal extent, and physical driver
- The event was triggered by a solar wind pressure pulse, which enhanced diffuse auroral precipitation and ionospheric conductivity

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

Y. Zou,
ying.zou@jhuapl.edu

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Author Contributions:

Conceptualization: Jesper W. Gjerloev, Shin Ohtani

Data curation: Matt Friel, Jun Liang

Formal analysis: Ying Zou

Funding acquisition: Banafsheh Ferdousi

Investigation: Ying Zou, Jesper W. Gjerloev, Shin Ohtani, Jun Liang, Larry L. Lyons, Yangyang Shen, Jiang Liu

Methodology: Ying Zou, Jesper W. Gjerloev, Shin Ohtani

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An Extreme Auroral Electrojet Spike During 2023 April 24th Storm

Ying Zou¹ , Jesper W. Gjerloev¹ , Shin Ohtani¹, Matt Friel¹, Jun Liang² , Larry L. Lyons³ , Yangyang Shen⁴ , Jiang Liu^{3,4} , Li-Jen Chen⁵ , Banafsheh Ferdousi⁶, Alex Chartier¹ , Sarah Vines¹ , and Colin L. Waters⁷ 

¹Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, ²University of Calgary, Calgary, AB, Canada, ³Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA, USA, ⁴Department of Earth, Planetary and Space Sciences, University of California, Los Angeles, CA, USA, ⁵NASA Goddard Space Flight Center, Greenbelt, MD, USA, ⁶Department of Physics and EOS Space Science Center, University of New Hampshire, Durham, NH, USA, ⁷University of Newcastle, Callaghan, NSW, Australia

Abstract Abrupt variations of auroral electrojets can induce geomagnetically induced currents, and the ability to model and forecast them is a pressing goal of space weather research. We report an auroral electrojet spike event that is extreme in magnitude, explosive in nature, and global in spatial extent that occurred on 24 April 2023. The event serves as a fundamental test of our understanding of the response of the geospace system to solar wind dynamics. Our results illustrate new and important characteristics that are drastically different from existing knowledge. Most important findings include (a) the event was only of ~5-min duration and was limited to a narrow (2°–3°) band of diffuse aurora; (b) the longitudinal span covered the entire nightside sector, possibly extending to the dayside; (c) the trigger seems to be a transient solar wind dynamic pressure pulse. In comparison, substorms usually last 1–2 hr and span almost the entire latitudinal width of the auroral oval. Magnetic perturbation events (MPEs) span hundreds km in radius. Both substorms and MPEs are mainly driven by disturbances in the magnetotail. A possible explanation is that the pressure pulse compresses the magnetosphere and enhances diffuse precipitation of electrons and protons from the inner plasma sheet, which elevates the ionospheric conductivity and intensifies the auroral electrojet. Therefore, the event exhibits a potentially new type of geomagnetic disturbance and highlights a solar wind driver that is enormously influential in driving extreme space weather events.

Plain Language Summary Auroral electrojets are horizontal electric currents that flow in the auroral ionosphere, and extreme auroral electrojet activities can induce geomagnetically induced currents that damage high-voltage power transformers and increase steel corrosion of pipeline networks. Understanding what drives the extreme events is therefore a pressing goal of space weather research. We report an auroral electrojet spike event that is extreme in magnitude, explosive in nature, and global in spatial extent that occurred on 24 April 2023. The event serves as a fundamental test of our understanding of the response of the geospace system to solar wind dynamics. Most important findings include (a) the event was only of ~5-min duration and was limited to a narrow band of diffuse aurora; (b) the longitudinal span covered the entire nightside sector; (c) the trigger seems to be a transient solar wind dynamic pressure pulse. These features differ drastically from other widely known geomagnetic disturbances such as substorms or magnetic perturbation events, and signify a potentially new type of disturbance. A possible explanation is that the solar wind pressure pulse compresses the magnetosphere, enhances diffuse precipitation of particles into the ionosphere, and elevates the ionospheric conductivity.

1. Introduction

Abrupt variations of auroral electrojets are an important space weather phenomenon as they cause geomagnetically induced currents (GICs). These events perturb the geomagnetic field, and the rapid changes of the geomagnetic fields induce surface geoelectric fields, which can excite GICs in ground-based technological systems, such as electric power transmission grids, oil and gas pipelines, phone cables, and railway systems. The GICs that led to the collapse of the Hydro-Quebec power system on 13 March 1989 were driven by geomagnetic field variations of 479 nT/min. Variations as low as 100 nT/min have also been observed to drive significant GICs (Kappenman, 2006).

Resources: Li-Jen Chen, Alex Chartier, Sarah Vines, Colin L. Waters
Writing – original draft: Ying Zou
Writing – review & editing: Jesper W. Gjerloev, Shin Ohtani, Larry L. Lyons, Yangyang Shen, Jiang Liu, Li-Jen Chen, Colin L. Waters

The ability to model and forecast extreme variations of auroral electrojets and the associated geomagnetic field perturbations is therefore a pressing goal for space weather research, yet the current understanding of the underlying physical driver is far from complete. On the nightside, the most widely recognized driver is substorms, since two thirds of events occur within 30 min of substorm onset (Engebretson, Pilipenko, et al., 2019; Engebretson, Ahmed, et al., 2021; Engebretson, Pilipenko, et al., 2021; Freeman et al., 2019; Juusola et al., 2016; McCuen et al., 2021; Viljanen et al., 2006; Weygand et al., 2021a, 2021b). When combined with auroral observations, events are found to coincide with westward traveling surges, poleward auroral expansion, and auroral streamers (Engebretson, Steinmetz, et al., 2019; Ngwira et al., 2018; Zou et al., 2022), which are auroral manifestations of magnetic field dipolarization and bursty bulk flows as the magnetotail unloads stored energy. They have also been observed to coincide with auroral omega bands (Apatenkov et al., 2020; Zou et al., 2022) that occur during the substorm expansion and recovery phases. On the dayside, a prominent driver is the foreshock and quasi-parallel region of the bow shock, since events tend to peak during periods of fast solar wind and radial IMF (Juusola et al., 2016).

In this paper, we report an extreme auroral electrojet spike event that occurred on 24 April 2023 and investigate the physical driver. This extreme event is significant for both space science and space operation for several reasons. First, the geomagnetic field perturbation had a very large amplitude and time derivative, the values being 2,798 nT and 914 nT/min based on 1-min data. Similar amplitude has been reported for so-called “super-substorms” that only occur a few times per year (Tsurutani et al., 2015), and a similar time derivative is believed to occur only once every 10 years (Rogers et al., 2020, 2021). Second, the event lasted 5 min and was limited to a narrow (2° – 3°) band of diffuse aurora. In comparison, substorms often last 1–2 hr and span almost the entire latitudinal width of the auroral oval. Third, the event spanned a wide local time where the geomagnetic field pulsed synchronously over almost the entire nightside sector. In comparison, magnetic perturbation events (MPEs), which are large changes of the geomagnetic field of 5–10 min duration, often span hundreds of km in radius (Engebretson, Pilipenko, et al., 2019). The event therefore exhibits characteristics of a potentially new type of geomagnetic disturbance distinct from substorms or MPEs. Finally, the event was not driven by disturbances in the magnetotail like substorms or MPEs, but by a solar wind dynamic pressure pulse, which has not previously been recognized to be important in statistical studies. For example, Rogers et al. (2020) reported that <5% of the auroral-zone geomagnetic perturbations were preceded by a solar wind pressure increase. The event highlights the influential role of solar wind pressure in driving extreme geomagnetic disturbances.

Extreme variations of the geomagnetic field have been reported as super-substorms, which are associated with westward auroral electrojets >2,500 nT (Despirak et al., 2019, 2020; Hajra & Tsurutani, 2018; Hajra et al., 2016; Tsurutani & Hajra, 2023; Tsurutani et al., 2015; Zong et al., 2021). Super-substorms only occur on average 0.9–3.8 times per year (Hajra et al., 2016). They mainly occur in the main phase of storms, but have been observed during the recovery phase and even quiet times. They are often driven by interplanetary shocks and a sharp increase in solar wind density and pressure (Tsurutani et al., 2015; Hajra et al., 2016). Evidence suggests that super-substorms can produce disturbances on a global scale, rather than being limited to the nightside sector which is a characteristic of substorms (Hajra & Tsurutani, 2018; Tsurutani & Hajra, 2023).

While super-substorms are an extreme example, an increase in solar wind pressure can trigger a negative disturbance of the north-south component of the geomagnetic field at auroral latitudes, that is, negative bays, for about 4%–49% of the time (Burch, 1972; Kawasaki et al., 1971; Kokubun et al., 1977; Liou et al., 2004, 2017; Schieldge & Siscoe, 1970). These negative bays often have an amplitude of several hundred nT and last around one to several hours. An outstanding question is why negative bays occur. Even after decades of investigation, there is no consensus of agreement. Some studies (Iyemori & Tsunomura, 1983; Keika et al., 2009; Zhou & Tsurutani, 2001) propose that as the high-pressure solar wind moves tailward compressing the magnetotail, the lobe magnetic pressure increases, and the plasma sheet thins. As the thinning reaches an unstable state, magnetic reconnection or plasma current instabilities occur which triggers a substorm. Other studies (Liou et al., 2003; Lyons et al., 2000; Zesta et al., 2000) argue that negative bays can be produced by any process that enhances the westward auroral electrojet, for example, through enhancing auroral precipitation. Observations have shown that enhanced solar wind pressure can brighten auroras on a global spatial scale. The brightening first occurs on the dayside and propagates azimuthally along the dawnside and duskside of the auroral oval, often in the form of diffuse auroras (Brittnacher et al., 2000; Holmes et al., 2014; Meurant et al., 2003, 2004; Zhou & Tsurutani, 1999; Zhou et al., 2009). Discrete aurora brightening such as poleward boundary intensifications and auroral streamers

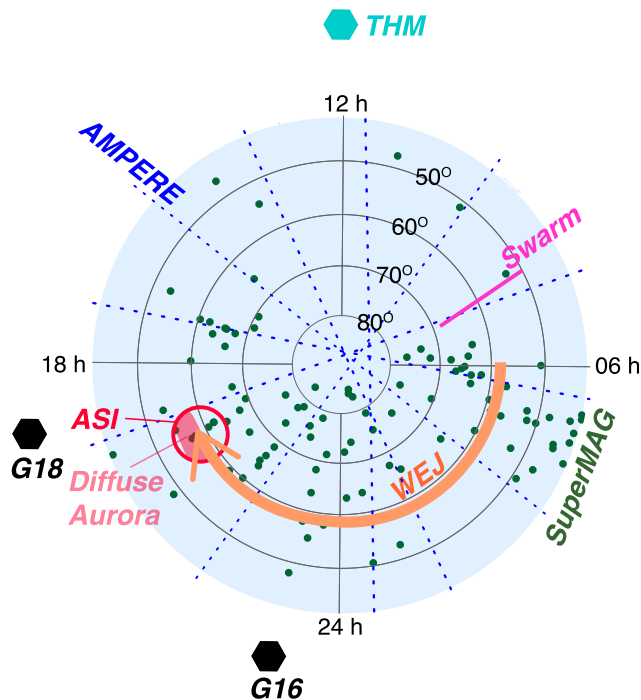


Figure 1. Configuration of the distributed observation network that consists of SuperMAG (green dots), Time History of Events and Macroscale Interactions during Substorms (THEMIS) (cyan hexagon), AMPERE (blue dotted lines), Geostationary Operational Environmental Satellites (GOES) (black hexagon), ASI (red circle) and Swarm (magenta line). Note that the radial distance of THEMIS and GOES is not drawn to scale.

data, consisted of magnetic field measurements from about 90 satellites in six equally spaced orbital planes, reflect large-scale field-aligned currents (FACs) at altitudes of ~ 780 km (Anderson et al., 2020; Waters et al., 2020). The AMPERE data come from the second-generation Iridium Communications satellite constellation (Iridium NEXT). GOES provides magnetic field and energetic particle data at geosynchronous orbit. TReX imagers detect auroral/airglow emissions at 557.7, 486.1, and 630.0 nm wavelengths in the auroral zone. The station with clear sky conditions was at Lucky Lake (LUCK, geomagnetic 58.5° MLAT, -41.6° MLON). Sensors onboard the three Swarm satellites provide electron density, electron temperature, ion velocity, and magnetic field, and the parameter of most interest is the ion velocity. Swarm-B orbits at an altitude of 530 km and provided quality measurements of the ion velocity when the event occurred.

3. Observations

3.1. Geomagnetic and Upstream Solar Wind Conditions

Figures 2a and 2b show the geomagnetic conditions of the 24 April 2023 storm as characterized by the SMR index, which is the SuperMAG-based partial ring current index (Newell & Gjerloev, 2012), and the SMU/SML index, which is the SuperMAG-based auroral electrojet indices (SMU for eastward and SML for westward electrojet) (Newell & Gjerloev, 2011). The SMR index began to decrease at around 09:00 UT on 23 April 2023, signifying the start of the storm. The first minimum of -184 nT occurred at 21:25 UT and the second minimum of -212 nT at 04:03 UT on 24 April 2023. The magnitude of the minimums indicate that the storm was intense, and the two-dip variation correlates with the upstream solar wind conditions shown in Figure 3. During the storm, both the westward and eastward electrojets were enhanced, as represented by the SML and SMU indices, with the absolute value of SML being overall larger. The SML index exhibited a series of dips, most of which had an absolute amplitude around or below 1,500 nT, except for 03:54 UT on 24 April 2024. The focus of this study is this largest SML dip which represents an abrupt and intense westward auroral electrojet spike.

have also been reported (Lyons et al., 2000). A detailed discussion of pressure-induced auroras is provided in Section 4.2.

This paper is structured as follows. Section 2 lists data sets employed to study the auroral electrojet spike event. Section 3 presents the observations, where it describes the geomagnetic and upstream solar wind conditions, the spatial and temporal characteristics of the auroral electrojet, as well as the physical driver. In Section 4 the geophysical implications of the results are described. The last section summarizes the main results.

2. Data Set

The main data set used to identify and characterize the auroral electrojet spike and the associated geomagnetic field perturbations is SuperMAG. The magnetic field data are provided in the NEZ local magnetic coordinate system (Gjerloev, 2012), where N, E, and Z refer to magnetic field components directed northward, eastward, and vertically downward, respectively. Undisturbed daily variations of the magnetic field were subtracted, so that the data represent perturbations of the geomagnetic field. The data mainly have a 1-min temporal resolution, although 1-s data, when available, were also used.

The physical process driving the event is investigated using sensors onboard the Deep Space Climate Observatory (DSCOVR), Time History of Events and Macroscale Interactions during Substorms (THEMIS), Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE-NEXT), Geostationary Operational Environmental Satellites (GOES), Transition Region Explorer (TReX) RGB auroral camera, and Swarm satellites. The configuration of this distributed observation network is illustrated in Figure 1 (radial distance of THEMIS and GOES not drawn to scale). Specifically, DSCOVR and THEMIS monitor the solar wind and IMF conditions from the L1 orbit and the subsolar magnetosheath, respectively. AMPERE

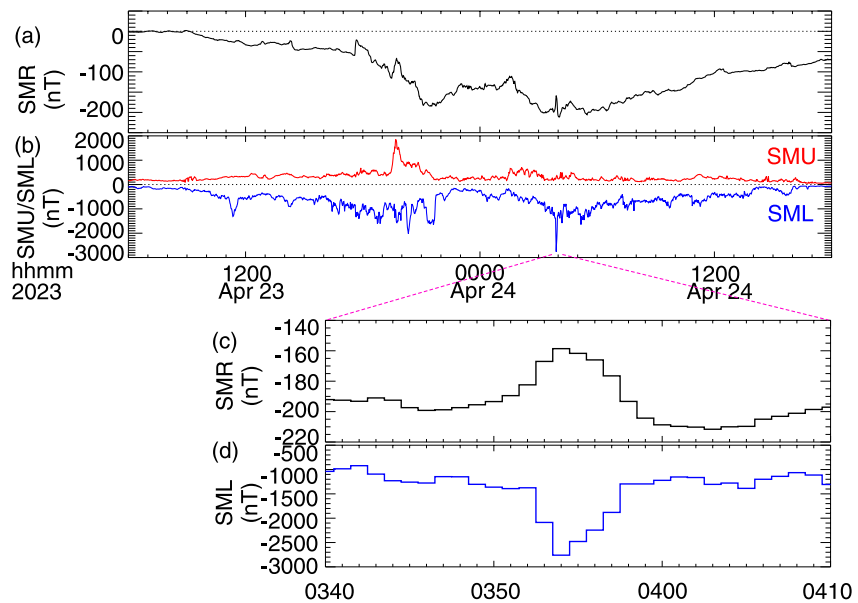


Figure 2. (a–b) Overview of the SMR, SMU, and SML indices during the 24 April 2023 storm. (c–d) Zoom-in view of the SMR and SML indices during the largest SML dip at 03:54 UT.

Figure 2d provides a zoom-in view of the auroral electrojet spike, which has an unusually large amplitude of 2,760 nT, by far the largest perturbation throughout the storm, and was transient in nature, lasting merely 5 min from 03:53 to 03:58 UT. Although events with similar SML amplitudes have been reported as so-called super-substorms, the spike is different because super-substorms have much longer durations, ranging from 42 min to 6 hr (Tsurutani & Hajra, 2023). It also differs from substorms in its spatial and temporal evolution, as detailed in Section 3.2, implying that the two phenomena are two fundamentally different processes.

The auroral electrojet spike coincided with a transient increase in the SMR index in Figure 2c. This increase indicates a transient compression of the magnetosphere which is often associated with a solar wind pressure pulse.

Figures 3a–3d show the solar wind and IMF conditions as measured by DSCOVR at L1. The dynamic pressure is estimated based on solar wind protons (i.e., density and the GSM X component of the velocity) as measurements of Helium were not available. The onset of the storm was associated with a strengthening of the IMF Bz component and an increase of the dynamic pressure, mainly due to an increase in the solar wind density. As the storm progressed, two prominent solar wind structures occurred at around 17:00–20:20 UT on 23 April 2023, and 00:40–14:55 UT on 24 April 2023, during which the IMF was strongly southward, the solar wind density was elevated, and the solar wind velocity also increased. These two intervals appear to align with the double-dip variation of the SMR index.

Embedded in the second interval is a distinct solar wind pressure pulse, as shown in Figures 3e–3h. The brief nature is consistent with the transient compression of the magnetosphere sensed by the SMR index, and the timing supports the notion that the pressure pulse was the solar wind driver of the auroral electrojet spike. At DSCOVR, the solar wind density increased from 11 cm^{-3} at 03:04:40 UT, reached a peak value of 65 cm^{-3} at 03:06:00 UT, and returned to 13 cm^{-3} at 03:07:20 UT, during which the solar wind velocity showed minimal variation. Correspondingly, the dynamic pressure varied from 6 to 36 nPa. Using the DSCOVR-measured solar wind velocity (570 km/s) and assuming a simple flat plane propagation, the propagation time of the solar wind from DSCOVR, located at $[247, 0, 32] R_E$ in GSM coordinates, is 44 min to the nominal location of the bow shock nose at $[14, 0, 0] R_E$. Although this estimation has not considered the inclination of the front of the IMF, nor the displacement of the bow shock from the nominal location, the estimated arrival time, which is 03:50 UT for the pressure peak, is close to the auroral electrojet spike during 03:53–03:58 UT. As discussed in Figure 3, THEMIS was located close to the bow shock nose and sensed the pressure pulse arrival around 03:53 UT.

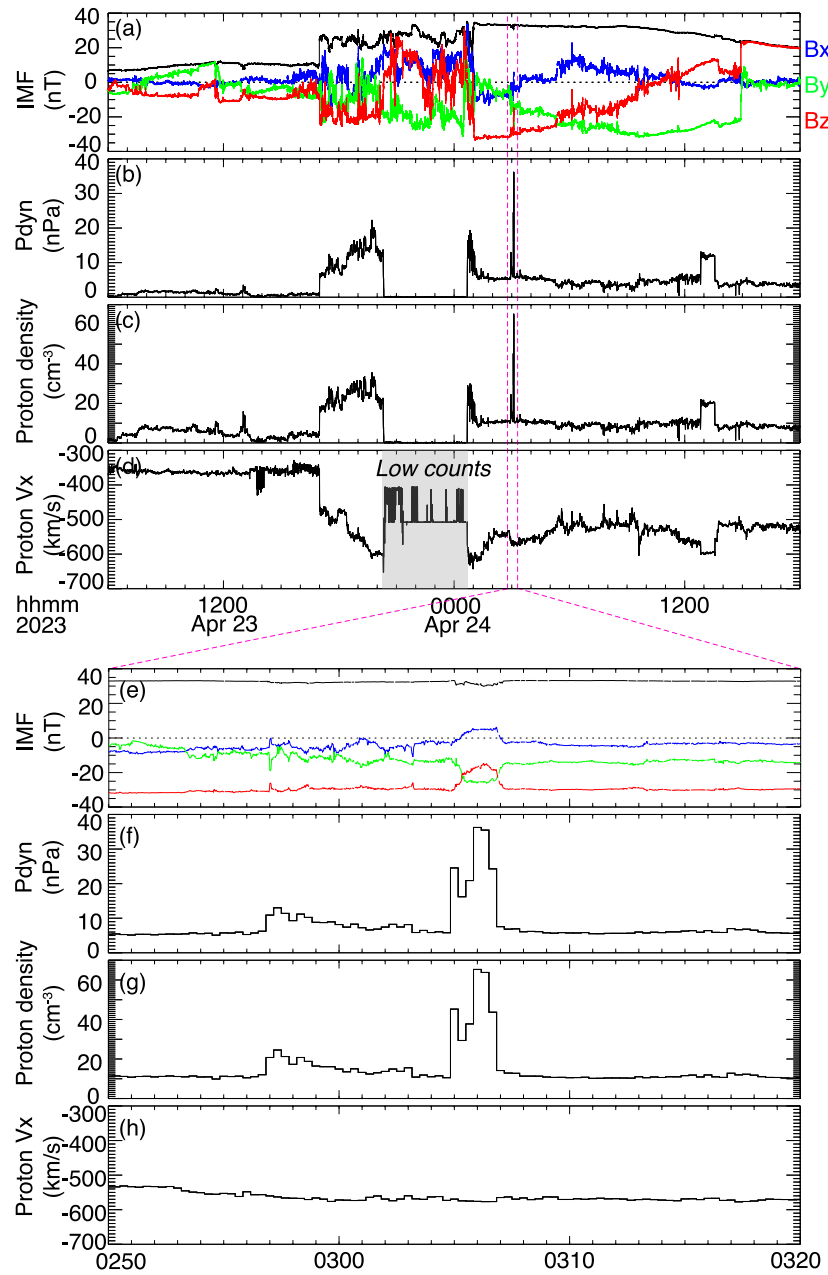


Figure 3. (a–d) Overview of IMF properties; solar wind dynamic pressure, proton density, proton velocity in the GSM X direction as measured by DSCOVR. (e–h) Zoom-in view of DSCOVR measurements to the large and transient pressure pulse.

Figure 4 shows the location of THEMIS satellites and measurements. THA, THD, and THE formed a constellation with THD (THE) being the most sunward (earthward) located satellite (Figure 4a). They were all positioned in the magnetosheath, as indicated by the southward magnetic field and the ion differential energy measurements (Figures 4b, 4c, 4g, 4h, 4l, and 4m). The proximity of the THEMIS satellites to the magnetopause determines the solar wind conditions of the auroral electrojet with high fidelity. The magnetosheath experienced a series of compressions, for instance, at ~03:48:50, ~03:51:26, and ~03:52:38 UT at THD, as indicated by the sharp increases of the ion density and ion temperature (Figures 4c and 4d). After the compression at ~03:52:38 UT, THD moved into the solar wind at 03:53:37 UT and returned to the magnetosheath at 03:55:10 UT. The multi-step compression appears to be associated with the multi-step variation in the solar wind pressure as measured by

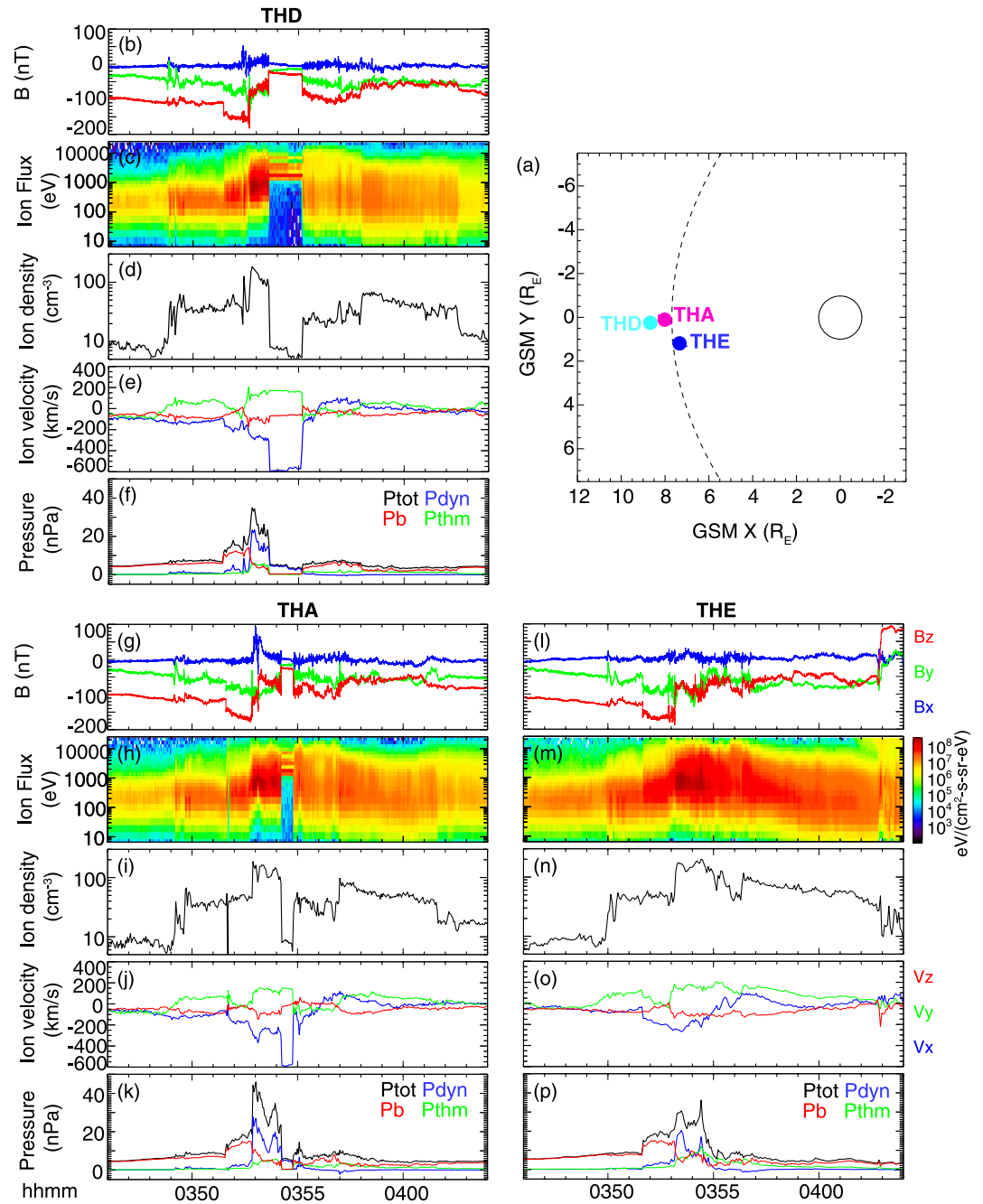


Figure 4. (a) Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft location at GSM X–Y plane. The dashed curve outlines the magnetopause estimated by Shue et al. (1997). (b–f) Magnetic field, ion differential energy flux, ion density, ion velocity, and pressure measured by THD. The magnetic field and ion velocity are in the GSM coordinates. Pressure measurements include dynamic pressure (blue), magnetic pressure (red), thermal pressure (green), and total pressure (black). The dynamic pressure was computed based on THEMIS ion density and the X component of the velocity. (g–k) Same format as Panels (b–f) but for THA. (l–p) Same format as Panels (b–f) but for THE.

DSCOVR. Specifically, prior to the large pressure pulse at 03:04:40–03:07:20 UT, a comparatively small enhancement initiated at 02:56:40 UT (Figure 3f), possibly accounting for the first magnetosphere compression. However, the solar wind may evolve during the course of propagation from L1 to the bow shock and the solar wind that arrived at the bow shock may not be the same parcel detected by DSCOVR. This may explain the lack of clear correspondence to the second magnetosphere compression in DSCOVR measurements.

Figures 4f, 4k, and 4p show the dynamic pressure, magnetic pressure, and thermal pressure. The total pressure, which is the sum of all pressure, is also shown. The total pressure was initially 4–5 nPa and exhibited multiple enhancements. The auroral electrojet spike initiated at the largest enhancement which appeared as a pulse. The pulse occurred during 03:52:38–03:53:38 UT at THD, 03:52:50–03:54:15 UT at THA, and 03:53:10–03:54:40 UT at THE. The peak amplitudes were 35, 41, and 36 nPa at THD, THA, and THE, respectively. The timing, amplitude, and duration of the pulse all match the pulse seen in the DSCOVR data. It is worth mentioning that this pulse was also captured by sensors onboard Magnetospheric Multiscale Mission located around the bow shock in the Southern Hemisphere (L.-J. Chen et al., 2024).

Although these results indicate that the solar wind pressure pulse was the upstream condition of the auroral electrojet spike, it is, at first glance, unclear whether the pulse was the direct driver of the spike, or whether it triggered energy unloading in the magnetotail (such as substorms) that led to the spike. We discuss this further in Section 4.2.

3.2. Spatial and Temporal Properties of the Auroral Electrojet

Figure 5 shows the 2-D distribution of the geomagnetic field perturbations (represented by the green vectors) around the time of the auroral electrojet spike in a polar map. The magnetic vectors were available mostly in the nightside sector and have been rotated clockwise by 90° to represent equivalent ionospheric currents. The vectors were already substantial at 03:50 and 03:52 UT, which is not surprising because of the peak of the storm under a strongly southward IMF (B_z around −30 nT). Interestingly, the vectors formed a distinct vortex centered at ~70° MLAT and a few hours past midnight. It was bounded by the westward electrojet and extended poleward to ~85° MLAT. Similar clockwise swirls have been reported in the polar cap (Gjerloev & Hoffman, 2014; Ohtani et al., 2021). Ohtani (2022) reported counter-clockwise swirls at lower latitudes. The swirling is consistent with the expected distribution of equivalent currents associated with a R1-sense current system (Fukushima, 1971), where net downward (upward) FAC flows at the morning (evening) edge of the vortex.

At 03:54 and 03:56 UT, during the auroral electrojet spike, the magnetic vectors exhibited an overall enhancement at high latitudes with little change in the configuration. Of particular interest are the peculiarly large enhancements over a latitudinally narrow region at and slightly below 60° MLAT (the magenta dotted circle). They represent the geomagnetic field perturbed by the auroral electrojet spike. The latitudinal location of the electrojet exhibited little, if any, poleward expansion between the two instances, which is different to what usually occurs during a substorm. Instead, the electrojet was confined to a very narrow 2°–3° wide latitudinal band throughout the event.

On the other hand, the longitudinal extent of the electrojet spanned a wide local time, from 20 to 6 hr MLT or >8,000 km, although it may have extended further into the morning sector where data were unavailable. This differs from a substorm which usually begins from a localized region and then expands eastward and westward. The event also differs from MPEs which are localized perturbations with a spatial scale of hundreds of km (Engebretson, Pilipenko, et al., 2019). The auroral electrojet spike disappeared by 03:58 and 04:00 UT.

Figure 6 shows the geomagnetic field perturbations at individual sites along three selective meridians (as delineated by the orange dashed lines in Figure 5a), where the spike-associated perturbations are examined quantitatively. Among all northern hemisphere magnetometers, the Dombas (DOB) station at 59.64° MLAT along ~5.3 hr MLT recorded the largest perturbation (left column) with a peak amplitude of 2,760 nT in the southward direction, and 2,798 nT in the horizontal direction. This is an increase of 1,580 nT in the southward direction, and 1,520 nT in the horizontal direction from the field immediately before the spike occurred (i.e., at 03:52 UT). The time derivative of the perturbation is calculated as

$$\frac{\Delta B_H}{\Delta t} = \sqrt{\left(\frac{\Delta B_N}{\Delta t}\right)^2 + \left(\frac{\Delta B_E}{\Delta t}\right)^2}$$

where B_N , B_E , B_H represent the northward, eastward, and horizontal component, respectively, and t represents time. The time derivative has a peak value of 914 nT/min which is much larger than the 99.97th percentiles of all geomagnetic field fluctuations that occurred over the past 20 years, the latter being about 250 nT/min (Rogers et al., 2020, 2021). In fact, the time derivative is comparable to the predicted once-in-10-year value by Rogers

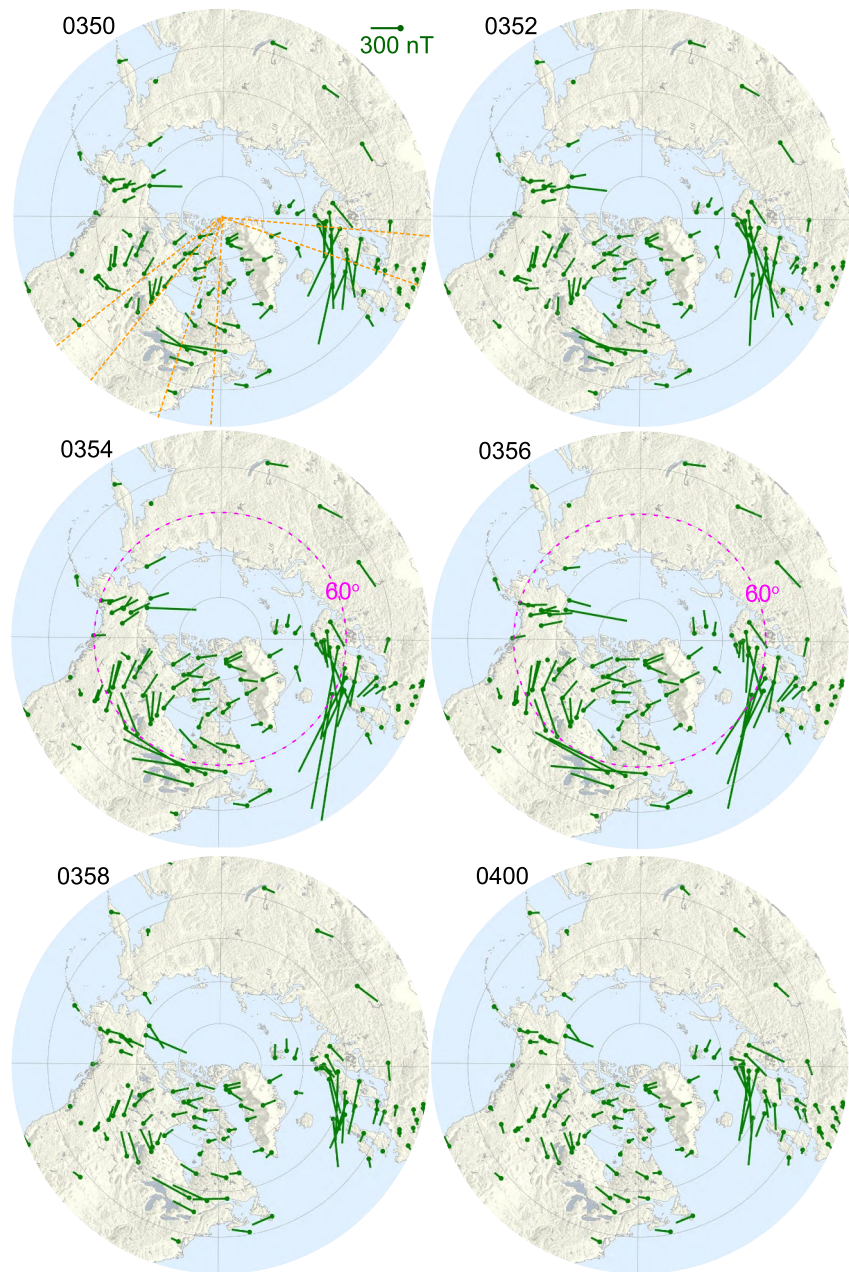


Figure 5. 2-D distribution of geomagnetic field (represented by the green vectors) in MLAT-MLT coordinates at selected instances. The orange dashed lines delineate the MLT ranges of the magnetometers whose data are analyzed in Figure 6.

et al. (2020, 2021). The amplitude and time derivative were based on 1-min sampled data because 1-s data are unfortunately not available at this station (generally speaking, 1-s data would show larger time derivatives). The magnetometer located at DOB also detected a significant vertically downward magnetic field component, indicating that the station was located on the poleward side of the electrojet.

The magnetometer located Solund (SOL), about one degree equatorward of DOB, recorded a perturbation with an amplitude and time derivative of 1,989 nT (or 824 nT compared to pre-spike) and 562 nT/min, respectively, for the horizontal component. The upward vertical component also indicates that SOL was located on the equatorward side of the electrojet. At about two degrees further equatorward, Uppsala (UPS) and Karmøy (KAR) recorded perturbations of 1,028 and 998 nT, respectively (or 476 and 481 nT compared to pre-spike). Note that the perturbation was also detected at lower latitudes such as at Brorfelde (BFE) with an increase of 344 nT from the

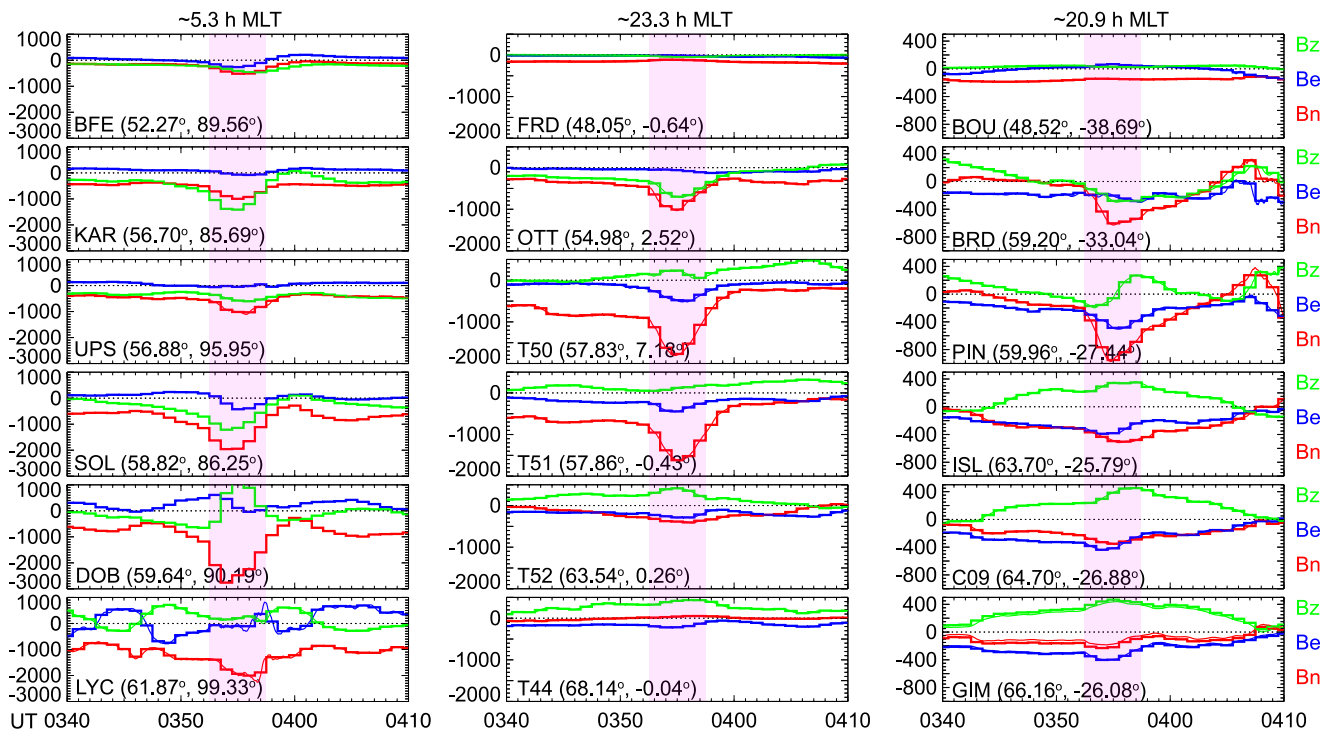


Figure 6. Geomagnetic field measurements from three selected MLT ranges (MLT ranges delineated by the orange dashed lines in Figure 4). The geomagnetic latitude and longitude (in AACGM coordinates) are labeled in each panel. Note that the range of the y axes are different at different MLTs with largest on the dawn (left column). The thick lines represent 1-min measurements, and the thin lines represent 1-s measurements, where available. The pink shaded region represents the time of auroral electrojet spike.

pre-spike value. Ohtani et al. (2021) showed that the current wedge system associated with substorms often produces global scale perturbations.

The main interest of the study is the geomagnetic field perturbation of extreme amplitudes, and such perturbations were only observed at DOB and SOL. If we define the latitudinal width of the auroral electrojet spike based on full-width-at-half-maximum of the amplitude of the horizontal perturbation from the pre-spike level, then the width is larger than the separation between DOB and SOL, and smaller than the separation between LYC and UPS, being $2.9^\circ \pm 2.1^\circ$. Although this estimate is limited by the spatial distribution of the magnetometers, a similar width of about 2° – 3° is suggested by AMPERE, TREx, and Swarm measurements discussed below.

Around magnetic midnight at ~ 23.3 hr MLT (middle column), the geomagnetic field perturbations exhibited a peak amplitude of 1,832 nT (or 916 nT compared to pre-spike) and time derivative of 511 nT/min at Saint-Felicien (T50) at 57.83° MLAT. Similar values were recorded at Val-d'Or (T51) which was located at nearly the same latitude but several degrees to the west. Such amplitudes were smaller than those at dawn and they continued to decrease toward the dusk. The possible underlying cause is attributed to enhanced ionospheric conductivity resulting from diffuse auroral precipitation (Section 4.2). Note that the larger perturbation at dawn compared with pre-midnight or dusk is again different from what is normally expected from substorms, as substorms often have largest perturbation in the pre-midnight sector (Gjerloev & Hoffman, 2014).

The electrojet extended equatorward beyond Ottawa (OTT) at 54.98° MLAT, where the amplitude of the horizontal magnetic field component was 1,008 nT (548 nT compared with pre-spike), and the vertical component was upward. The separation between OTT and T51 hence provides a lower estimate of the electrojet width of 2.9° . However, an upper estimate could not be reliably determined due to the large gap in the magnetometer network poleward of T51.

In the pre-midnight sector at ~ 20.9 hr MLT (right column), the electrojet had the latitudinally largest amplitude recorded at Pinawa (PIN) at 59.96° MLAT as 1,066 nT (or 757 nT compared to pre-spike). The downward vertical magnetic field component indicates that PIN was located on the poleward side of the electrojet. The electrojet

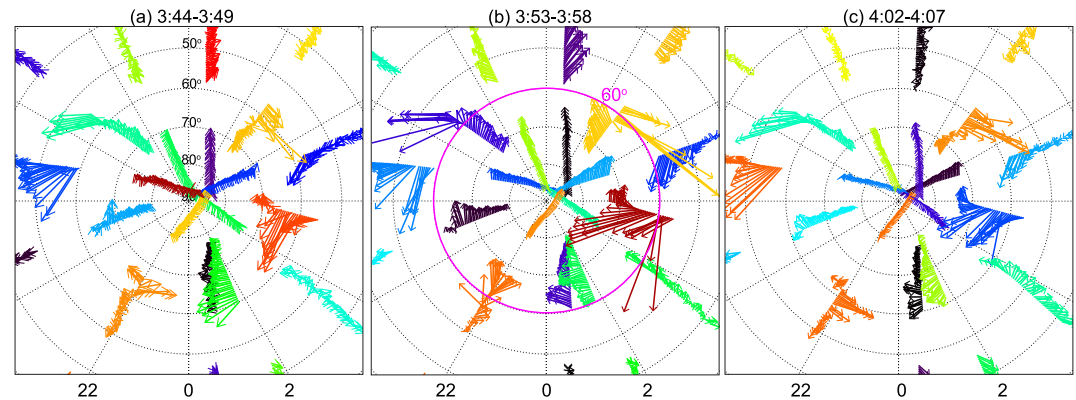


Figure 7. Distribution of in-situ magnetic field line perturbations (dB) measured by AMPERE-NEXT in MLAT-MLT coordinates. Panels (a–c) represent conditions before, during, and after the spike event. The magenta circle represents 60° MLAT where the auroral electrojet spike-associated magnetic perturbations occurred.

extended to Brandon (BRD) at 59.20° MLAT, with an amplitude of 636 nT (or 462 nT compared to pre-spike). This indicates a latitudinal width larger than 0.76°. The upper estimate is again limited by the spatial distribution of the magnetometers.

Figure 7 shows the in-situ magnetic field perturbations measured by AMPERE-NEXT which were presumably produced by FACs associated with the auroral electrojet spike. The color vectors represent in-situ magnetic field values, and different colors represent measurements from the different satellites in the Iridium constellation. AMPERE maps are often constituted of 10 min of data updated every 2 min, but here we show data over a 5-min interval so that the vectors in Figure 7b were selected over the duration of the spike event. Data taken 9 min before (after) are used to represent the conditions before (after) the spike, because the consecutive satellites along the same orbital plane are separated by ~9 min.

Comparing Figure 7b with Figures 7a and 7c shows that the occurrence of the auroral electrojet spike coincided with the appearance of large perturbations of in-situ magnetic field over a latitudinally narrow region around 58°–60° MLAT. They were most noticeable along 5.5, 9.5, and 15.0 hr MLT, but also discernible along 17.0 and 22.0 hr MLT. The large perturbations may actually have spanned the entire globe, but only satellites that traversed the right latitude range captured them. Moreover, the time when the satellites crossed the relevant latitude range is also important for detection. For example, if a satellite entered or exited the latitude range at the very beginning (end) of the 5-min interval, the onboard magnetometer may not capture the effect of the spike at its full strength. Similar large perturbations also occurred in the Southern Hemisphere (not shown).

The narrow latitude extent compared with the longitudinal extent suggests that the associated FAC structures can be well represented by a pair of FAC sheets with opposite polarities. We now assess whether the electrojet occurred at R1, R2 FACs or the interface in-between. Assuming a sheet current structure, R2 FACs in the dusk (dawn) sector are associated with eastward (westward) magnetic perturbations that increase with latitude and R1 FACs with eastward (westward) perturbations that decrease with latitude. Therefore, the interface between R1 and R2 FACs occurs at the latitudinal peak of perturbations, except around the dayside cusp and magnetic midnight where the FACs often consist of more than two current sheets (Iijima & Potemra, 1976, 1978). Table 1 compares the MLATs of the R1–R2 interface shown in Figure 7a and the peak of the electrojet shown in

Table 1

Comparison of MLAT of the R1–R2 Interface in Figure 7a, and MLAT of the Peak of the Auroral Electrojet Spike in Figure 7b

	15.0 hr MLT	17.0 hr MLT	5.5 hr MLT	9.5 hr MLT
R1/R2 Interface	59.5° MLAT	58.7° MLAT	60.7° MLAT	61.2° MLAT
Electrojet-related FAC Peak	58.5° MLAT	57.5° MLAT	59.4° MLAT	60.1° MLAT

Note. The comparison is performed at local times where (1) FACs exhibit two sheet structure and (2) the electrojet spike-associated dB was observed (i.e., satellite was located at the right location and time).

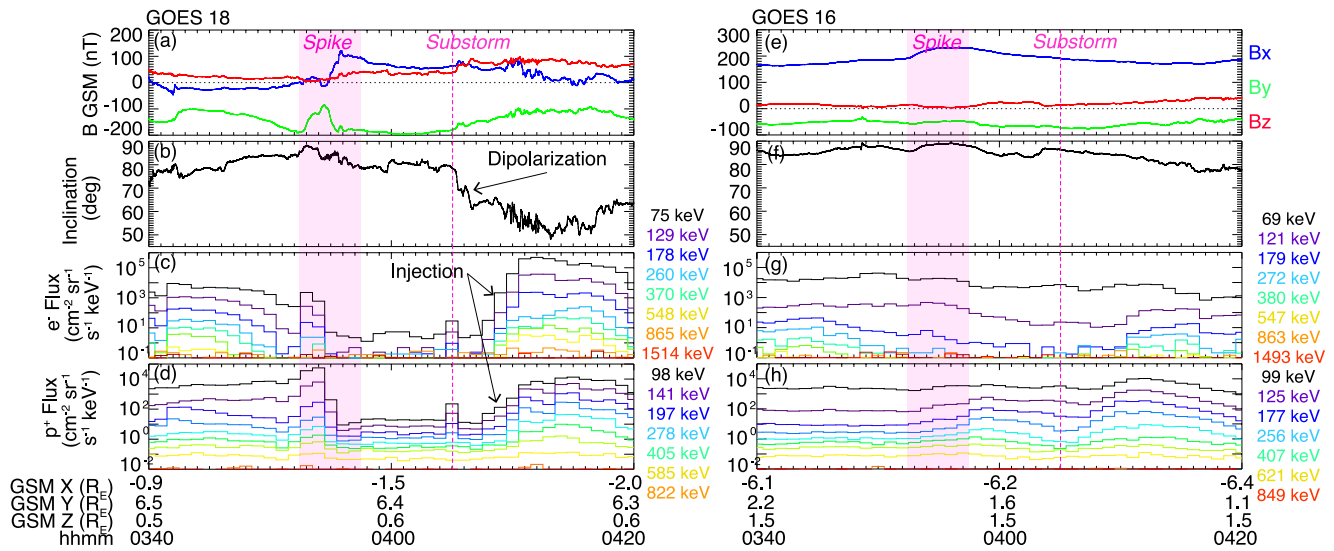


Figure 8. (a–d) Magnetic field and inclination angle. The inclination angle is defined as the angle of the magnetic field vector deviating from the GSM Z direction. (c–d) Energetic electron and proton fluxes as measured by Geostationary Operational Environmental Satellites 18 (G18). (e–h) Similar to Panels (a–d) but for G16.

Figure 7b. The results show that the electrojet occurred close to the interface but on the equatorward side, the separation being about 1° in MLAT.

The AMPERE data show excellent agreement with SuperMAG polar maps, spatially as well as temporally. Both suggest that the auroral electrojet spike was limited to a narrow latitude region at and slightly below 60° MLAT. The AMPERE data further show that the electrojet extended to the dayside auroral zone, where the ground-based magnetometer coverage was sparse. The dayside extension could be due to the different nature of the currents captured by AMPERE and ground magnetometers. Specifically, ground magnetometers capture the divergence-free component of the current system, which is, to a first approximation, a Hall current. AMPERE captures the rotation-free component, which closes in the ionosphere as Pedersen currents. The Hall to Pedersen conductivity ratio increases with precipitating particle energy, implying that the currents in AMPERE can have a spatial peak at an earlier MLT than SuperMAG. Alternatively, the dayside extension could possibly indicate a real extension of the auroral electrojet spike to the dayside. Whether the dayside and nightside electrojets originate from one common current system or two separate ones is unknown, but Ohtani (2022) reported that the nightside westward auroral electrojet can be connected to a dayside R1-sense wedge system. The limited dayside ground magnetometers do not allow a similar analysis and so we focus on the nightside electrojet where the magnetometer data were available.

3.3. Physical Driver: Substorms, Pressure-Induced Aurora, or Convection Electric Field

As indicated in the introduction, negative bays in the nightside auroral zone have been traditionally perceived to be due to substorms or other processes that enhance the auroral electrojets. Substorms are associated with a current wedge system where the cross-tail current is diverted into the high-latitude ionosphere (McPherron et al., 1973). At geosynchronous orbit, the current system manifests as sustained magnetic field dipolarization.

Figure 8 shows magnetic field and particle measurements from G18, located at dusk, and G16, located close to midnight. The inclination angle is defined as the angle of the magnetic field vector deviating from the GSM Z direction. Prior to the auroral electrojet spike, the magnetotail was stretched, as indicated by the small Bz component and the large inclination angle at G18 and G16. The radial magnetic field component was dominated by -By at G18, and +Bx at G16, as expected from the spacecraft locations. During the spike, the inclination angle retained a large value with minor variations of a few degrees, suggesting that the magnetic field configuration changed only marginally. Specifically, at dusk (G18), the magnetic field showed a subtle dipolarization because the Bz component exhibited a small and gradual increase. The Bx component changed sign from negative to positive, implying a crossing of the neutral sheet. The absolute By component first decreased and then increased

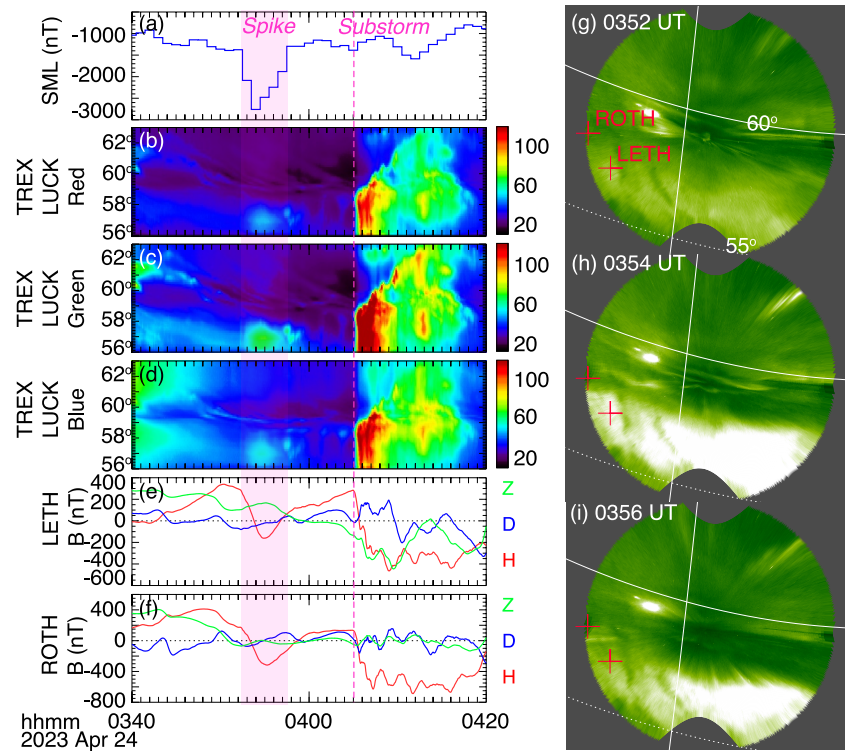


Figure 9. (a) SML index from SuperMAG. (b–d) Auroral emissions in the red, green, and blue wavelengths as measured by Transition Region Explorer (TREx) at LUCK. (e–f) Geomagnetic field measured by LETH and ROTH, the locations of which are plotted as red plus sign in Panels (g–i). (g–i) Snapshots of the TREx auroral emissions in green line before and during the auroral electrojet spike.

as the spacecraft moved away from the neutral sheet. At midnight (G16), the magnetic field was further stretched because the B_z component decreased to near zero and the B_x component increased.

In contrast, the inclination angle decreased drastically starting around 04:05 UT at dusk, after the spike subsided. This change, which is a dipolarization, was associated with a notable increase in the B_z component and decrease in both B_x and B_y components. Although less significant, the dipolarization is still discernible at midnight. The dipolarization is consistent with the establishment of the substorm current wedge. The different configuration between the auroral electrojet spike and the substorm suggests that the spike is not associated with substorms.

Also shown in Figure 8 are energetic electron fluxes from telescope 4 and ion fluxes from telescope 2 looking radially outward in the orbital plane. Substorms are associated with impulsive particle injections, some of which can penetrate to geosynchronous orbit. The substorm that initiated at 04:05 UT was accompanied by enhancements of electron and ion fluxes at dusk and midnight. On the other hand, the electrojet spike either saw little change of particle fluxes (at midnight), or a sharp decrease of fluxes (at dusk). The decrease in flux was probably due to G18 moving away from the neutral sheet and crossing field lines that thread the more distant tail where fluxes of energetic particles are generally smaller (Fennell et al., 1996).

One potential limitation is the lack of magnetospheric observations at dawn, where the auroral electrojet peaked. Whether the peak electrojet amplitude was at least partially due to magnetotail dipolarization and/or particle injection is unknown. Nevertheless, the fact that the auroral electrojet showed no noticeable azimuthal propagation but spanned the entire nightside sector suggests that dipolarization or particle injection is not essential for initiating the spike, otherwise they should have occurred at midnight and dusk as well.

Auroral activity is well known for its capability to remotely sense dynamics in the magnetosphere. The auroral activity during the auroral electrojet spike is presented in Figure 9. The TREx RGB imager network consists of six imagers, and only the one located at Lucky Lake (LUCK) was located at the relevant latitude to monitor the spike-related auroras with clear sky conditions. LUCK was located around 20.3 hr MLT during the event.

Figure 9 shows the red, green, and blue emissions as a function of time. Coincident with the spike is an intensification of emissions at 56° – 58° MLAT, with a mapping uncertainty of $\sim 1^{\circ}$. The intensified emissions were diffusive, indicating diffuse auroras. Discrete auroras can be discerned poleward, but they exhibited little variation during the spike. Neither the discrete or diffuse auroras expanded poleward. The 2-D snapshots shown in Figures 9g–9i show that the diffusive emissions spanned a wide longitudinal extent upon occurrence, extending beyond the imager field-of-view. The diffusive nature of the aurora and the lack of poleward and azimuthal expansion clearly suggests that the event was not a substorm. Interestingly, a poleward expanding auroral bulge occurred at 04:05 UT, which was a substorm, and its timing is consistent with the magnetic field dipolarization observed at G18.

The close correspondence in time and latitude between the intensified diffuse aurora and the auroral electrojet spike indicates that the two are likely to be causally related. The possible mechanism is that the ionization associated with the diffusive precipitation can elevate the ionospheric conductivity and hence the horizontal currents flowing in the ionosphere. The two magnetometer stations of ROTH and LETH located beneath the diffuse auroras at LUCK observed an increase of 491 and 457 nT in the southward geomagnetic field, respectively. Although not as extreme as the amplitudes in Figure 6, these values are consistent with the electrojet weakening toward dusk. This can be understood from the fact that the diffuse auroras at dusk are produced mostly by proton precipitation (Zou et al., 2012), which has a much smaller energy flux and causes less ionization than the diffuse electron precipitation at dawn. The ionospheric Hall conductance due to proton precipitation can be an order of magnitude smaller than that due to electrons (M. W. Chen et al., 2019). This also explains why the substorm auroral bulge (mainly produced by electron precipitation) which emerged at 04:05 UT perturbed the geomagnetic field more significantly than the electrojet spike at this local time.

We postulate that the relation between the auroral electrojet spike and diffuse auroras persist through midnight to dawn. Discrete auroras are generally less pronounced in the post- than in the pre-midnight sector, except for auroral omega bands (Partamies et al., 2017), which often occur along the poleward boundary of the brightest diffuse auroras. DMSP SSUSI observations captured auroral omega bands with fold structures of >500 km in the Southern Hemisphere (not shown) during the event. However, these omega bands were too broad to explain the latitudinally narrow auroral electrojet spike.

Auroral electrojets can also be enhanced due to an increase of the convection electric field. Studies have related an increase of solar wind pressure to an increase in the polar cap index (Liou et al., 2004, 2017), as well as the ratio of the cross-polar-cap potential to the cross-magnetospheric potential (indicative of the coupling efficiency between the solar wind and the magnetosphere) (Boudouridis et al., 2005). In order to assess the importance of the convection electric field, Figure 10 shows ionospheric ion drift measured by Swarm B that fortuitously traversed the auroral zone at around 8 hr MLT before and during the auroral electrojet spike. The spike is associated with locally enhanced ionospheric electron density, highly structured ion drift, and strongly perturbed in-situ magnetic field, which all occurred at around 59° – 61° MLAT. In particular, the perturbed magnetic field appeared as latitudinally localized structures embedded within the large-scale R1–R2 system, and their position was located equatorward of the original R1–R2 interface at around 62° MLAT, consistent with AMPERE measurements.

For a direct comparison of the convection electric field, Figure 10h superposes the pre-spike ion drift measurements (blue) onto those during the spike (red). The pre-spike measurements have been shifted equatorward by 1.5° so that the convection reversal boundaries during the two passes match, although the shift is not important for the results. The ion drift exhibits rapid fluctuations with amplitudes of hundreds to thousands of m/s, suggesting that the convection electric field contains latitudinally fine structures. Similar variability in the electrojet cannot be captured by the scattered ground magnetometer stations, and we therefore mainly focus on a spatial scale comparable to the electrojet by smoothing the ion drift data with a 10-s sliding window (equivalent to 76 km or 0.6° in latitude). The ion drift increased over the latitude of the electrojet spike, but only modestly by a factor $<125\%$. In comparison, the intensity of the electrojet was enhanced by a factor of $>200\%$, or even $>300\%$, according to the perturbation geomagnetic field in Figure 6. This difference indicates that the pressure-driven electric field cannot sufficiently account for the large amplitude of the auroral electrojet spike, and implies that the pressure-driven conductivity increase is likely to be the main contributor.

One potential limitation is that the convection electric field measured by Swarm was displaced from the dense ground magnetometer network by ~ 3 hr toward the dayside, and information of the electric field at the longitude of the magnetometer network is not known. Collocated electric and magnetic field measurements can be obtained

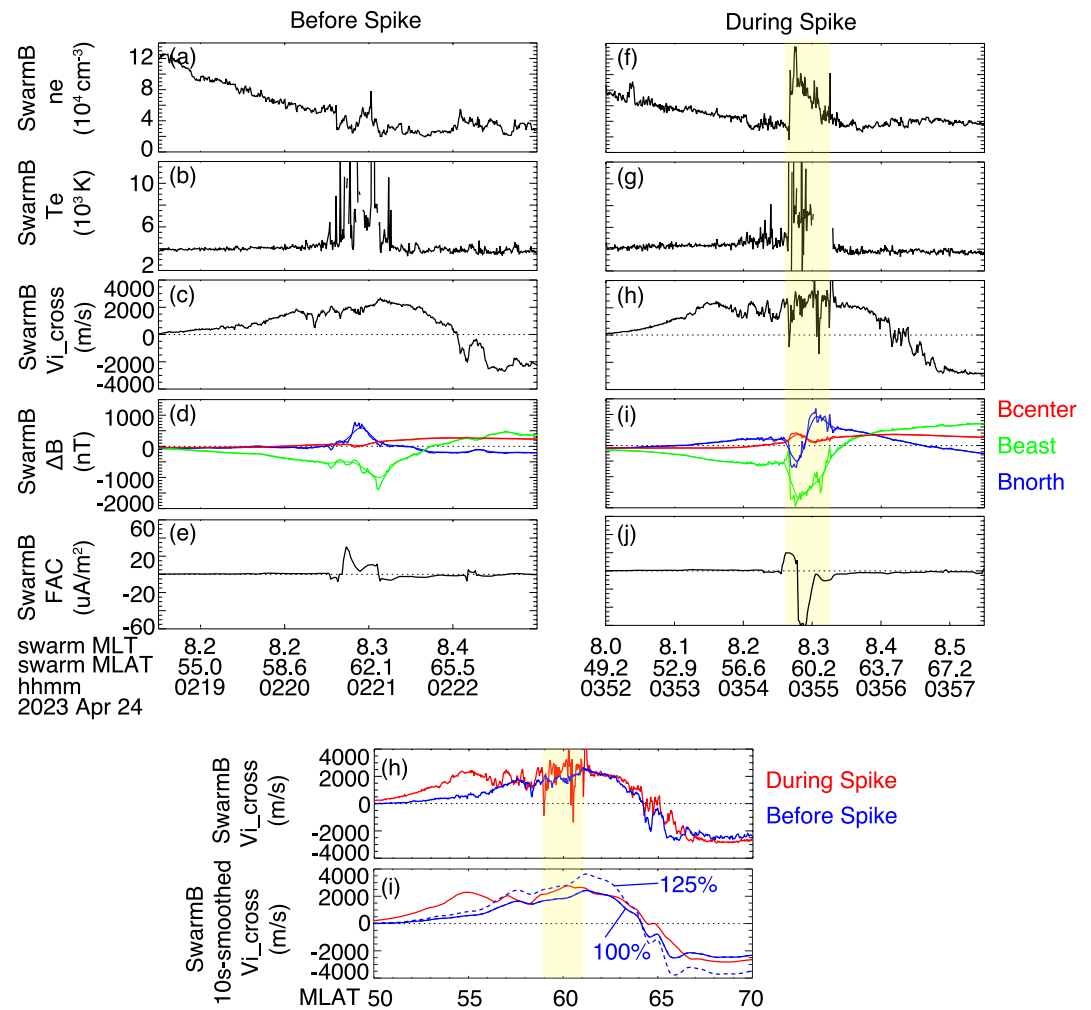


Figure 10. (a–e) Electron density and temperature, ion cross-track velocity, magnetic field perturbed from the IGRF model, and estimated field-aligned current (FAC) intensities before the auroral electrojet spike occurred. FAC intensities are estimated by smoothing the Swarm magnetic field with the same 10-s smoothing window as the electric field (see thick lines in panels (d) and (i)), and using the infinite sheet current approximation (Fukunishi et al., 1991). (f–j) Same format as Panels a–e but during the spike. (h–i) Direct comparison of the ion cross-track velocity before (blue) and during the spike (red). The data in Panel (i) have been smoothed with a 10-s window to retain the large-scale ion drift. The dotted blue line represents the pre-spike drift multiplied by 125%.

from Swarm. Figures 10e and 10j show that the maximum absolute FAC intensities were 31 and 62 $\mu\text{A}/\text{m}^2$ before and during the electrojet spike, respectively. This indicates a remarkable increase of 200% in the spatial gradient of the ionospheric Petersen currents, a change again much larger than the one associated with the local electric field.

4. Discussion

4.1. Comparison of the Extreme Auroral Electrojet Spike With Substorms and MPEs

The observations presented in Section 3 have illuminated differences between the extreme auroral electrojet spike, typical substorms, and typical MPEs. These differences are summarized in Table 2, and they encompass magnitude, temporal and spatial extent, and physical driver.

4.2. Physical Driver of the Extreme Auroral Electrojet Spike

The intensity of auroral electrojets, according to Ohm's law, depends on the ionospheric conductivity and the electric field. Conductivity on the nightside is almost solely contributed by precipitation of particles that originate

Table 2
Comparison of the Characteristics of the Extreme Auroral Electrojet Spike, Substorms, and Magnetic Perturbation Events

	Auroral electrojet spike	Substorm	MPE
Peak-to-Peak Amplitude	About 1,500 nT	Several hundreds of nT	Several hundreds of nT
Time derivative	914 nT/min	Low hundreds of nT/min and below	Low hundreds of nT/min
Duration	5 min	1–2 hr	5–10 min
Latitudinal extent	A narrow fraction of the auroral oval (here 2°–3°)	Start as a localized region and expand poleward covering the entire auroral oval	Hundreds of km
Longitudinal extent	Entire nightside with the electrojet peaking at dawn. Possible extension to dayside.	Start as a localized region around midnight and expand azimuthally covering nightside.	Hundreds of km
Relation to auroras	Diffuse auroras	Discrete and diffuse auroras	Discrete auroras
Solar wind driver	Dynamic pressure pulse	Southward IMF (for energy loading)	Southward IMF
Magnetotail driver	Diffuse particle precipitation	Magnetospheric substorm (energy unloading)	Magnetospheric substorm

from the magnetotail plasma sheet, and these precipitating particles also produce auroras. In the present study, the auroral electrojet spike coincided with brightened diffuse auroras, suggesting that the Hall conductivity associated with diffuse particle precipitation is likely a primary cause of the event. Diffuse auroras can further explain the wide longitudinal extent of the event and the increasing electrojet intensity toward dawn. The former is because diffuse auroras extend azimuthally across many hours of MLT continuously, and the latter because electron diffuse auroras are more intense at post-midnight and into the morning than from post-noon through dusk (Newell et al., 2009). Proton diffuse auroras, on the other hand, can extend to the dusk under the combined effect of the magnetic curvature and gradient drifts and the $\mathbf{E} \times \mathbf{B}$ convection drifts. Since diffuse electron precipitation is associated with much higher energy flux and induces a much larger increase in the ionospheric Hall conductivity than proton precipitation, the resultant conductivity on a global scale decreases from dawn to dusk, with a maximum located in the post-midnight or morning sector (M. W. Chen et al., 2019; Coumans et al., 2004).

The occurrence of diffuse auroral brightening is not surprising because it is frequently observed following a solar wind pressure increase. It often starts on the dayside and propagates azimuthally to the nightside at a speed of ~6–11 km/s (about 0.5–1 MLT/min) (Brittnacher et al., 2000; Holmes et al., 2014; Meurant et al., 2003, 2004; Zhou & Tsurutani, 1999; Zhou et al., 2009). Near-instantaneous brightening over the entire oval has also been reported (Chua et al., 2001). The cause of the propagation is attributed to either the propagation of the pressure front along the magnetopause (Zhou & Tsurutani, 1999) or the propagation of Alfvén waves launched by the pressure change (Meurant et al., 2003). In the present study, the solar wind pressure pulse arrived at the magnetosheath at around 03:53 UT, and the diffuse auroras brightened nearly instantaneously (within 1 min) at 20.3 hr MLT. This small time delay suggests that the propagation of auroral brightening, if it exists, must have a large speed so that auroras appear to brighten near-simultaneously on the day- and nightside, similar to the data discussed by Chua et al. (2001). This hypothesis is also supported by the wide longitudinal span of the electrojet spike. However, there are important differences between the observed auroras and the results of Chua et al. (2001). The auroras in Chua et al. (2001) were long-lasting (tens of minutes) and expanded poleward with time, whereas the auroras shown in this study lasted 5 min with no noticeable poleward expansion.

The exact process in the magnetosphere that drove the diffuse precipitation remains unclear due to the lack of in-situ observations at the conjugate location. We can, however, refer to processes that have been identified to be important in previous studies, as listed below. Their relative importance can be assessed when direct measurements of magnetospheric waves are available.

1. A sudden increase of the magnetic field intensity in the magnetosphere, such as due to magnetosphere compression, can lead to an increase of the perpendicular kinetic energy of particles, and hence an increase of the particle temperature anisotropy. This triggers loss cone instability and enhances growth of plasma waves which scatter particles into the loss cone by wave-particle interactions (Tsurutani et al., 2001; Zhou & Tsurutani, 1999). The increase of the kinetic energy of particles also means an increase of energy flux into the ionosphere.

2. An increase of the magnetic field intensity at the equator can reduce the mirror ratio ($R_m = B_m/B_{eq}$) and enlarge the particle loss cone, allowing more particles to precipitate in presence of scattering processes (Liou et al., 2007).
3. Proton precipitation can be additionally attributed to a reduced curvature radius of the nightside magnetic field lines (Laundal & Østgaard, 2008).

These listed processes can explain the latitudinally narrow yet longitudinally wide auroral electrojet spike reasonably well. For Process (a), observations have shown enhancement of whistler-mode chorus waves, a major driver of diffuse electron precipitation at $L < 7$, as well as electromagnetic ion cyclotron waves, a major driver of diffuse proton precipitation, in the inner magnetosphere triggered by solar wind pressure enhancement (Angelopoulos et al., 2023; Cho et al., 2017; Engebretson et al., 2015; Fu et al., 2012; Jin et al., 2022; Lessard et al., 2019; Li et al., 2016; Peng et al., 2020; Xue et al., 2022; Zhou et al., 2015). For Process (b), although enhancement of the equatorial magnetic field can extend over a broad radial distance, the resultant precipitation is likely to be strongest at the inner edge of the plasma sheet, where the density of plasma sheet electrons and ions is highest (Lee et al., 2011). Either process indicates a radially localized magnetospheric source for precipitation, which should map to a limited latitude range in the ionosphere. The very narrow (2° – 3°) latitude range observed in the present event can be attributed to the fact that a large amount of open magnetic flux has accumulated in the tail during the prolonged, strong southward IMF preceding the event. This caused the magnetic field to become more stretched than usual, resulting in a narrower projection of the source region in the ionosphere. On the other hand, the wave and the equatorial magnetic field enhancement could occur near-instantaneously across a wide local time due to the propagation of fast Alfvén waves launched by the pressure change. This would produce a near-instantaneous elevation of ionospheric conductivity over a wide range of longitudes.

4.3. Solar Wind Driving Condition of the Extreme Auroral Electrojet Spike

The most striking solar wind feature associated with the event is the transient pressure pulse, which enhanced diffuse particle precipitation through magnetosphere compression (as opposed to through triggering substorms). The pressure pulse was mostly due to solar wind density enhancement with little variation in solar wind velocity. However, a solar wind pressure enhancement may not be a sufficient condition because other types of disturbances, including substorms and pseudo-breakups, have also been reported in the literature to occur after it. The outstanding question is what other factors may have determined the response of the system. The answer will also help us to understand why similarly auroral electrojet spike events have not been commonly noted before.

An understanding of the driving condition requires surveying similar extreme events and identifying their common solar wind conditions. We nevertheless would like to note three important solar wind conditions associated with the event:

1. Pre-conditioning: The event was preceded by long-lasting and large amplitude southward IMF. Such IMF conditions may have favored plasma convection from the magnetotail to the inner magnetosphere, providing abundant source populations for diffuse particle precipitation.
2. Abrupt decrease in IMF driving: The event occurred when the southward IMF weakened. The necessity of this variation to the formation of the auroral electrojet spike is unknown, but Rostoker (1983) and Lyons et al. (1997) suggested that a northward IMF turning can trigger substorms by reducing the magnetospheric convection electric field.
3. Short-duration of pressure pulse: The pressure pulse lasted about 2 min, similar to the rise time of the auroral electrojet spike (2–3 min). Generally speaking, pressure can stay elevated for tens of minutes to hours. Whether and how the duration affects the spatial and temporal scale as well as the mechanisms of the magnetosphere response is unknown.

5. Summary

An extreme auroral electrojet spike occurred on 24 April 2023 in association with an unusually large amplitude and time derivative of the geomagnetic field perturbation. This event differs from typical substorms or MPEs with regards to magnitude, temporal and spatial extent, and physical driver. It therefore signifies a potentially new type of geomagnetic disturbance and highlights a solar wind driver that is enormously influential for triggering space weather events. Key findings of the event are summarized as below.

1. The extreme auroral electrojet spike had an amplitude that peaked at 2,798 nT (or 1,520 nT compared to pre-spike) and a time derivative that peaked at 914 nT/min. Similar amplitudes have been reported in so-called super-substorms, and similar time derivative correspond to the 99.97th percentiles of all geomagnetic field fluctuations that occurred over 20 years.
2. The event lasted 5 min, and its onset was associated with a transient solar wind dynamic pressure pulse of about 40 nPa. The pressure pulse was mostly due to solar wind density enhancement with little variation in solar wind velocity.
3. The event was confined to a narrow (2° – 3°) latitude band within the auroral oval. It was positioned close to but slightly equatorward of the interface between R1 and R2 FACs. However, it had a longitudinal span that covered the entire nightside, possibly extending to the dayside. The electrojet intensity showed a peak at dawn and decreased toward dusk. It exhibited no noticeable latitudinal or longitudinal expansion.
4. The event coincided with a sudden brightening of diffuse auroras in space and time. It was not accompanied by magnetic field dipolarization or energetic particle injections at geosynchronous orbit.
5. We postulate that the event occurred because the solar wind pressure compressed the magnetosphere, enhanced diffuse precipitation of electrons and protons from the inner plasma sheet, and elevated the ionospheric Hall conductivity. The convection electric field also increased but its contribution appeared to be a secondary effect.
6. Unanswered questions remain with respect to the solar wind driving conditions of the event. The rareness of similar spike events in the literature suggests that besides the pressure pulse, other solar wind conditions, such as pre-conditioning, a decrease in IMF driving, and a short duration of the pulse, might have also played an important role.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

SuperMAG data are available from <https://supermag.jhuapl.edu/info/>. DSCOVR data are available from https://www.ngdc.noaa.gov/dscovr/portal/index.html#. Time History of Events and Macroscale Interactions during Substorms data are available from <http://themis.ssl.berkeley.edu/data/themis/>. AMPERE-NEXT data are available from <https://ampere.jhuapl.edu/>. GOES data are available from <https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes/goes16/12/data/>. TREx data are available from https://data.phys.ucalgary.ca/sort_by_project/TREx/. Swarm data are available from <https://swarm-diss.esa.int/#>.

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Erratum

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