Magnetic storm-time red aurora as seen from Hokkaido, Japan on December 1, 2023 associated with high-density solar wind

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Key Points:

- Unusually bright red aurora was witnessed by citizen scientists from Hokkaido, Japan on December 1, 2023.
- The magnetic storm amplitude was not unusually large, but the solar wind density was extremely high as large as >50 /cc.
- Asymmetric evolution of the ring current is important to understand the cause of red-aurora magnetic storm events.

Abstract

We report a citizen science-motivated study on the cause of an unusually bright red aurora as witnessed from Hokkaido, Japan during a magnetic storm on December 1, 2023. Such an intense red aurora event has occurred in the Halloween 2003 super storm, but the Dst index peak of this December 2023 storm was only -107 nT. In spite of the moderate storm amplitude, the extremely high solar wind density of >50 /cc caused the aurora oval extension to 53 MLAT (L=2.8). We discuss that the drift loss of the ring current particles across the small-size magnetopause is important, and Hokkaido was at the right position to see the direct effect of the large particle injection of the storm-time substorm.

Plain Language Summary

Citizen scientists identified an unusually bright red aurora from Hokkaido, Japan during a not-so-unusual magnetic storm on December 1, 2023. This is weird because such an intense red aurora event only occurred in the Halloween 2003 super magnetic storm. The extremely high solar wind density of >50 /cc must be the key to solve this problem. The hypothesis of this study is that the loss of ring current particles across the small-size magnetopause played an important role. Also, we discuss that Hokkaido was at the right position to see the direct effect of storm-time substorm.

1 Introduction

During intense magnetic storms, red auroras can be seen and recorded from middle latitudes like Japan, as the auroral oval expands to lower latitude than usual (Yokoyama et al., 2018; Kataoka and Nakano, 2021). In the historically extreme case, an outstanding red aurora was witnessed and painted from Kyoto, Japan (Kataoka and Iwahashi, 2017). Better understanding of the red aurora appearance, auroral oval extension toward low latitude, and the possible origins and causes are important for improving the space weather forecast of magnetic storm-related hazards such as geomagnetically induced currents in middle latitudes (e.g. Kataoka and Ngwira, 2006).

There are at least two different mechanisms to cause the so-called low-latitude auroras. One is called stable red aurora (SAR) arcs, which is related to the heat conduction from the hot ring current ions (Kozyra et al.,1997, Inaba et al., 2021) to cause a pure red line emission at 630.0 nm. Another type is called broadband electrons (BBE), which is related to low-to-high energy electrons (tens of eV to several keV) to cause tall curtain-shaped auroras extending up to 600 km altitude in the sub-auroral latitude (Shiokawa et al., 1996; 1997). The BBE auroras are extended to so high altitude that the top red part of the aurora can be seen near the north horizon even from the middle latitudes.

The origins of such an intense magnetic storm are coronal mass ejections (CMEs)-related solar wind structures. Following the arrival of an interplanetary shock, there is so-called sheath region where the interplanetary magnetic field (IMF) strength and the density was strongly compressed in the shock downstream (Kataoka et al., 2005). Then after the sheath structure, so-called magnetic cloud is occasionally observed, where a smooth rotation of the strong IMF is the marker, although the whole CME-related structure can be complex in some cases.

This paper shows the recent example that an bright red aurora was witnessed by naked eyes and also photographed by more than dozen of citizen scientists from Hokkaido, Japan (the northern most region of Japan, and the magnetic latitude of 36~38 deg) on December 1, 2023.

Such a naked-eye witness of red aurora is rare in Hokkaido. The last time was 2003 Halloween storm when the Dst index peaked at -383 nT (Kataoka et al., 2017). Therefore, what is truly unusual for this red-aurora event in December 2023 is that the storm amplitude was not so strong and the real-time Dst index peaked at only -107 nT.

In this *Letter*, we first show the contribution of the citizen science. We then consult the ground-based and space-born monitoring observation data to discuss the possible mechanisms to cause the unusually bright red-aurora event on December 1, 2023.

2 Red aurora event details

The first contribution of the citizen science is that the ray structure was clearly identified in the red aurora. **Figure 1** shows the initial appearance of the red aurora at 1130 UT on December 1, 2023, as taken by the professional photographer KAGAYA. The ray structure indicates the BBE rather than SAR arc.

Figure 1. Red aurora as seen from Bihoro (43.63N, 144.23E, 37.2 MLAT), Hokkaido, Japan at 1130 UT on December 1, 2023. (Courtesy of KAGAYA)

The solar origin of this magnetic storm was the full-halo CME associated with the M9.8 solar flare occurred around the central meridian position of the Sun at 1930 UT on Nov 28, 2023. More specifically, the magnetic storm on December 1, 2023 was caused by the Earth's arrival of the CME-related interplanetary shock at ~0930 UT, and the strongly compressed solar wind in the shock downstream played the essential role to enhance the geomagnetic activities.

Figure 2 shows the OMNI-2 1-min solar wind data and the SYM-H index. The shock arrival at the magnetopause was at ~0930 UT. In the first stage of the magnetic storm after 1000 UT, the ring current was rapidly developed (the SYM-H index decreased) in an hour due to the strongly southward directing IMF (strong SBZ) of -20 ~ -30 nT. In the second stage after 1100 UT until 1330 UT, the SBZ was weakened to -10 nT while the solar wind density was unusually enhanced to >50 /cc. The red aurora was witnessed from Hokkaido for the time interval of 1130-1330 UT.

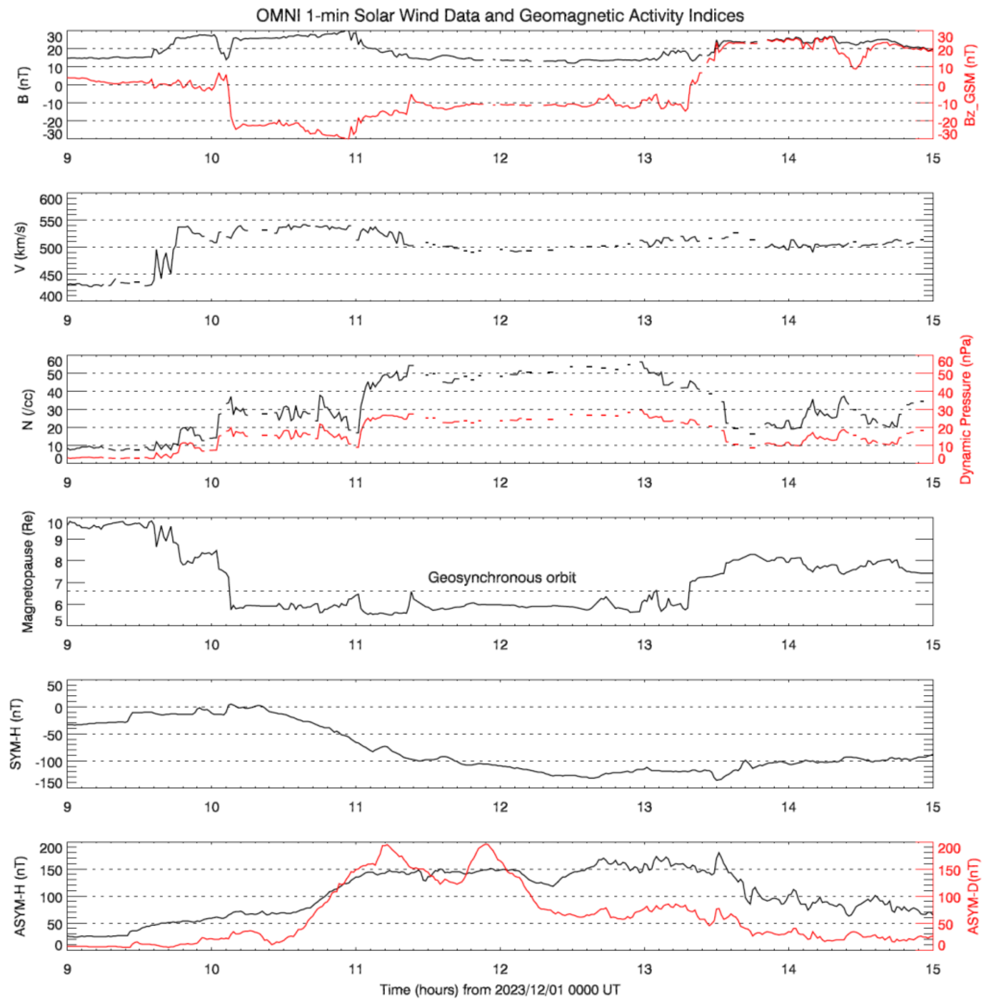

Figure 2. OMNI-2 solar wind data and geomagnetic activity indices. Top three panels show the magnetic field (southward component in red), solar wind speed, and density (dynamic pressure in red). The model magnetopause distance at the subsolar point is also shown. Bottom two panels show the SYM-H index and ASYM-H index (ASYM-D in red). The time axes of the solar wind parameters were already shifted as to the magnetopause arrival time to compare with the geomagnetic activity indices.

As the second contribution of the citizen science, the photo shootings of the red aurora obtained at different timing and locations (**Supplemental Information S1**) enable us to estimate the equatorward edge of the auroral oval as well as the emission height. We identified that the photos were taken by different persons at close timing at different latitude positions, i.e. from Nayoro, Hokkaido (1320 UT, 44.34E, 142.38E, 38 MLAT) and from Hidaka (1314 UT, 42.45N, 142.29E, 36 MLAT). Using the stars around the Edasich (Iota Draconis) which appeared to the north at that time, the elevation angles of the top part of aurora where the color changes from red to blue were determined to be ~15 deg and ~11 deg at Nayoro and Hidaka, respectively (**Supplemental Information S2 and S3**).

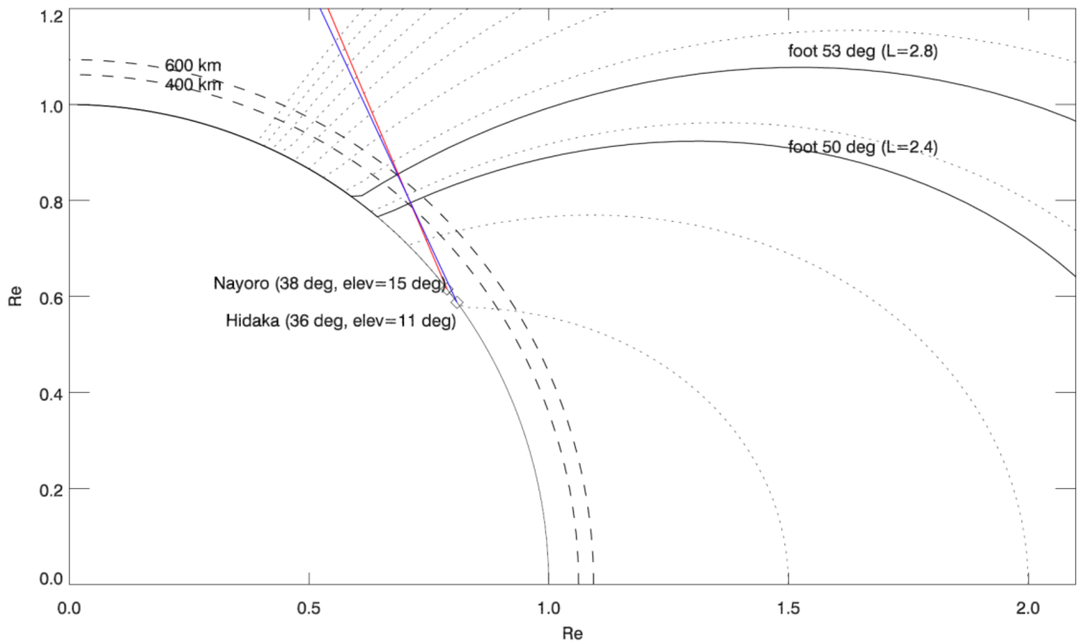

Figure 3. The relationship among the emission altitudes, magnetic field lines of the equatorward edge of the auroral oval, and observers at ground. The lines-of-sight from Nayoro and Hidaka are denoted by red and blue lines.

Here we draw the dipole magnetic field lines in **Figure 3** to calculate the possible ranges of auroral oval positions based on these two photographs. As a result, although the ambiguity is large in this simplest analysis, it is estimated that the top emission altitudes were 400 km to 600 km at the equatorward edge of the auroral oval at 50 deg to 53 deg magnetic latitudes (MLAT), respectively.

Monitoring observations of Nagoya University were also available in Hokkaido area to see the whole event sequence. **Figure 4** shows the photometer and magnetometer observations at Moshiri Station, Hokkaido (44.37E, 142.27E, 38 MLAT). Red aurora intensity at 630.0 nm wavelength was enhanced from 1130 UT to 1330 UT with the peak intensity as large as ~5 kR. The two-hour time interval (1130-1330 UT) corresponds to the peak time of the magnetic storm as seen by the H-component depression. Also, there were outstanding large-amplitude negative and positive peaks in the D-component around 1200 UT. We will come back to this bipolar D-component variation later again. Similar observation data was also obtained from Rikubetsu station (**Supplemental Information S4**). Note also that the SuperDARN Hokkaido radar detected the flow enhancement in the 50~55 MLT range, associated with the red aurora enhancement (https://cicr.isee.nagoya-u.ac.jp/cgi-bin/superdarn/hokkaidowest.cgi?year=2023&month=12&day=01&beam=12&jump=Plot). The details of the SuperDARN data analysis will be reported elsewhere.

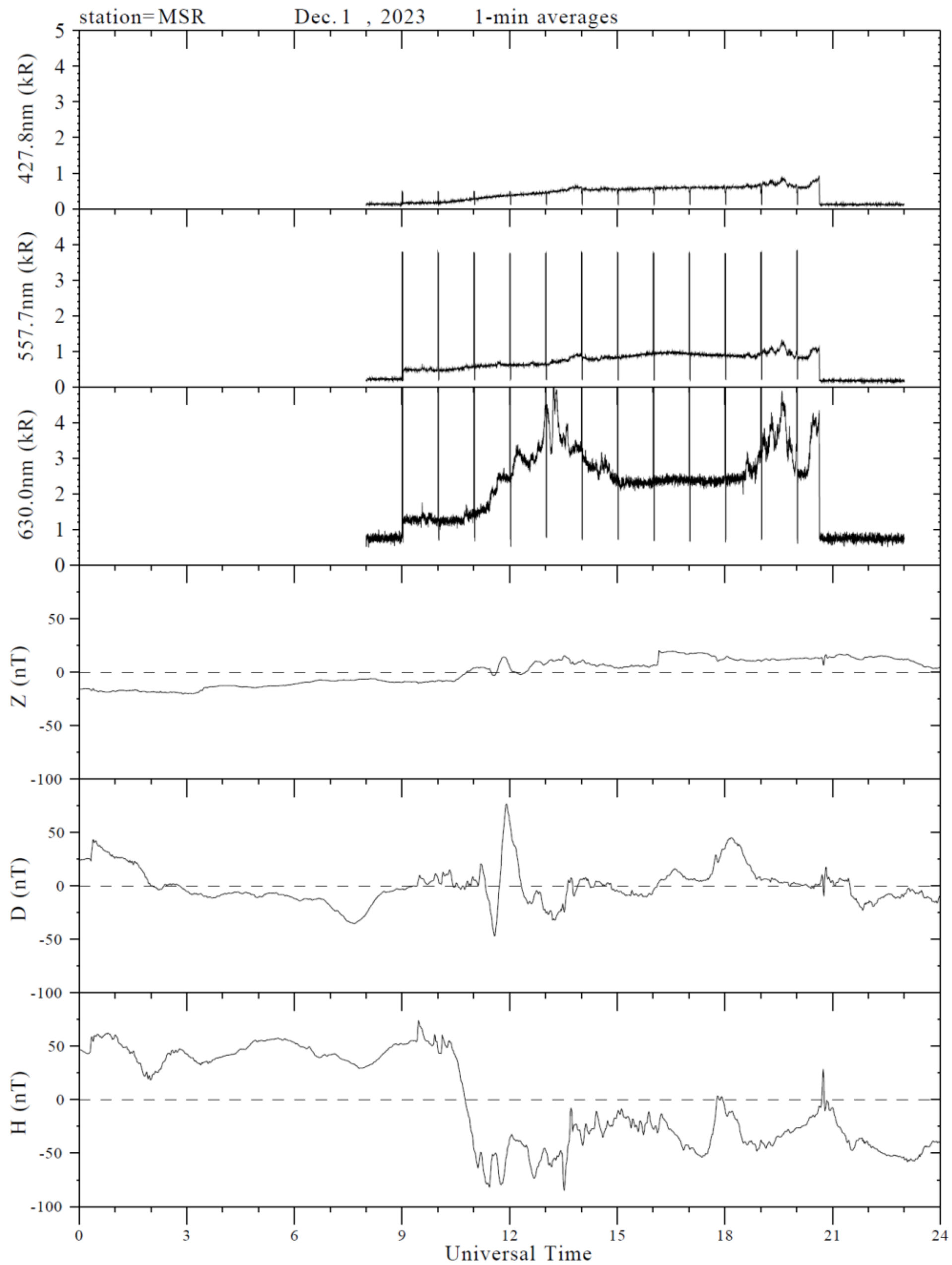

Figure 4. Ground-based monitoring observation at Moshiri Station, Hokkaido. Rapid evolution of the ring current occurred at 1030-1100 UT (bottom panel, magnetometer H-component). After the ring current evolution peak, the red auroral intensity was gradually enhanced from 1130 UT and peaked at 5 kR at 1300-1330 UT (third panel, to geographic north and 15 deg. elevation angle) when the solar wind density was unusually high. The artificial pulse every hour is for the brightneess calibration. After the pre-heating of the photometer from 0800 UT, the photometer observation actually started at 0900 UT by opening the shutter.

3 Satellite observation across the auroral oval

Fortunately, the MetOp3 satellite orbiting at ~830 km altitude passed across the auroral oval from 40 to 70 MLAT (from 21 to 19 magnetic local time (MLT), the pre-midnight sector including the Japan's local time and the MLT) at from 1220 to 1230 UT, respectively. The enhancement of low-energy electrons from 0.2 keV to 8 keV was identified over the auroral oval. Note that the deeper intrusion of the protons compared to the electrons are not surprising at this pre-midnight MLT sector. Although the total integral energy flux (**Figure 5**, top panel) was not beyond the so-called "visible level" of 1 mW/m^2 at the low-latitude boundary, the red aurora can be visible from ground-based observer via the line-of-sight integration in the current case of looking toward near the horizon. As shown in the forth panel of **Figure 5**, it is also found that the ring current particles deeply intruded at around 53~54 MLAT, close to the auroral oval equatorward boundary.

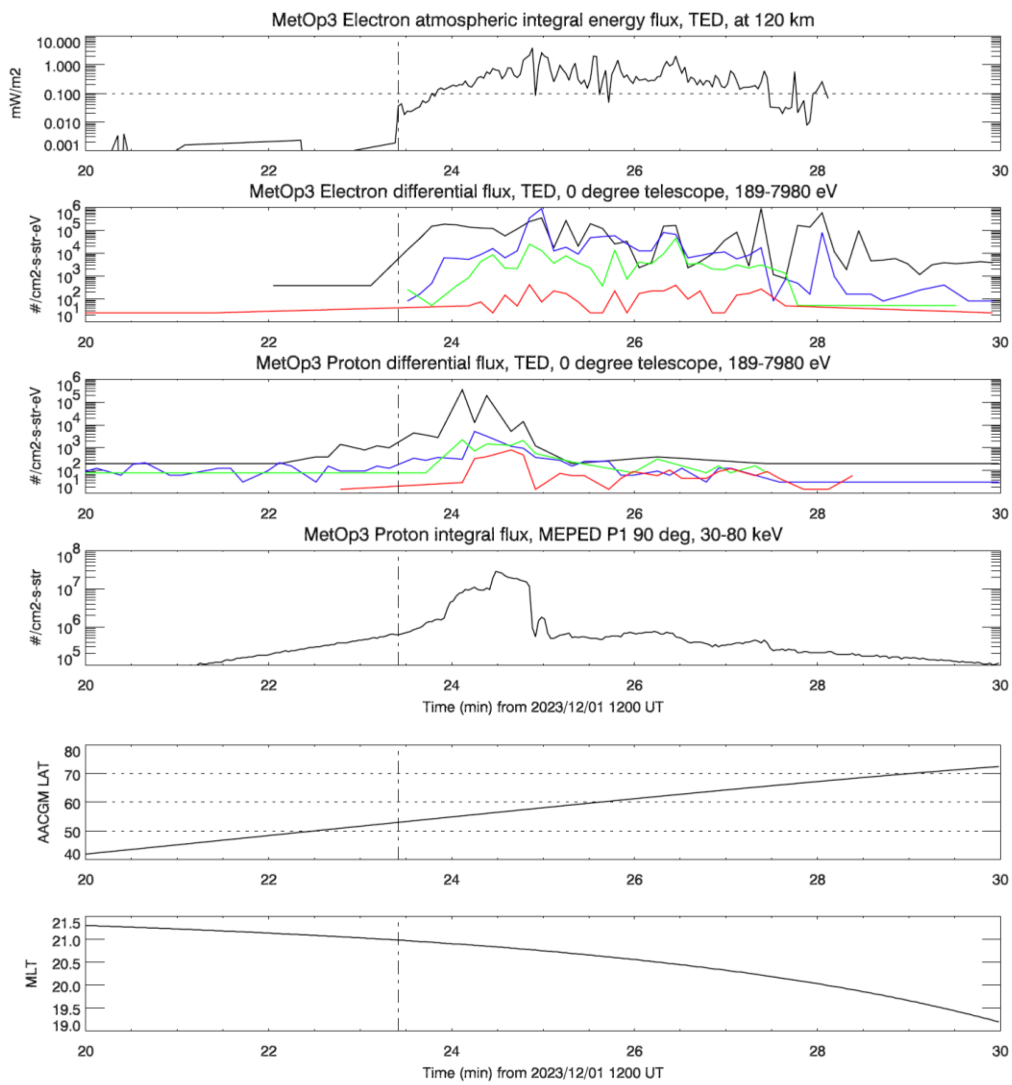

Figure 5. MetOp3 satellite's data across the auroral oval at the pre-midnight MLT sector. The top four panels show the total electron energy flux, electron precipitation differential flux, proton precipitation differential flux, and the trapped proton integral flux at 30-80 keV. The energies of

differential fluxes are 189, 844, 2595, and 7980 eV as colored by black, blue, green, and red, respectively. Bottom two panels show the footprint MLAT of the satellite orbit and the MLT.

As indicated by the vertical dash-dotted lines at 1223:25 UT, the low-latitude boundary of the auroral oval can be identified at ~53 MLAT, and the lowest energy electrons at 189 eV are dominated at the lowest latitude. The low energy electrons are consistent with the red ray-structured aurora as identified from the ground-based photos (**Figure 1**). Yodav et al. (2021) reported the similar characteristic that low energy electrons precipitate at the lowest edge of the auroral oval, which has been considered as one of the important origins of the low-latitude red auroras.

4 Summary and discussions

From the dataset shown above, it is found that the auroral oval actually extended to ~53 MLAT (**Figure 5**), and the top red part of the auroral oval was witnessed and photographed by citizen scientists in Hokkaido (**Figure 3**). We first discuss that both the equatorward extension of the auroral oval to the 53 MLAT and the brightness of the red aurora were unusual for the relatively small amplitude of this magnetic storm with the Dst index peak at -107 nT.

Using the 22-year satellite dataset, Kataoka and Nakano (2021) estimated that possible range of the low-latitude boundary of the auroral oval is 53~57 MLAT for -100 nT Dst levels. The latitude range is along the theoretical curves that the ring current energy corresponds to 10~20 % of the ambient magnetic energy. Therefore, the oval extension of the December 2023 storm locates at the lowest edge of the 22-year statistics.

Note also that, even though they were not seen by naked eyes, red auroras have recently been photographed from Hokkaido during the St. Patrik storm on March 17, 2015 (Dst peak -234 nT, 630.0 nm brightness ~0.5 kR, solar wind density ~30 /cc; see Kataoka et al., 2015) and November 5, 2023 storm (Dst peak -172 nT, 630.0 nm brightness ~1 kR, solar wind density ~30/cc, see Kataoka and Bamba, 2023). The brightness of the red aurora is therefore 5~10 times larger for the December 2023 event, even though the storm amplitude is much smaller than those of St. Patrik storm and November 2023 storm.

The common points of these three storm events are the high solar wind densities and the resultant geosynchronous magnetopause crossing (GMC), i.e. magnetopause size becomes smaller than 6.6 R_E, occurring at the same time of the red aurora appearance. Although the locations of GOES satellites were not at the right positions to observe the GMC event in the December 2023 storm (GOES spacecraft were in the dawn side), the model calculation (Shue et al., 1998) shows that the December 2023 event could also be under the GMC condition (**Figure 2**).

If we seek the differences, the solar wind density of ~50 /cc in the December 2023 event is the largest among these three red aurora events. Further, as shown in **Figure 2**, the ASYM-H index was as large as 150~180 nT, which was 30~50 nT larger than the |SYM-H| of ~130 nT when the red aurora appeared. The large difference between ASYM-H and |SYM-H| means that the partial ring current was highly evolved. Note here that for both the St. Patrik storm and November 2023 storm, |SYM-H| was larger than ASYM-H during the red aurora timings.

In fact, the local storm amplitude ΔH for the December 2023 storm was 141 nT at Japan's Kakioka station, which is significantly larger amplitude than the Dst storm level. Considering the large dynamic pressure of 25 nPa (**Figure 1**), the pressure-corrected ΔH can be 166 nT. Therefore, the storm amplitude was not so small as it looked like from the real-time Dst index.

Another unique point of this December 2023 event is the large-amplitude bipolar D-component variation during the red aurora appearance (**Figure 4**), which is related to the unusually large ASYM-D index in **Figure 1**. The bipolar variation can be explained by the expansion and the westward motion of the so-called substorm "current wedge" current system, i.e. the positive and negative D-component peaks at middle latitude correspond to the upward and downward field-aligned currents, respectively. It is common that the red aurora appearance as seen from Japan was associated with storm-time substorms (Shiokawa et al., 1994; 2005), but the unusually large amplitude of the D-component variation for this event indicates that the substorm's current system was located so close to the Earth.

In summary, it was found that the unusually bright red aurora in the December 2023 storm was the product of the combinations of 1) extremely high solar wind density (strongly compressed magnetosphere), 2) unusually low-latitude extension of the auroral oval (deep intrusion of ring current particles), 3) large ASYM-H index (asymmetric ring current), and 4) the large-amplitude bipolar D-component variation and unusually large ASYM-D index (near-Earth substorm current system evolution).

As the physical mechanism, the drift loss of ring current particles across the magnetopause (e.g., Keika et al., 2005) can naturally connect these four characteristics as follows. Given a strong plasma injection occurred associated with the storm-time substorm (#4), the auroral oval accordingly extended to low latitude associated with the deep intrusion of the ring current particles (#2). The contribution of the injected particles to the magnetic storm amplitude was, however, limited because of the large amount of the drift loss of the ring current particles across the unusually small magnetopause (#1), which also caused the evolution of the largely asymmetric ring current (#3).

In additional to the basic hypothesis described above, other different density effects on the auroral oval intensity might also boost the brightness of the December 2023 event. For example, Shue et al. (2002) showed that the density effect of the nightside auroral intensity is strong in the winter season during the SBZ conditions. Therefore, the ionosphere may play some roles, although the exact mechanism has not yet been elucidated. The density effects have also been known as non-linear in the high-latitude auroral current system (Nakano and Kataoka, 2022; Kataoka and Nakano, 2023). In future works, it would therefore be important to investigate the nonlinear density effects on the auroral current system and on the ring current particles in much more details.

Lessons learned from this December 2023 red-aurora storm event would be the importance of citizen science not to miss the rare interesting auroral phenomenon, and the importance of consulting the ASYM-H index or local storm amplitude ΔH in addition to the SYM-H or the Dst index to understand the possibly large space weather impacts associated with the GMC events, as well as to fairly evaluate the actual magnitudes of the super magnetic storms causing the red aurora witnesses events such as preserved in the historical records.

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Open Research

The OMNI-2 1 min data is available from the OMNIWeb (https://omniweb.gsfc.nasa.gov/ow_min.html). SYM-H, ASYM-H, and ASYM-D indices were obtained from WDC Kyoto University (https://wdc.kugi.kyoto-u.ac.jp/aeasy/index.html). The MetOp3 TED and MEPED data were obtained from (https://www.ncei.noaa.gov/data/poes-metop-space-environment-monitor/access/l1b/v01r00/2023/metop03/).

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