Dayside Auroral Observation Resulting From a Rapid Localized Compression of the Earth's Magnetic Field

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Abstract This paper presents observations of dayside auroral signatures resulting from a massive localized compression of the magnetopause, magnetosheath, and bow shock. On 10 December 2016, the Magnetospheric Multiscale Mission (MMS) spacecraft observed a compression of the entire magnetosheath and bow shock, which moved past the spacecraft in 1 min and 45 s. Shortly afterward, the resulting auroral signature was observed at the Kjell Henriksen Observatory located in Longyearbyen, Norway. The characteristics of this unique event have major ramifications for understanding dayside magnetospheric physics.

Plain Language Summary The aurora borealis and australis are the visible signatures of interactions between the Earth’s magnetic field and the solar wind. When the solar wind's magnetic field interacts with the Earth's magnetic field, there can be large fluctuations in its positioning and shape. This paper presents observations from satellites of a very large compression of the magnetic field, resulting in unique ionospheric signatures directly over an all-sky camera at Kjell Henriksen Observatory in Svalbard, Norway. One minute and 57 s after the compression at the magnetosphere, previously unstructured aurora began to intensify and organize, first propagating eastward and then brightening westward. The auroral arcs then began to spiral in a counterclockwise direction forming a spiral structure over the field of view. This defined shape only lasted for a few seconds before dispersing and moving poleward. The characteristics of this unique event have major ramifications for understanding dayside magnetospheric physics.

1. Introduction

Solar wind-magnetosphere-ionosphere interactions are central to understanding magnetospheric physics. Magnetic reconnection, proposed by Dungey (1961), is the most important among these interactions. Reconnection enables the interplanetary magnetic field (IMF) to interact with the geomagnetic field, further energizing the shocked solar wind plasma in the magnetosheath as it enters the magnetosphere. This plasma then flows down the dayside magnetospheric magnetic field lines to produce aurora that can be seen when the high latitude ionosphere lies in darkness near local noon. As noted by Vorobjev et al. (1975) and Horwitz and Akasofu (1977), southward IMF turnings initiate brightenings and equatorward motion of the dayside auroral oval. As the oval moves equatorward, short-lived arcs brighten and move poleward. Fasel (1995) reported a statistical study of the transient arcs, which he termed poleward-moving auroral forms or PMAFs, finding that they typically recur each 6 min, have durations of 5 min, generally occur for southward IMF orientations, and are not associated with variations in the solar wind dynamic pressure.

Other types of solar wind-magnetosphere interaction also produce signatures in the dayside auroral oval. Attempts to classify dayside aurora date back to Störmer (1955), who used the classifications: forms without ray structure, forms with ray structure, and flaming aura. Later, Yang et al. (2000) reclassified the dayside aurora into corona and arc aurora. Corona aurora is a common type of auroral display in which both discrete and small-scale sporadically move, appear, and disappear in the sky. Zhou and Tsurutani (1999) employed Polar UVI to show that the pressure variations associated with interplanetary shocks cause global auroral brightenings that first occur near local noon and then propagate along the auroral oval toward dawn and dusk at speeds from 6–11 km/s. Using a global network of all-sky cameras (ASCs), Vorobjev (1974) showed
that interplanetary shocks also increase auroral activity on the nightside. Vorobjev et al. (2009) used ASCs to document dayside auroras after these shocks for both $B_z < 0$ and $B_z > 0$, concluding that auroral arcs form at the equatorward edge of the auroral oval for $B_z < 0$ and on the poleward edge for $B_z > 0$. Zhou et al. (2009) documented a factor of 2 intensification of the aurora seen by an all-sky imager located in Svalbard, Norway, that followed the arrival of an interplanetary shock by 5 min. Liu et al. (2015) documented intensified discrete red aurora and broadening of the auroral oval in ground-based optical aurora observations in response to an interplanetary shock. They suggest that shocks intensify interactions in the inner magnetosphere and enhance the lobe magnetic reconnection rate. Other researchers have documented the occurrence of shock aurora at latitudes lower than Svalbard (Jin et al., 2016; Meurant et al., 2004). Kozlovsky et al. (2005) showed that an interplanetary shock caused a poleward shift of the dayside oval by $3^\circ$. All of these interplanetary shocks were documented by satellites far upstream in the solar wind.

However, not all the pressure variations that arrive at the magnetopause can be found far upstream in the solar wind. Some solar wind discontinuities, marked by abrupt changes in the IMF direction, generate strong variations in the density and dynamic pressure when they interact with Earth’s bow shock. Transients include hot flow anomalies (Schwartz, 1995), foreshock cavities (Sibeck, 1991), and foreshock bubbles (Omidi et al., 2010). These transients drive large-amplitude bow shock and magnetopause motion and transmit pressure variations into the magnetosphere. Generation of these foreshock transients is enhanced during intervals of radial IMF orientation in the presence of a foreshock.

There have been occasional reports indicating that these transients can cause large-scale movement of the entire magnetosheath. Sibeck et al. (1999) documented a Hot Flow Anomaly that caused the entire magnetosheath and magnetopause to expand outward past Interball-1 in 2 min and 33 s. This corresponds to a prediction made by Suvorova et al. (2010) who used the fact that plasma densities and dynamic pressures diminish within the foreshock (Fairfield et al., 1990) to predict that intervals of radial IMF should be associated with reduced magnetosheath pressures and magnetopause expansion. Suvorova et al. (2010) reported that the magnetopause moves outward 3–5 $R_E$ and the magnetosheath thins to $\approx 1.9 R_E$ during intervals of radial IMF.

One of the events reported by Suvorova et al. (2010) was included in a paper by Jelinek et al. (2010), who found 10 cases where the entire magnetopause, magnetosheath, and bow shock moved passed a THEMIS spacecraft in 2–5 min. It is unclear whether all of these cases were compressions or expansions. They used the fact that the typical magnetopause speed is 30–60 km/s to conclude that these crossings must be the result of a very thin magnetosheath. Examining a compression on 7 July 2016, Jelinek et al. (2010) concluded that the magnetosheath had a thickness of 1.9 $R_E$ (compared to the nominal 4 $R_E$). In this event, it took 4 min and 40 s for the magnetopause, magnetosheath, and bow shock to move over THEMIS. They were unable to find or report the IMF discontinuity that triggered this event or the resulting aurora signatures.

The vital ionospheric signatures of these rapid crossing events have yet to be well analyzed. Sitar and Clauer (1999) showed a ground magnetometer signature of an IMF discontinuity, and both Sitar et al. (1998) and Sibeck et al. (1999) presented polar auroral observations of the response to an HFA. From this distance, they could only document that the brightening moved antisunward.

This paper presents the dayside ionospheric signatures of a rapid compression of the bow shock-magnetosheath-magnetopause-magnetosphere system. On 10 December 2016, the Magnetospheric Multiscale Mission (MMS) spacecraft were located in the subsolar magnetosphere, when a massive localized compression occurred, resulting in the entire magnetosheath and bow shock moving past the spacecraft in 1 min and 45 s. The magnetosheath width was calculated to be at least 1.9 $R_E$. The speed of the magnetosheath boundary motion during this compression was incredibly fast, moving at 353 km/s compared to the nominal speed of 30–60 km/s. There was no significant change in the solar wind parameters observed by upstream monitors at L1. Nevertheless, because the upstream IMF was nearly radial and MMS observations themselves provide evidence for a sharp IMF discontinuity, we conclude that this event was caused by a transient generated in the foreshock via the interaction of an IMF discontinuity with the bow shock. Therefore, we are henceforth naming the event a Foreshock-Generated Localized Compression (FGLC). This event was not only captured by MMS, but also by ground-based optical instruments at the Kjell Henriksen Observatory in Longyearbyen, Norway, just after magnetic noon. The absence of an interplanetary shock and localization of this aurora makes this signature distinctly different than the shock aurora reported by Zhou & Tsurutani, 1999). We are hence forth calling this signature a foreshock transient-driven aura. This
foreshock transient-driven aurora can be identified on the basis of rayed structures shifting westward and then rotating in a counter clockwise direction. The classification fits under the broader category of corona, or “crown,” auroras because of the presence of rayed bands and small-scale auroral structure. This event reveals the close association between foreshock transients, magnetosheath motion, and resulting auroral signatures. This paper presents the data and initial analysis for these uniquely coupled events.

2. Observations

2.1. Instruments

This study compares bow shock, magnetosheath, and magnetopause observations with those by solar wind monitors and a ground-based observatory in the dayside auroral oval. In particular, we present MMS1 observations of the magnetic field (Russell et al., 2016) and plasma (Pollock et al., 2016) parameters in the vicinity of the dayside subsolar magnetosheath with cadences of 16 S/s and 4.5 s respectively. We present Wind IMF (Ogilvie et al., 1995) and solar wind plasma (Lin et al., 1995) observations with cadences of 0.092 and 6–12 s, respectively. Lastly, we present ASC observations with 3 s cadences from the Kjell Henriksen observatory in Longyearbyen, Svalbard, Norway (Sigernes et al., 2014, 2017).

2.2. MMS

On 10 December 2016, from 09:07–09:14 UT, MMS1 was located at (11.4 RE, 2.9 RE, and −0.4 RE) GSM (shown in Figure 1a). The spacecraft was nominally located in the magnetosheath. Figure 1b shows magnetic field and plasma data from MMS1 from 09:07–09:14 UT, also in GSM coordinates. During this time period, the spacecraft encountered the magnetosphere, magnetosheath, and the solar wind. Due to the small distances separating them, all four MMS satellites display the same event with no significant time delay. Therefore, the choice to use MMS1 was arbitrary. Throughout this paper, the subscripts sw, sh, and ms will be used to denote solar wind, magnetosheath, and magnetosphere, respectively.

MMS1 was in the magnetosphere (Figure 1b highlighted in purple) at 9:07:42 UT (Figure 1b, Region ms1), 9:08:53 UT (ms2), and 9:09:03 UT (ms3). Magnetospheric densities are low (1–2 cm−3), magnetic field strengths high (40–50 nT), and plasma distributions are broad.

MMS1 was in the magnetosheath for 1 min 45 s from 9:10:24–09:12:09 UT (Figure 1b nonhighlighted regions). Magnetosheath regions exhibit high densities (5–25 cm−3) and weaker variable magnetic fields. The magnetosheath has two distinct two stages, shown in Figure 1b Regions sh1 and sh2 and separated by a vertical dashed black line. The first stage was from 09:10:24–09:11:25 UT. It is characterized by an orientation shift in \( B_{shX} \), which turns from positive to negative. Other notable features are the \( \sim B_{shZ} \), relatively low particle density \( \sim 5 \) cm−3, and decreasing but positive \( V_{shX} \). \( V_{shX} \) is likely positive because the magnetopause is moving outward in response to the lower pressure on it.

Just before the start of Stage II, the magnetosheath orientation is \( \approx (−4.5, −10, and 2.5 \) nT). At 9:11:25 UT, the particle density rapidly increases from 5 to 25 cm−3 and \( B_{shTOT} \) increases from \( \approx 5 \) to 30 nT. This indicates the start of Stage II and a massive compression of the magnetosheath. This stage occurs from 09:11:25–09:12:09 UT and can be seen in Figure 1b, Region sh2, following the dotted line.

MMS1 was in the solar wind from 09:12:09–09:13:34 UT (Figure 1b, Region sw1, highlighted in yellow). Solar wind exhibits weak magnetic field strengths \( \approx 6 \) nT, with a typical orientation of \( B_{x}, B_{y}, \) and \( B_{z} \) ranging from 3.5 to 5, −2 to −1, and −3.5 to −2.5 nT, respectively, and a strong antisunward flow (\( V_{x} \approx −600 \) km/s). While MMS1 was in the solar wind, it detected high-energy, low-density particles, indicating the presence of a foreshock. Two significant increases in parallel temperature occurred during this interval. Pitch angle distributions (not shown here) suggest two clear populations of ions: One is the solar wind (1 keV, 5 keV), while the other is composed by high-energy ions (>10 keV) streaming parallel to \( B \). The additional high-energy ions produced significant increases in parallel temperature that occurred during this interval. This suggests the presence of a disturbed foreshock just after the time of the event.

This is shown in Figure 1b Panel 8 with a band of yellow above 10 keV. Finally, MMS1 was in the magnetosheath from 09:13:34 onward.

2.3. Solar Wind

Between the hours of 06:00–09:00 UT, the solar wind packets passing all three of the satellites located at the Lagrange point, ACE, Wind, and DSCOVR, were highly variable. Analysis of IMF and clock angle showed
Figure 1. MMS1 location, magnetic field data, and plasma data from 09:07:00–09:14:30 UT. (a) The estimated locations of magnetopause and magnetosphere (Roelof & Sibeck, 1993) and location of MMS1 on the X-Z plane in GSM coordinates. Magnetopause is shown by a curved line closer to the origin and the bow shock is the leftmost black line. Labels X1, X2, and X3 indicate solar wind/foreshock, magnetosheath, and magnetosphere, respectively. MMS1 is shown in blue. (b) The MMS1 magnetic field and plasma data in GSM coordinates over 7 min. Time is shown on the x axis below the three location coordinates. Panels 1–4 show magnetic field data from MMS1 in nT, $B_{ZTOT}$, $B_z$, $B_y$, and $B_x$, respectively. Panel 5 shows temperature in eV both perpendicular and parallel (blue and green, respectively). Panel 6 shows velocity, data in km/s with blue, green, and red indicating $V_x$, $V_y$, and $V_z$. Panel 7 shows particle density in cm$^{-3}$. The spectrographs (Panels 8 and 9) use a color spectrum to show the number of particles (ions and electrons respectively) at a specific energy range. Red (vertical axis on right side) indicates the largest flux and violet indicates the smallest flux of particles. The left vertical axis on this panel shows the distribution of energies, ranging from 10–10,000 eV. Magnetosphere crossings are highlighted in purple and labeled ms1, ms2, and ms3. Magnetosheath are all nonhighlighted areas, labeled sh1 and sh2. Stage I (sh1) is separated from Stage II (sh2) with a black dashed line. The solar wind crossing is highlighted in yellow and labeled sw1.

that the solar wind packet passing Wind, located at (194.786, −26.118, and −2.325 RE) GSM, had a good overall correspondence with MMS. However, there were instances of smaller discontinuities at MMS that were not seen by Wind.

The $B_x$ orientation shift in Stage I of the compression does correspond with a discontinuity at Wind that occurs 22.92 min earlier. Here, Wind records a momentary shift from highly radial IMF to nonradial with an increase in $B_{swX}$. Other IMF features during this time have a medium level of correspondence.

The solar wind that passed Wind satellite (figure not shown here) was incredibly $B_{swX}$ dominant ($B_{swX}/B_{swTOT}$ ≈ 0.8–1.0) for ≈15 min. This IMF orientation is known as radial IMF and will be very important in understanding the compression trigger. The solar wind velocity was fast and stable, averaging ~700 km/s in $-V_{swX}$ direction, with a Mach number of 8.8. Density was also very stable around 2.75/cm$^3$, meaning that there were no large fluctuations in dynamic pressure.

2.4. Ionospheric Signatures

The most novel impact of this compression were its signatures in the ionosphere. The MMS1 footprint was mapped down to Longyearbyen, Norway, where the ASC, located at Kjell Henrichsen observatory (KHO) (N78°8’52.5” E16°2’34.8”), captured the auroral signature of this compression. From 6–10 UT, the daytime auroral oval was directly over Longyearbyen. ASC imagers observed wild, unstructured auroral activity (See
Figure 2. ASC images from 9:12:19–9:16:08 UT. Panels show the time series of events, white arrows highlight direction of motion, and white triangles outline auroral oval. Panel (d) shows full compression aurora shape, followed by poleward motion. Panel (a) shows the ionosphere before the disruption from the compression. Panel (b) at 9:13:53 UT shows aurora change course and move westward. Panel (c) is the most important panel, showing the full formation of the compression caused aurora. This occurs at 9:14:26 UT, 4 min 2 s after compression at the magnetosphere. The structure has a clearly defined seashell shape for less than a second before it morphs. Panels (d) and (e) show the aurora morphing from the seashell-like shape into a more clearly defined arc that has broken off of the auroral oval.

Figure 2a). Starting at 9:13:22, after the compression began at the magnetosphere, an auroral intensification began directly above KHO. At 9:13:58 (Figure 2b), a short arc segment aligned along the north-south direction propagated eastward. While on the westward side of the FOV, there appeared to be a north-south rayed band that propagates eastward. On the eastward side of the field of view (FOV), the aurora intensified and brightened westward. The auroral arcs then began to spiral in a counter clockwise direction (Figure 2c). By 9:14:26, the aurora had a spiral seashell-like structure in the middle of the FOV. This is approximately 20 min past magnetic noon, putting the event close to the theoretical cusp. This defined shape only lasted for a few seconds before dispersing (Figure 2d).

At 9:16:08, this now clearly defined arc moved poleward and faded (Figure 2e). Poleward motion is consistent with a Poleward Moving Auroral Form (PMAF) (Fasel, 1995), which is thought to be the ionospheric signature of magnetic reconnection. After the aurora faded, the ionosphere became very quiet with a well-defined auroral oval.

This aurora appeared directly over Longyearbyen, but only faintly or not at all on other all-sky imagers in the Northern Hemisphere. Additionally, only one magnetometer in the area was triggered. (However, this trigger was a massive 250 nT.) This leads us to conclude that the compression was highly localized.

This motion is the exact opposite of a night side aurora documented by Kornilova and Kornilov (2009), whose aurora propagated Eastward and brightened westward. However, these aurora when DST index reached from −75 to −350 nT. The DST index for 10 December 2016 was a minimum of −27 nT. This aurora can be classified as a coronal aura because of its small size and rapid nature. The center of the “crown” appeared directly over the magnetic zenith of Longyearbyen. The video of this event can be found in the supporting information.
3. Discussion

Coplanarity and multivariable (MVA) (Shi et al., 2019) analyses were done to determine the normal to the compression compared with the bow shock. Both of these methods are commonly used to determine shock normals. Coplanarity assumes that the shock normal and magnetic field on one side of the shock lie in the same plane, while MVA assumes that the structure is one dimensional. By using both analyses, we can reduce the margin of error.

Figure 3 shows a cartoon of the FGLC resulting from these analyses. MMS1 crossings at 9:12:09 UT (Figure 3b) into the solar wind and 9:13:34 UT (Figure 3c) out of the solar wind were chosen for this analysis. Coplanarity resulted in a normal of (0.901, −0.2879, and 0.325) for Crossing 1 and (0.986, 0.157, and −0.063) for Crossing 2. MVA resulted in a normal of (0.858, −0.477, and 0.189) for Crossing 1 and (0.958, 0.249, and 0.020) for Crossing 2. Both analyses calculated the first crossing to have a normal with a strong +x and a weak −y (Figure 3b) and the second crossing to have a normal pointing in the opposite y from the first (see Figure 3c). This implies that the compression was an inverted hole that passed by MMS1. Both sides of this compression structure passed by MMS1 in 1:14 min, corroborating the localized nature of the FGLC. This corresponds to MVA analysis done at the magnetopause. The calculated shock angle was $B_n = 54^\circ$, which is weakly quasi-perpendicular.

Timing analysis of the magnetopause and bow shock crossing estimated a propagation speed of 261.47 km/s (56.03, 68.02, −246.16 km/s) and 353.084 km/s (−265.159, 80.524, −218.803 km/s) respectively. The positive $V_x$ component at the beginning of Stage I and the lack of density or $B_t$ increase imply that not much compression was occurring. This leaves MMS near the magnetopause until the beginning of Stage II, in which the entire magnetosheath moves over MMS in 49 s. Using the fact this speed and time, we estimate that a path of $\approx 1.9 \, R_E$ (this analysis is similar to Suvorova et al., 2010).

Next, we explore the possible causes and nature of this compression. This event cannot be an HFA because it compresses rather than expands, further motional electric field points away from the discontinuity. A model by Wang et al. (2018) predicts that upstream dynamic pressure changes are more influential on bow shock and magnetopause locations than IMF orientation. Therefore, we expect that such an intense compression would be caused by a massive dynamic pressure change. However, this analysis shows that the solar wind dynamic pressure was constant during the interval of interest. It is possible that the pressure variations that caused the compression simply alluded Wind or, more likely, that the pressure formed upstream of Wind.

Numerical simulations by Lin and Wang (2005) have shown that under similar conditions with a steady solar wind and radial IMF, foreshock waves and cavities generated in bow shock are constantly hitting the nose region of the magnetopause, causing ripples. Another possibility is that the IMF discontinuity associated with the $B_x$ orientation switch caused a foreshock transient to form. This hypothesis is backed by the...
localized nature of the compression, which suggests that the trigger may lie in the foreshock and not the solar wind. If this hypothesis turns out correct, we are naming this compression phenomenon a FGLC.

Further support of this hypothesis is given by Geotail, located in the magnetosheath, upstream of MMS1. From 9:00–9:24 UT, the IMF at Geotail was highly unstable. At 9:24 UT, the IMF became stable, without any significant fluctuations. These observations indicate a magnetic field line connection to the bow shock before 9:24 UT and then a sudden disconnection at 9:24 UT, indicating a very localized pressure pulse generated in the foreshock.

We suggest that the aurora is the ionospheric signature of the FGLC. We will henceforth be calling this aurora a foreshock transient-driven aurora. This aurora is identified by organized aurora and a clearly defined seashell or spiral shape.

4. Conclusions

On 10 December 2016 at 9:10:24 UT, a powerful compression was observed via spacecraft and ground-based data. This event was a localized, but massive compression that caused the entire magnetosphere and bow shock to pass over MMS1 in an extremely short time (1:45 min). We suggest the trigger of this compression was a discontinuity in the radial IMF, generating a pressure pulse in the foreshock region pressure, hints the name FGLC. The FGLC propagated ions down turbulent, reconnected field lines into the ionosphere, and generated the foreshock transient-driven aurora. The ionospheric signature of compression of this magnitude and short time duration. Understanding these interactions has significant implications in the theory of dayside magnetospheric physics.

Data Availability Statement

All spacecraft data can be found online (https://cdaweb.gsfc.nasa.gov/index.html). We use the following data sets: MMS1_FGM_BRST_L2, MMS1_FGM_SRVY_L2, MMS1_FPI_BRST_L2_DES-DIST, MMS1_FPI_BRST_L2_DIS-DIST, MMS1_FPI_FAST_L2_DES-DIST, WI_H2_MFI, and WI_K0_SWE, WI_H0_SWE. Ground-based data include the all-sky camera (ASC) from Kjell Hendriksen Observatory located in Longyearbyen, Norway, which can be found online (http://kho.unis.no). The 6 min video surrounding the event can be viewed in supporting information.

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