



Global Citizen-Science Observations of Fragmented Aurora-Like Emissions

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Abstract. Fragmented aurora-like emissions (fragments) are small-scale green E-region structures that have previously been reported mainly from high-latitude locations near the poleward auroral oval boundary. Here we present a global citizen-science dataset of 26 fragment observations from 2017 to 2025, collected through an international citizen-science campaign via the Skywarden platform. The observations span magnetic latitudes from approximately 53 to 76°, a wide range of magnetic local times and activity levels, both hemispheres, and diverse auroral conditions. The dataset substantially extends the observational record of fragments beyond previously reported high-latitude regions. Both isolated (type I) and quasi-periodic, wave-like (type II) fragments are represented in this broader geographical context.

To assess fragment locations relative to the auroral oval, three case studies combining satellite observations with ground-based auroral images were analysed in detail. These demonstrate that fragments occur poleward of the oval in Antarctica, equatorward of the oval in Manitoba, and within the oval near the diffuse-discrete boundary in Iceland. Together, the global dataset and case studies show that fragments occur across a much broader range of auroral and geomagnetic conditions and oval positions than previously documented. The results demonstrate the scientific value of citizen-science observations for studying short-lived and localised auroral phenomena.

1 Introduction

The ionosphere is a dynamic region, rich in plasma instabilities that create structures on many different scales, some of which are visible in auroral emissions. Even after many decades of exploration, surprising new structures of visible green (557.7 nm) emission have recently been discovered, remarkable due to their very small sizes (Dreyer et al., 2021). Most ionospheric



emissions seen during the night are classified as auroras, caused by precipitation of magnetospheric particles in the atmosphere, or as airglow, caused by chemical processes (Gallardo-Lacourt et al., 2018). The newly discovered green features are puzzling as they do not fit neatly into either category. They are therefore named fragmented aurora-like emissions (FAEs), or simply "fragments". Two previous studies of fragments (Dreyer et al., 2021; Whiter et al., 2021) noted that these structures lack an obvious field-aligned extent and instead often appear to be orientated nearly perpendicular to nearby field-aligned auroral structures. Their green emission suggests that the fragments are associated with processes in the E-region. Fragments are typically short-lived, lasting less than approximately one minute, and have characteristic spatial scales of only a few kilometres (Dreyer et al., 2021). Dreyer et al. (2021) divided fragments into two categories: type I fragments, which appear in isolation, and type II fragments, which appear in quasi-periodic wave-like chains. So far, fragments had mainly been reported from high-latitude locations near the poleward side of the auroral oval (Dreyer et al., 2021; Whiter et al., 2021; Li et al., 2025; Nanjo et al., 2026). Above Svalbard, fragments have also been observed alongside GHOSTs (Geo-magnetic High-bandwidth Optical Spectra from the Thermosphere), pale broadband continuum emission structures (~400–700 nm) (Partamies et al., 2025; Dayton-Oxland et al.).

Another unusual aurora-like phenomenon observed on the equatorward side of the auroral oval is STEVE (Strong Thermal Emission Velocity Enhancement), a narrow subauroral purple-white ribbon-like structure that is linked to strong ion drifts (MacDonald et al., 2018; Archer et al., 2019). STEVE is often accompanied by a green picket-fence structure, consisting of field-aligned rays, and by small-scale green emissions known as streaks, which are occasionally seen at the bottom of the picket fence (Semeter et al., 2020). Semeter et al. (2020) showed that the streaks are narrow, nearly horizontal green structures that appear on the poleward side of STEVE and propagate toward the main STEVE arc. They occur at altitudes of approximately 100–110 km, have characteristic scales of less than 1 km, and typically last only 20–30 s. They are suggested to be produced by direct excitation of oxygen by suprathermal electrons in the ionosphere, rather than by precipitation from the magnetosphere (Semeter et al., 2020). Nishimura et al. (2023) further noted that the picket fence can remain visible even after STEVE itself has faded and that there are cases in which the picket fence and streaks are observed without simultaneously visible STEVE. The similar morphology, short lifetimes, and small spatial scales of fragments and streaks suggest that they may share related small-scale ionospheric generation processes, although the exact generation mechanisms remain uncertain. However, streaks have so far only been reported together with picket-fence structures, whereas fragments have been observed both alone and, in some cases, together with GHOSTs.

Fragments have likely remained largely overlooked in scientific auroral observations until recently because of their short lifetimes and small spatial scales. Over the past two decades, camera technology has become more advanced and is easily capable of capturing small, transient features. In addition, current elevated solar activity has created excellent opportunities to view and capture aurora at lower latitudes as well as in the typical auroral zones. At the same time, affordable smartphones and digital cameras have enabled members of the public to form a large global observing network. The potential of this network has become more and more apparent as citizen scientists have increasingly contributed to auroral research with their images and observational reports (Grandin et al., 2025). Previous citizen-science-based auroral studies have shown that distributed public observations can provide scientifically useful information on auroral occurrence and



morphology, and have led to the identification and investigation of unusual optical phenomena such as STEVE and dunes (MacDonald et al., 2018; Palmroth et al., 2020). Notably, earlier work on fragments included events identified by AuroraZoo (https://www.zooniverse.org/projects/dwhiter/aurora-zoo; Whiter et al. (2021)), a contributory citizen-science project in which volunteers classify science data. Citizen science (and not only public observation) has been highly valuable to the study of fragments, and remains central to research in this work. For this study, the Auroral Research Coordination: Towards Internationalised Citizen Science (ARCTICS) Working Group, supported by the International Space Science Institute (ISSI) in Bern, Switzerland, reached out to the wider citizen science community to collect fragment observations from as many locations as possible (https://collab.issibern.ch/arctics/). The aim was to investigate where fragments can form, under which solar-wind and geomagnetic conditions they are observed, and how their locations relate to the auroral oval.

2 Data collection & methods

2.1 ARCTICS campaign

The ARCTICS working group coordinated an international citizen-science campaign to collect observations of fragmented aurora-like emissions from as many locations as possible. The campaign was promoted through established auroral photography communities, social media platforms, and collaborative initiatives such as SolarMaX, a global observation campaign that united auroral researchers, astronauts, and citizen scientists to build an open-source database of auroral photographs collected over a multi-day interval (https://www.solarmaxmission.com). In addition, ARCTICS members shared campaign information and encouraged submissions within their local and online photography groups. To help contributors classify auroral structures, the ARCTICS team produced and distributed the *ARCTICS Aurora Field Guide for Citizen Science*, which provides visual examples of common forms, while more detailed information is available in the *ARCTICS Aurora Handbook for Citizen Science* (Herlingshaw et al., 2024).

2.2 Skywarden

Skywarden (<http://www.taivaanvahti.fi>) is an online citizen science platform operated by the Ursa Astronomical Association (Finland) that serves as a central repository for visual observations of aurora and other sky phenomena collected by amateur and professional photographers. For this study, the ARCTICS team invited participants from existing auroral photography networks and social media communities to submit candidate fragment events to Skywarden. Each submission consists of time-stamped images and associated metadata (including location, camera settings, and a short descriptive text), which are uploaded together through the web interface. Submissions are reviewed and tagged by experienced moderators who classify the reported phenomena and flag events of particular scientific interest. Many reports originated from regions lacking dedicated auroral instruments, providing a wide geographical spread. While scientific all-sky cameras for auroral observations are limited to fixed sites within the auroral zones, citizen scientists can fill observational gaps from under-represented locations around the world.



2.3 Event selection

85 Candidate fragment observations were retrieved from the Skywarden database from reports marked by moderators as "Fragments (FAE)" in response to the ARCTICS campaign call. Each candidate event was visually inspected for a clear fragment signature, including compact size, short lifetime, green emission, and the absence of obvious field-aligned extent. Events were accepted only when the morphology was consistent with these criteria and when there was no obvious confusion with lens flares or other auroral or aurora-like structures. To distinguish fragments from streaks, events in the subauroral region were
90 examined for evidence of STEVE or picket-fence structures. If either feature was present during the event or in the surrounding time interval, the event was excluded. When discrepancies were identified in the reported event times, the timing used in the compiled event list was determined by cross-checking the submitted images, metadata, accompanying descriptions, and correspondence with the photographers.

2.4 DMSP/SSUSI data

95 In this study, data from the Defense Meteorological Satellite Program (DMSP) satellites were used to determine the position of the auroral oval. Specifically, measurements from the DMSP F17 and F18 satellites were used, which operate in a 101 min polar, Sun-synchronous orbit at an altitude of 840 km. Each satellite carries the Special Sensor Ultraviolet Spectrographic Imager (SSUSI), which images large regions of the auroral zone in far-ultraviolet wavelengths (165–180 nm) (Paxton et al., 2002). SSUSI is a scanning imaging spectrograph in which a rotating mirror scans an area perpendicular to the satellite track during
100 each polar overpass, producing a 16x165 pixel image over 20–30 minutes (Paxton et al., 2002). SSUSI observes auroral emissions in five far-ultraviolet channels. In this study, only the N₂ Lyman–Birge–Hopfield Short (LBHS) band at 140–150 nm was used. The Local Mapping of Polar Ionospheric Electrodynamics (Lompe) code (Hovland et al., 2022) was used to download and plot the SSUSI data.

For each event, the DMSP/SSUSI overpass closest in time to the fragment observation was used as a reference to estimate
105 the fragment location relative to the auroral oval. Because each overpass spans approximately 20–25 minutes, the time corresponding to the swath segment closest to the observer location was used. In some cases, no overpass was available close to the fragment observation, which increases the uncertainty in the oval estimate. Where available, SSUSI imagery provided additional context for identifying the main auroral oval boundaries and classifying the fragment location relative to them. When two overpasses bracketed an observation, they provided a more reliable estimate of the oval location. Events located between the
110 poleward and equatorward boundaries were classified as *auroral* (i.e. within the auroral oval), events equatorward of the oval as *subauroral*, and events poleward of the oval as *poleward*. For reference, the auroral oval under low-to-moderate geomagnetic conditions is typically centred near 65–70° geomagnetic latitude and expands during enhanced geomagnetic activity (Maffei et al., 2023).



2.5 Solar wind parameters & magnetic indices

115 Solar wind parameters and geomagnetic indices were retrieved from the OMNI database hosted by NASA's Space Physics Data Facility (SPDF) via OMNIWeb (Papitashvili, Natalia E. and King, Joseph H., 2020). This study used the 1-minute OMNI dataset, which provides solar wind and geomagnetic parameters propagated to the Earth's bow shock nose, including the interplanetary magnetic field (IMF) components (B_t , B_y , B_z), solar wind speed (v), proton number density (ρ), and auroral electrojet indices (AU, AL) (World Data Center for Geomagnetism et al., 2015). We use 1-minute OMNI data for their higher
120 temporal resolution, but note that the OMNI propagation delay is uncertain and can differ from statistically estimated values (Tasnim et al., 2025). The half-hourly Hp30 index from GFZ Potsdam, derived from the Hpo dataset (Matzka et al., 2022), was used to classify geomagnetic activity as low (<3), moderate (3–4), elevated (5–6; minor storm), or high (≥ 7 ; strong storm), following commonly used activity categories (British Geological Survey, 2026).

3 Results

125 We classified 26 fragment observations according to the event selection criteria outlined in Section 2.3. These fragment events are presented in Appendix A (Table A1). The full set of images for all events is available on Skywarden, with links provided in the event list in Appendix A. Figure 1 shows representative fragment images from six observing sites selected from our compiled event list. These examples illustrate the range of observing conditions and morphologies present in the observations. Figures 1a, c, d, and f show type II (chain) fragments, whereas Fig. 1b and e show type I (isolated) fragments.

130 We first present the location distribution, IMF B_z driving conditions, and the level of geomagnetic activity for all fragment events. We then select three cases with complementary DMSP/SSUSI data to assess the position of the fragments relative to the auroral oval. For each case study, we provide a detailed description of the observations and the corresponding solar wind and geomagnetic conditions.

3.1 Event distribution & background conditions

135 Figure 2 shows the locations of all 26 fragment events in geomagnetic and geographic coordinates. The events were observed from 2017 to 2025, spanning all months except May and August. Figure 2a shows a geographic map of the observer locations labelled by event number (see Table A1 for site names). The observations are distributed across auroral and subauroral regions in several continents and in both hemispheres. Figure 2b shows a magnetic local time (MLT) versus magnetic latitude (MLAT) plot for all of the fragment events. The geomagnetic activity for each event is colour coded by Hp30 into four levels: low
140 (yellow), moderate (mint green), elevated (cyan-blue), and high (dark blue). The events cover a wide range of MLTs and MLATs, showing that fragments occur throughout the day-night cycle and across a broad latitude range. Figure 2c shows MLAT versus AL for each event, colour-coded to IMF B_z . The mean values for AL and IMF B_z were calculated over the one-hour interval before the start of each fragment event. Three distinct populations emerge: low-activity events at high-latitude, moderate-activity events at mid-latitude, and high-activity events at low-latitude, as also visible in Fig. 2b. More negative B_z ,

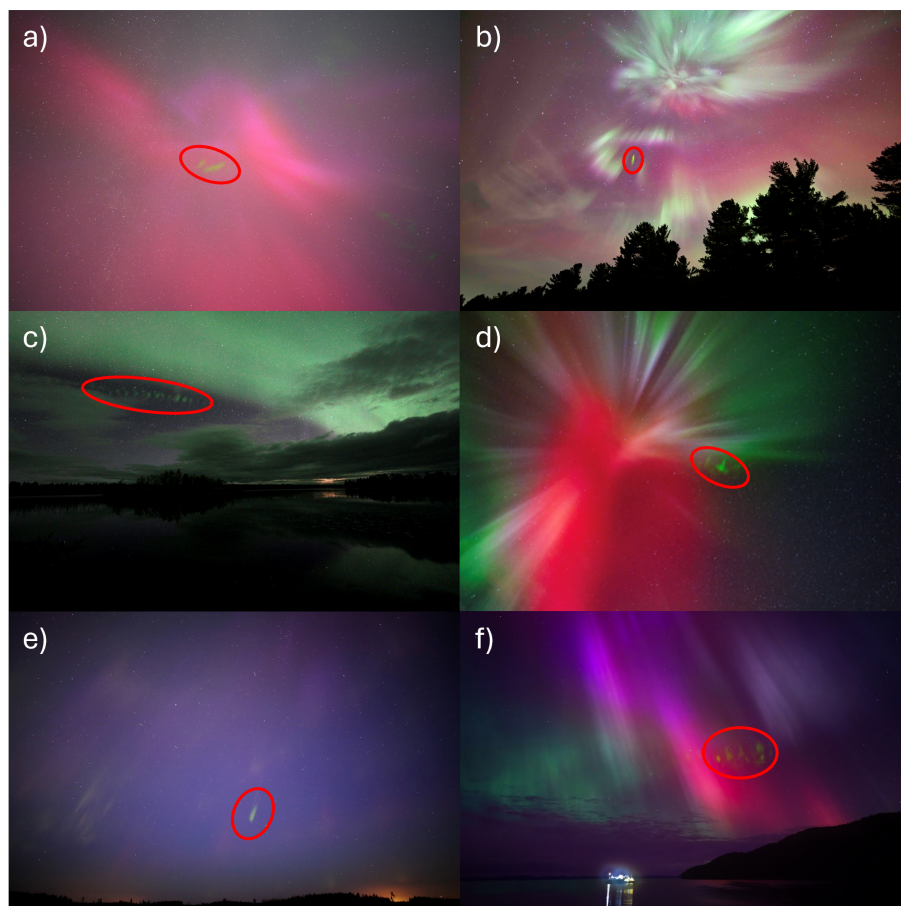


Figure 1. Example fragment observations from (a) Longyearbyen (Svalbard; Event 18), (b) Michigan (USA; Event 20), (c) Enontekiö (Finland; Event 10), (d) Arjeplog (Sweden; Event 25), (e) Kouvola (Finland; Event 15), and (f) Chugach (Canada; Event 23). Fragments are indicated by red circles in each panel.

145 more negative AL, and higher H_p30 values are associated with equatorward oval expansion, which can make fragments visible at lower latitudes. Note that fragment locations may differ from observer locations when cameras point far from zenith, which can shift the fragment position in MLAT and MLT.

3.2 Relation to auroral oval

Three events were selected for detailed analysis of fragment locations relative to the auroral oval: one located within the auroral oval (Iceland; Event 17), one near the equatorward boundary (Manitoba; Event 22), and one near the poleward boundary in the Southern Hemisphere (Antarctica; Event 6). These cases were chosen to compare fragments observed under distinct auroral conditions and to assess whether they can form at different locations relative to the auroral oval, beyond the previously reported locations. The selected events had suitable DMSP/SSUSI coverage and sufficient optical information to determine

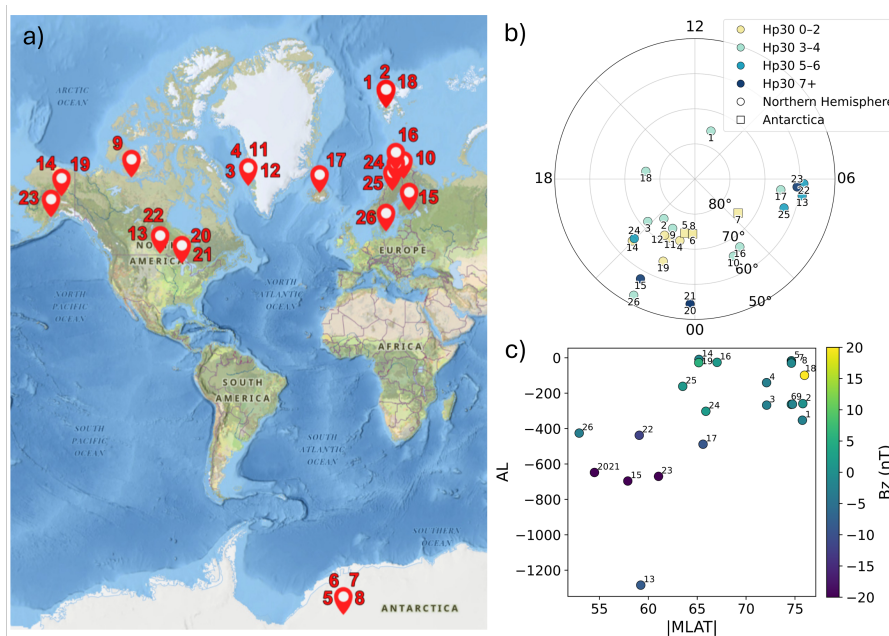


Figure 2. Distribution of fragment events, which are labelled by event number. Panel (a) shows the geographic observer locations overlaid onto a world map created using National Geographic MapMaker. Panel (b) is a MLT/MLAT polar plot colour coded to Hp30 activity as low (<3), moderate (3–4), minor storm (5–6), or strong storm (≥ 7). Northern (southern) hemisphere points are represented with circles (squares). Panel (c) is an MLAT vs. AL plot, with colour indicating the IMF B_z strength and direction.

the viewing geometry. The optical information was obtained either from the metadata and descriptive text submitted with the Skywarden observations or from image-based assessment of camera pointing by manually matching visible star constellations with Stellarium version 25.3 (Zotti et al., 2021). For each case, we describe the optical observations and imaging setup, determine the event location relative to the auroral oval using the available DMSP/SSUSI overpasses, and summarise the concurrent geomagnetic and solar wind conditions.

3.2.1 Within the auroral oval

On 21 October 2023, fragments were observed over Guesthouse Brekka, south of Húsavík, Iceland (65.84° N, 17.34° W geographic; 65.29° MLAT and 05:31 MLT at the event start). The event occurred between 05:31 and 06:06 UTC and is listed as Event 17 in Appendix A (Table A1).

The observations were made by citizen scientist Olivier Staiger, who used two Canon EOS R-series cameras with fisheye lenses for timelapse imaging and a Sony a7s2 with a Sigma 20 mm f/1.4 lens and a speedbooster, operated at f/1.0.

The aurora was very active and variable over several hours, alternating between all-sky and half-sky coverage, with occasional corona forms and intervals of weaker emission followed by renewed brightening. During the fragment interval, diffuse pulsating aurora was visible toward the southern side of the sky, while a brighter active band was present toward the northern



side. The fragments appeared between these two regions, at the transition between the diffuse and discrete aurora. Both chain-like fragments (type II) and individual fragments (type I) were observed. The active band was green, with blue/purple auroral emission visible above it. The solar zenith angle at the time of the event was 107° , indicating twilight conditions and sunlit aurora. Sunlit aurora refers to the enhancement of blue/purple N_2^+ emission by resonance scattering of sunlight at sufficiently high altitudes that remain illuminated (Jokiahho et al., 2009).

Supplementary material includes two videos of this event: a real-time video recorded with a handheld Sony a7s2 camera, spanning 05:40–05:42 UTC, and a timelapse video recorded with a Canon EOS R-series, spanning 05:10–06:06 UTC. The supplementary videos are available on Zenodo (Mielke et al., 2026). The real-time video was recorded at 25 fps, whereas the timelapse video was assembled from 811 individual images into a 30 fps video. The event begins with type II fragments at 05:31 UTC, followed by two type I fragments at 05:32 UTC. Figure 3a shows a frame extracted at 05:41 UTC from the real-time video, and Fig. 3b shows a frame extracted at 05:41 UTC from the timelapse video. Both frames show the same type II fragment sequence at the same time, but from two cameras with different pointing directions.

The boundaries of the auroral oval were determined using DMSP/SSUSI overpasses from satellites F18 and F17. DMSP data over Iceland were recorded at 04:41 UTC and 06:08 UTC for DMSP F18 and F17 respectively. The observer's location, south of Húsavík, Iceland (65.29° MLAT, 05:31 MLT), is indicated by a red cross in Fig. 4. The F18 overpass occurred approximately 50 minutes before the event started at 05:31 UTC, while the F17 overpass was approximately 2 minutes after the event ended. The satellite measurements confirm that Iceland was within the auroral oval at both overpass times. Since the event took place between those overpasses, the observer location in Iceland was most likely within the auroral oval during the event. This statement is also reinforced by the position of the aurora within the images. The fragments appear close to the zenith, whereas auroral emission is visible both to the south and to the north of the fragments, which gives further evidence that the event occurred within the auroral oval.

Figure 5 shows the solar wind and geomagnetic conditions from 03:00 to 08:00 UTC on 21 October 2023. In Fig. 5a, the IMF B_z component remains negative during the interval, at around -8 to -10 nT, indicating persistent southward IMF and favourable conditions for dayside magnetopause reconnection (Trattner et al., 2021). Figure 5a also shows that B_t stays high, near 10 nT over the whole period.

In Fig. 5b, the solar wind speed remains low, mostly between 320 and 350 km/s, without distinct spikes. Figure 5c shows that the proton density is elevated, ranging between ~ 10 and 17 n/cc, suggesting a more dense or compressed solar wind.

The value of H_p30 was 4.667 at the time of the event, indicating moderate geomagnetic activity. In Fig. 5d, the AL and AU indices further show that auroral electrojet activity was elevated but variable around the time of the event. The AL index reached approximately -750 nT ~ 1.5 –2 h before the event and again approximately half an hour afterward, whereas during the event itself it was less negative, around -500 to -300 nT. Similarly, the AU index exceeded 250 nT approximately 1.5–2 h before the event start, but was lower during the event, at 130 nT. These values indicate that the fragments occurred during an active interval, although not at the time of the strongest electrojet activity.

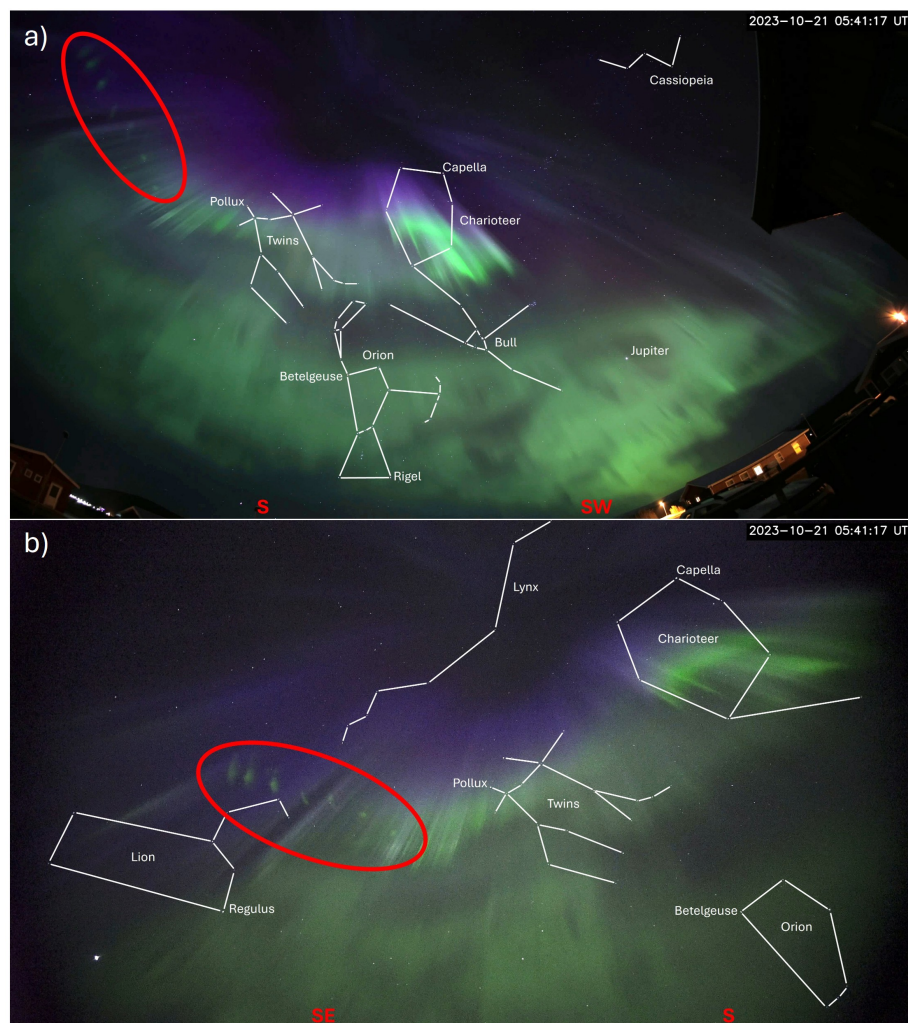


Figure 3. Fragments (indicated by red ovals) observed south of Húsavík, Iceland, on 21 October 2023 at 05:41 UTC, shown from two different cameras: (a) a handheld Sony a7s2 and (b) a Canon EOS R6. The two panels show the same event at the same time from different viewing angles, and overlaid star constellations are used to determine the camera pointing direction, which is marked in red at the bottom of each panel.

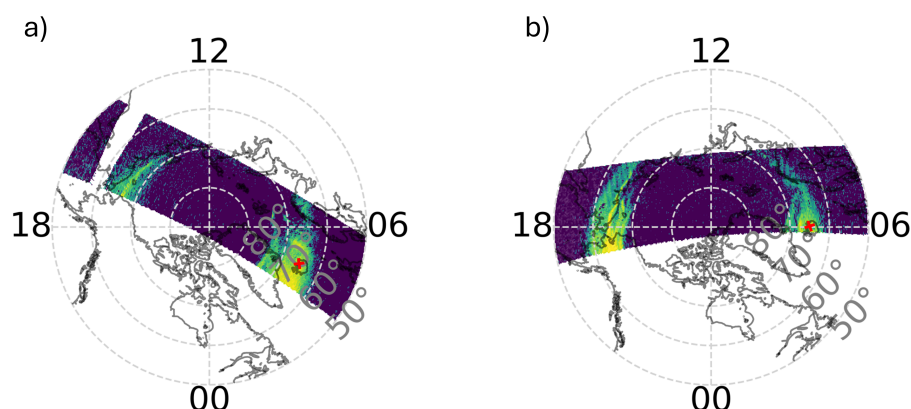


Figure 4. DMSP/SSUSI observations for the Iceland event: (a) F18 auroral oval overpass from ~04:24–04:46 UTC, collecting data over Iceland at 04:41 UTC and (b) F17 auroral oval overpass from ~05:50–06:12 UTC, collecting data over Iceland at 06:08 UTC. The red cross marks the observer location near Húsavík, Iceland (65.29° MLAT, 05:31 MLT).

3.2.2 Equatorward of the auroral oval

Fragments were recorded over Plumas, Manitoba, Canada, on 9 November 2024. The observation site is located at 50.39° N, 99.09° W geographic, corresponding to 58.87° MLAT and 05:50 MLT at the event start. The event lasted from 12:18 to 12:20 UTC and is listed as Event 22 in Appendix A (Table A1).

205 The event was documented by citizen scientist Donna Lach. It was observed under clear skies just before dawn. The aurora was active, with bright structures covering roughly half of the sky. The main auroral activity was located north of the observation site, almost overhead, with faint diffuse aurora visible directly above, and no aurora visible toward the south. At the time of observation, the solar zenith angle was approximately 103°, consistent with the observed sunlit aurora, visible as pink/purple emission. A small chain of fragments appeared at the boundary of the active aurora. Figure 6 shows the auroral display at
210 12:19 UTC, including tall rays in the northern part of the sky and a small chain of fragments marked by the red circle. Star constellations in the image were used to determine the camera facing direction as approximately north, placing the active auroral oval just poleward of the camera field of view.

The absence of aurora toward the south indicates that the fragments were observed near the equatorward edge of the auroral activity.

215 The position of the auroral oval was determined from the DMSP/SSUSI F17 satellite. DMSP data over the observer location in Manitoba were recorded at 11:43 UTC on the day of the event. In Fig. 7, the observer location is marked by the red cross at 58.87° MLAT and 05:50 MLT. Although this overpass occurred approximately 35 minutes before the fragment event (12:18–12:20 UTC), it places the observer near the equatorward edge of the auroral oval, in agreement with the image-based interpretation.

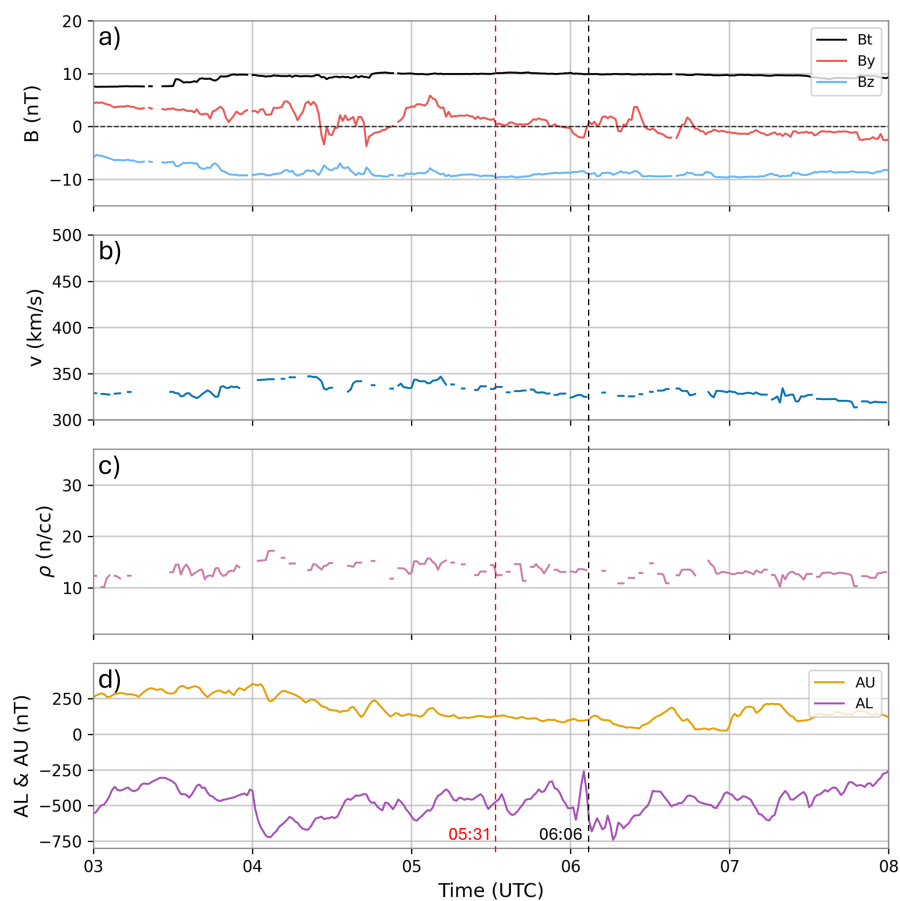


Figure 5. OMNI solar wind parameters and geomagnetic indices for the Iceland event on 21 October 2023. Panel (a) shows the interplanetary magnetic field (IMF) components B_t (black line), B_y (red line), and B_z (light blue line), panel (b) the solar wind speed v , panel (c) the proton number density ρ , and panel (d) the AU and AL indices. The dashed red line marks the event start (UTC) and the dashed black line marks the event end (UTC).

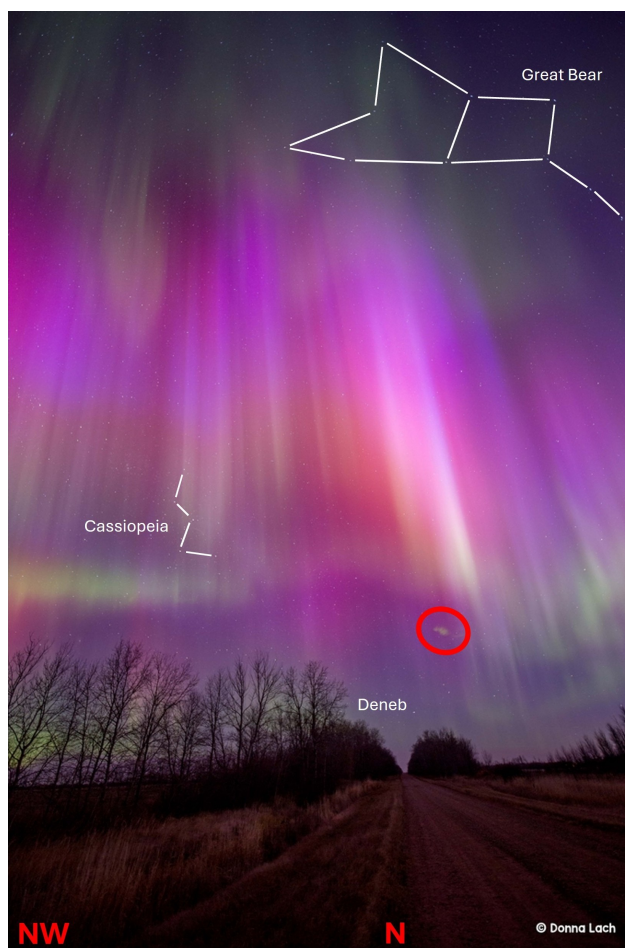


Figure 6. Fragments (indicated by a red circle) observed close to Plumas, Manitoba, Canada on 9 November 2024. Overlaid star constellations are shown to resolve the camera pointing direction, which is marked in red at the bottom of the image.

Figure 8 provides the solar wind and geomagnetic parameters for the Manitoba event over the interval 10:00–15:00 UTC on 9 November 2024. In Fig. 8a B_y oscillates around zero, while B_z is mostly negative around -10 nT before the event, although there is a brief excursion to positive B_z just after the event. B_t remains relatively steady at 10–14 nT before the event and becomes more variable afterward. Figure 8b shows the solar wind speed, ranging from 380 to 420 km/s. The proton density in Fig. 8c decreases from ~25 n/cc to values between 10 and 15 n/cc before the event and rises again to around 35 n/cc afterward, with large density variations. Large density variations reflect changes in solar wind dynamic pressure and can drive magnetospheric compression and variability (Madelaine et al., 2022).

At the time of the event, H_p30 was 5.33, indicating elevated geomagnetic activity, reaching minor storm levels. Figure 8d shows AU and AL indices. Before the event, AU stays near 0 nT and AL fluctuates between -250 and -500 nT, indicating an

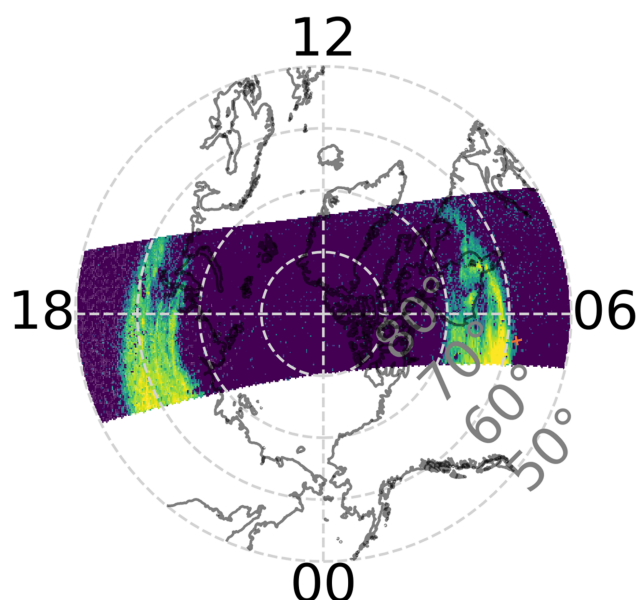


Figure 7. DMSP/SSUSI observation for the Manitoba event, showing the F17 auroral oval overpass from ~11:35–12:00 UTC, collecting data over the observer location at 11:43 UTC. The red cross marks the observer location in Plumas, Manitoba, Canada (58.87° MLAT, 05:50 MLT).

enhancement in the westward electrojet. After the event, AU climbs to ~400 nT, while AL oscillates around -250 nT before
230 dropping sharply to -750 nT near the end of the interval, indicating intensified auroral activity and geomagnetic disturbance.

3.2.3 Poleward of the auroral oval

On 9 June 2019, fragments were observed near the geographic South Pole in Antarctica (90° S, 90° E geographic; -74.32° MLAT, 23:50 MLT at the event start). The event occurred between 03:20 and 05:00 UTC and is listed as Event 6 in Appendix A (Table A1).

235 The observations were made by photographer and astrophysicist Benjamin Eberhardt using a Sony ILCE-7RM3 camera with a focal length of 14 mm, aperture f/1.8, 10 seconds exposure, and ISO 4000. The camera was on a motorised tripod that was moving against Earth's rotation, capturing a 25-hour time-lapse near the South Pole Telescope (SPT). During this interval, several fragments appeared: a single fragment at 03:20 UTC, multiple fragments at 03:52 UTC, and a fragment chain at 04:57–05:00 UTC (Fig. 9). A segment of the timelapse is provided as supplementary video material on Zenodo, in which the
240 fragments are visible (Mielke et al., 2026). Faint fragments are also visible at 04:41 UTC, but since high-resolution raw files are not available for this case, this occurrence is excluded from the analysis. A faint off-white emission is present near the end of the event and appears at the same time as the fragment chain (around 04:57 UTC). The off-white emission appears together with the fragment chain, drifts together with the fragments for a short interval, and then disappears again. This co-temporal evolution and colour could suggest that the off-white emission is a continuum emission.

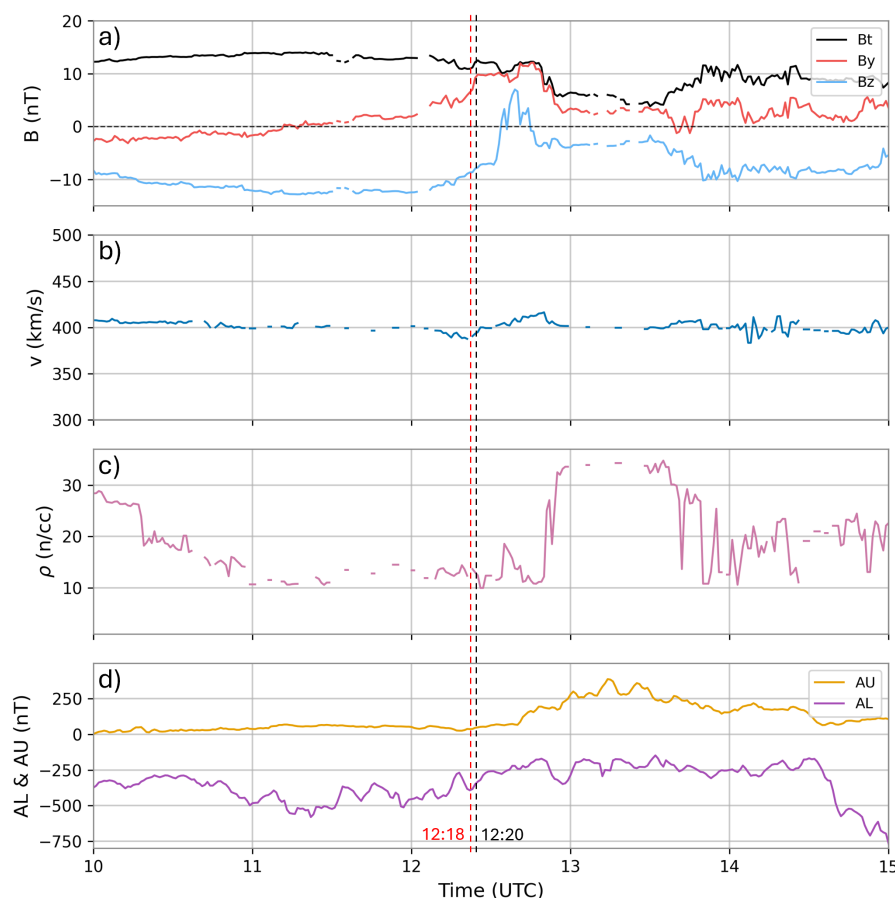


Figure 8. OMNI solar wind parameters and geomagnetic indices for the Manitoba event on 9 November 2024. The format and plotted parameters are the same as in Figure 5. The dashed red line marks the event start (UTC) and the dashed black line marks the event end (UTC).

245 The sky was clear and the aurora was bright and active during the polar night. The solar zenith angle during the observation was 113° , indicating that there were no twilight or daylight effects.

The DMSP/SSUSI F18 overpass covered approximately 02:55–03:19 UTC, with the data point closest to the observer location at 03:08 UTC, and the F17 overpass covered approximately 03:15–03:39 UTC, with the closest data point at 03:29 UTC. Together, these overpasses bracket the event start at 03:20 UTC and provide a good estimate of the auroral oval configuration
250 equatorward of the observer, although no direct coverage exists over the observer location itself.

The location of the observer close to the geographic South Pole (-74.32° MLAT, 23:50 MLT) is marked with a red cross on the DMSP/SSUSI plots in Fig. 10. The DMSP/SSUSI data show the main auroral emission just equatorward of the red cross. A quiet, contracted oval typically places its poleward boundary between $70\text{--}75^\circ$ MLAT during quiet times (Feldstein

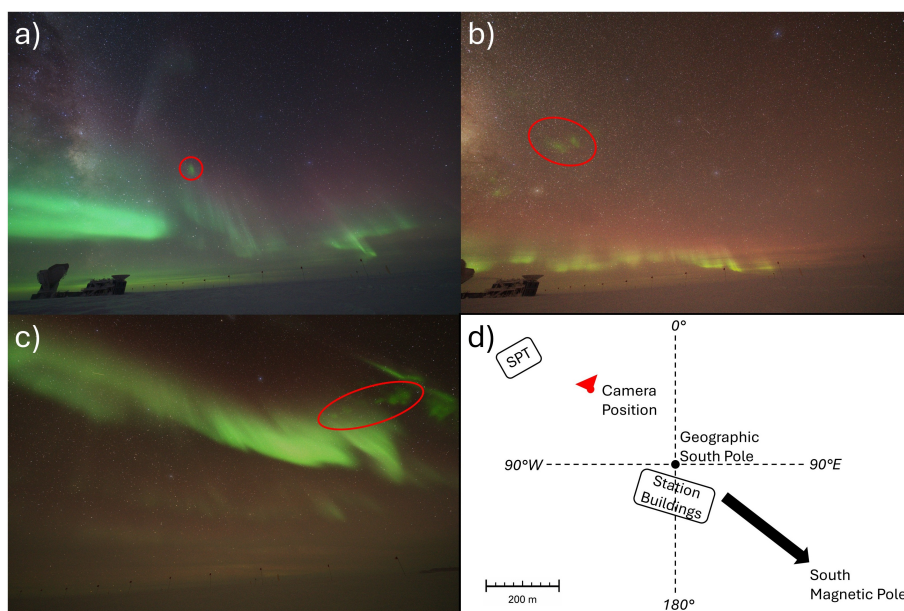


Figure 9. Fragments (indicated by red ovals) observed close to the geographic South Pole in Antarctica on 9 June 2019 at (a) 03:20 UTC, (b) 03:52 UTC, and (c) 04:57 UTC. Panel (d) is a sketch showing the camera position and viewing direction at the Amundsen-Scott Station relative to the geographic and magnetic poles.

and Starkov, 1967). Although the fragment position relative to the auroral oval cannot be established from the satellite data alone, the satellite observations suggest that the observer was located near the poleward side of the auroral oval.

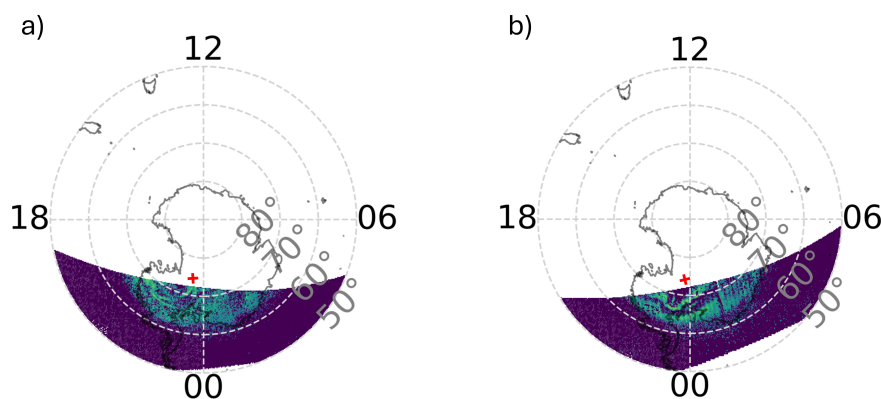


Figure 10. DMSP/SSUSI observations for the Antarctica event: (a) F18 auroral oval overpass from ~02:55–03:19 UTC, collecting data closest to the observer location at 03:08 UTC and (b) F17 auroral oval overpass from ~03:15–03:39 UTC, collecting data closest to the observer location at 03:29 UTC. The red cross marks the position of the observer, close to the geographic South Pole (-74.32° MLAT, 23:50 MLT).



Typically, the camera orientation can be determined from the positions of star constellations in the sky. However, close to the geographic South Pole this method becomes unreliable. Therefore, in this case, the viewing direction of the camera was determined from its location relative to the geographic and magnetic poles instead. The camera was placed between the SPT and the geographic South Pole, facing away from the Pole (towards the equator). In this orientation, the South Magnetic Pole is behind the camera, as shown in the sketch in Fig. 9d. The aurora in Fig. 9a and b is close to the horizon, and no aurora is visible poleward of the fragments in these images. This observation provides additional evidence that the fragments in this event are located at the poleward boundary of the auroral oval.

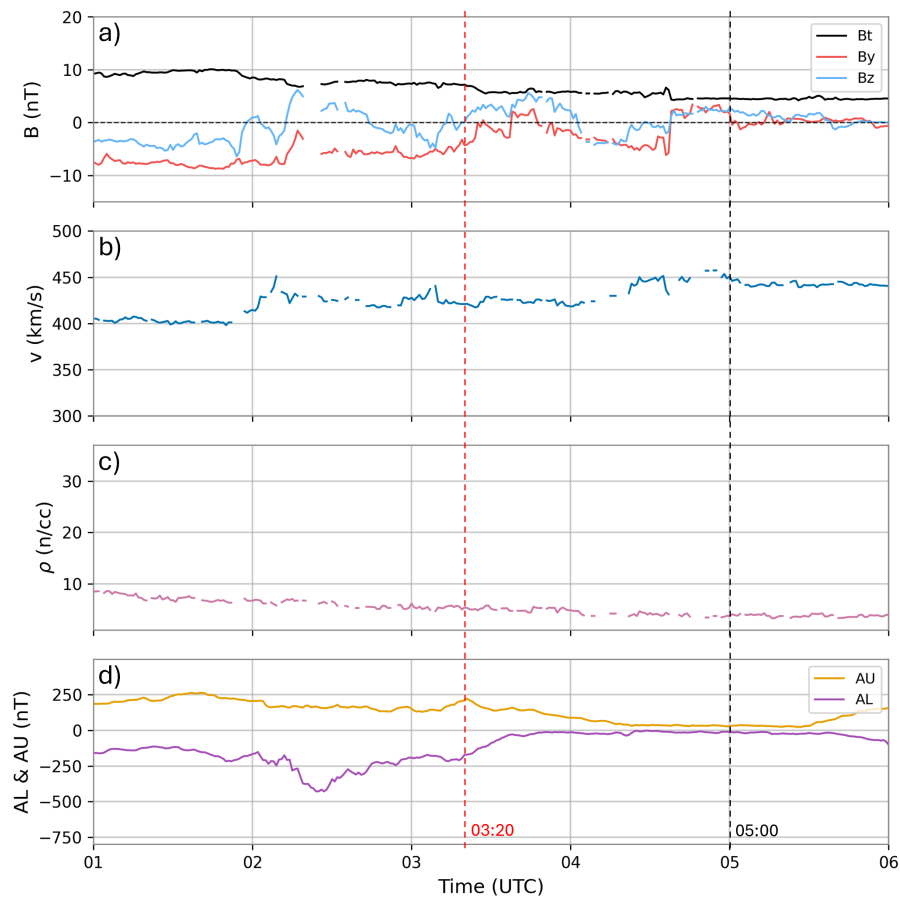


Figure 11. OMNI solar wind parameters and geomagnetic indices for the Antarctica event on 9 June 2019. The format and plotted parameters are the same as in Figure 5. The dashed red line marks the event start (UTC) and the dashed black line marks the event end (UTC).

Figure 11 displays the solar wind and geomagnetic parameters for two hours before and after the event start at 03:20 UTC. The IMF components B_y and B_z fluctuate around zero throughout the interval, without prolonged southward B_z . Repeated northward turnings of IMF B_z are expected to reduce the efficiency of solar wind-magnetosphere coupling, since even brief northward excursions can place the magnetosphere-ionosphere system in a reduced state of coupling (Pham et al., 2016). B_t



decreases from ~10 to 5 nT. The solar wind speed remains moderate throughout the interval, increasing stepwise from ~400 to 450 km/s. The proton density gradually decreases during the interval and is relatively low, which supports that the solar wind is not particularly compressed or turbulent.

270 Geomagnetic activity was low during the event with the Hp30 value at 2.0. The AU and AL indices show elevated activity before the event start, with AL reaching below -400 nT. This suggests moderate substorm activity in the time before the fragment observations. Around the event start (03:20 UTC) and during the following period, both AU and AL indices decrease, indicating reduced electrojet intensity and quieter geomagnetic conditions. AU and AL are derived from selected Northern Hemisphere auroral-zone observatories (Wu and Ridley, 2024), whereas SMU and SML (not shown) are based on a more
275 extensive magnetometer network and therefore are less restricted by the coverage of Northern Hemisphere stations (Waters et al., 2015). However, for the interval considered here, the corresponding SMU and SML variations were similar to AU and AL, so AU and AL are used in all cases in this study for consistency.

The moderate solar wind speed, low proton density, and oscillating B_z without sustained southward orientation, as shown in the plot, correspond well to the observed low Hp30 index, indicating weak solar wind coupling and low geomagnetic activity
280 during this period.

4 Discussion

The ARCTICS citizen-science campaign and the Skywarden platform enabled fragment observations over a much broader geographic range than could be achieved with fixed scientific observatories alone. The dataset presented in Appendix A (Table A1) combines 26 fragment events from both hemispheres and from a wide range of MLATs, MLTs, and auroral conditions. This
285 expanded coverage makes it possible to assess where fragments can occur relative to the auroral oval and under which solar wind and geomagnetic conditions they appear. Public observations provide coverage that fixed scientific imagers cannot easily match, especially for short-lived and localised events, so the study highlights the value of citizen science for studying transient auroral phenomena.

4.1 Fragment occurrence and formation context

290 Overall, the observations show that fragments are not confined to a single set of geomagnetic and solar wind driving conditions. They are seen across a wide range of MLATs and MLTs, from low-latitude high-activity cases to high-latitude quiet-time cases, and in both hemispheres. This suggests that fragment formation is driven by local ionospheric conditions that can arise under different large-scale drivers. This interpretation is consistent with Dreyer et al. (2021), who suggested that fragments are related to local ionospheric instabilities and electron heating rather than to ordinary particle precipitation.

295 The global dataset extends the observational record of fragments beyond the previously reported Svalbard (Dreyer et al., 2021), northern Norway (Nanjo et al., 2026), and Antarctic (Li et al., 2025) cases. It also demonstrates that both type I and type II fragments occur in this wider geographical context, consistent with the morphological classes introduced by Dreyer et al. (2021).



The present dataset is limited by detectability and selection effects. Fragment identification depends on image cadence, exposure time, field of view, sensitivity, and observing conditions (e.g. darkness, cloudiness, measurement frequency and duration), so the event list should not be treated as a normalised occurrence survey. Nevertheless, the dataset supports the conclusion that fragments occur across a broad range of auroral settings and positions relative to the auroral oval. This broadens the known occurrence context of fragments. The diversity of the solar wind driving and geomagnetic conditions indicates that there is no single global cause of the fragments and instead supports the view that they are linked to local ionospheric conditions arising under different large-scale drivers. The present observations do not allow definitive conclusions about the generation mechanism, true occurrence rate, or any causal link to specific solar-wind drivers, and more research is required on these topics.

Fragments may form where strong electric fields, conductivity gradients, or density gradients create conditions favourable for plasma instabilities. Whiter et al. (2021) showed that the fine-scale motion of fragments is consistent with wave-like dynamics in the lower E-region ionosphere, and Nanjo et al. (2026) further suggested that the background electric field and spatial gradients in electron density may influence their formation.

4.2 Fragment locations relative to the auroral oval

The three case studies presented in this paper show that fragments occur at different positions relative to the auroral oval, from poleward (Antarctica) and equatorward (Manitoba) to within the oval near the diffuse-discrete boundary (Iceland). This indicates that fragments are not limited to previously reported poleward locations (Dreyer et al., 2021; Whiter et al., 2021; Nanjo et al., 2026). The events also occurred under diverse auroral conditions, spanning a mixed diffuse-discrete auroral environment with strong activity and pulsations (Iceland), bright sunlit aurora near dawn (Manitoba), and quiet polar night conditions (Antarctica). This supports the idea that fragments are not restricted to particular auroral contexts or light conditions but can occur wherever local conditions are favourable.

In the Iceland case, fragments appear in the region of active aurora, near the boundary between diffuse and discrete aurora. The transition region marks a change in the precipitation regime, with diffuse aurora linked to unaccelerated wave-scattered electrons and discrete aurora linked to field-aligned acceleration (Newell et al., 2009; Han, 2021). Han (2021) showed that diffuse and discrete aurora can occur directly next to each other and drift together, indicating that the boundary is dynamically active rather than a simple visual transition. In that context, auroral precipitation can modify local conductivity and the structure of the electric field in the E-region (Ivarsen et al., 2023, 2024), potentially creating or enhancing small-scale gradients that could support fragment formation. This suggests that the diffuse-discrete boundary may provide favourable conditions for the local ionospheric structuring involved in fragment formation.

The Manitoba case shows that fragments can occur near the equatorward boundary of the auroral oval under sunlit, near-dawn conditions, at lower magnetic latitudes than in previously reported poleward cases. This places fragments in a boundary region more commonly associated with subauroral optical phenomena such as STEVE (Gallardo-Lacourt et al., 2018, 2026). The Antarctica event shows that fragments can occur in the Southern Hemisphere under quiet geomagnetic conditions with a contracted auroral oval. This is consistent with the Antarctic fragment observations from Zhongshan Station (-74.66° MLAT)



reported by Li et al. (2025), who described fragments near the poleward edge of local auroral arcs at a magnetic latitude very similar to our event (-74.32° MLAT).

Together, the three cases suggest that fragments may favour boundaries and transition regions, including not only the auroral oval edges but also internal boundaries such as the diffuse-discrete boundary. A key geometric limitation is that fragments are not necessarily located directly above the observer. When a fragment is observed away from zenith, its estimated MLAT, MLT, and position relative to the auroral oval can differ from the observer coordinates. For example, assuming Cartesian geometry as a first-order approximation, a fragment observed at a zenith angle of 60° (30° elevation) and a typical green-line emission height of 100–110 km would be horizontally displaced by approximately 170–190 km, corresponding to ~ 1.5 – 1.7° in latitude for a north-south displacement. Camera pointing and viewing geometry therefore affect the estimated location of the fragment observations (Wagner et al., 2022). The relation-to-oval classification is also limited by the timing and structure of the DMSP/SSUSI observations. Although the satellite overpass closest to the fragment event times and observer location was used as a reference, the overpass does not coincide exactly with the fragment event, so the identified oval boundaries may differ from the actual auroral configuration at the time of observation. In addition, identifying poleward and equatorward oval limits from the structured ultraviolet auroral emission observed by DMSP/SSUSI is not always straightforward and generally requires dedicated boundary detection methods (Ding et al., 2017). Although both datasets have limitations, the combination of DMSP/SSUSI observations with the auroral images strengthens the robustness of the relation-to-oval classifications and supports the conclusion that the cases cover a wide range of positions relative to the auroral oval.

4.3 Fragments' link to other aurora(-like) forms

The comparison of fragments with other aurora or aurora-like forms is also informative. As in earlier fragment studies, we were careful to distinguish fragments from field-aligned structures such as picket-fence-like forms. The lack of obvious field-aligned extent in our events remains consistent with a lower E-region origin rather than precipitation-driven auroral rays. This distinction remains important because Nanjo et al. (2026) showed that fragments and picket fence structures can occur simultaneously near the poleward edge of the auroral oval, even though they remain morphologically different.

Fragments share morphological similarities with streaks, as both appear as small-scale green structures and are not thought to be caused by particle precipitation. However, unlike streaks, which have so far only been reported with the picket fence and are usually detached from the auroral oval, fragments can occur alone, near auroral arcs, or together with GHOSTs. The Antarctica event points to a possible connection with continuum emission structures. It includes a faint off-white emission that appears co-temporal with the fragment chain and drifts with it. This may represent the first reported Southern Hemisphere GHOST candidate, although a case with spectroscopic measurements is required to be certain. This case is similar to Northern Hemisphere GHOSTs observed at the poleward auroral oval boundary during dynamic aurora with strong ionospheric shear flows and heating (Partamies et al., 2025). Partamies et al. (2025) observed that fragments were seen in all of their GHOST events, and Houghton et al. (2026) similarly noted that some continuum emission structures occur together with fragments. This co-occurrence suggests that fragments and GHOSTs may be related to similar heating or instability processes.



365 Future work would benefit from complementing imaging reports with simple additional instrumentation, such as small spectrometers deployed with experienced citizen scientists. Building on the metadata already available through Skywarden, more coordinated citizen-science campaigns could improve event interpretation and strengthen the link between public observations and scientific instrumentation.

5 Conclusions

370 This study presents a global citizen-science dataset of 26 fragment observations, collected through the ARCTICS campaign and the Skywarden platform. The dataset covers a wide range of MLATs (52.6–75.6°), MLTs, activity levels, and auroral conditions, and includes observations from both hemispheres, demonstrating that fragments are not confined to a single set of geomagnetic or solar wind driving conditions.

The diversity of conditions indicates that there is no single global driver for fragments. Instead, they are linked to local ionospheric conditions that can arise under different large-scale drivers. This interpretation is consistent with previous findings that fragments are related to local ionospheric instabilities and electron heating rather than ordinary particle precipitation (Dreyer et al., 2021; Whiter et al., 2021).

The global dataset extends the observational record beyond previous reports from Svalbard (Dreyer et al., 2021), northern Norway (Nanjo et al., 2026), and Antarctica (Li et al., 2025), and demonstrates that both type I and type II fragments occur in this wider geographical context. Three case studies with complementary DMSP/SSUSI data confirm that fragments occur at different positions relative to the auroral oval: poleward (Antarctica), equatorward (Manitoba), and within the oval near the diffuse-discrete boundary (Iceland). The combination of DMSP/SSUSI observations with auroral images strengthens the robustness of these relation-to-oval classifications.

The cases further show that fragments occur under diverse auroral conditions, including mixed diffuse-discrete environments with pulsations (Iceland), bright sunlit aurora near dawn (Manitoba), and quiet polar night conditions (Antarctica). Together, they suggest that fragments may favour boundaries and transition regions, including not only the auroral oval edges but also internal boundaries such as the diffuse-discrete boundary.

Morphologically, fragments remain distinct from field-aligned structures such as picket-fence forms and share similarities with streaks, but differ in their occurrence contexts. The Antarctica event points to a possible connection with continuum emission structures, representing a potential Southern Hemisphere GHOST candidate. The co-occurrence of fragments and GHOSTs suggests that they may be related to similar heating or instability processes (Partamies et al., 2025; Houghton et al., 2026).

This study highlights the value of citizen science for filling critical gaps in observations of transient, short-lived auroral features. Future work would benefit from complementing imaging reports with portable spectrometers deployed with experienced citizen scientists, to better characterise fragments, their co-occurrence with GHOSTs, and related E-region structures.



Appendix A: Event list

Table A1: Event list of the 26 fragment observations used in this study. Times are given in UTC and follow the format dd-mm-yyyy hh:mm, with start and end times referring to the beginning and end of each observed event. Event no. is the event identifier. Place gives the observing location. Geogr. Lat. and Geogr. Long. give the observer location in geographic coordinates, and Type indicates the fragment morphology observed in the event (I: isolated; II: chains; I & II: both). The final column gives the Skywarden event link.

Event no.	Start in UTC	End in UTC	Place	Geogr. Lat.	Geogr. Long.	Type	Skywarden link
1	18-12-2017 08:05	18-12-2017 08:05	Longyearbyen, Svalbard	78.23° N	15.65° E	I	Event 1
2	17-12-2018 19:10	17-12-2018 19:27	Longyearbyen, Svalbard	78.23° N	15.65° E	I & II	Event 2
3	01-03-2019 23:34	01-03-2019 23:38	Sisimiut, Greenland	66.93° N	53.66° W	II	Event 3
4	09-03-2019 01:48	09-03-2019 02:24	Sisimiut, Greenland ^a	66.93° N	53.66° W	II	Event 4.1; Event 4.2
5	03-06-2019 02:45	03-06-2019 02:45	South Pole	90.00° S	90.00° E	II	Event 5
6	09-06-2019 03:20	09-06-2019 05:00	South Pole	90.00° S	90.00° E	I & II	Event 6
7	26-07-2019 07:15	26-07-2019 07:15	South Pole	90.00° S	90.00° E	I	Event 7
8	30-07-2019 03:29	30-07-2019 03:30	South Pole	90.00° S	90.00° E	I & II	Event 8
9	04-09-2019 07:07	04-09-2019 07:39	Kitikmeot Region, Canada	68.75° N	114.03° W	I & II	Event 9
10	14-09-2020 23:36	14-09-2020 23:40	Enontekiö, Finland	68.38° N	23.63° E	II	Event 10
11	15-12-2020 01:08	15-12-2020 01:47	Sisimiut, Greenland	66.93° N	53.66° W	I & II	Event 11
12	17-12-2020 00:48	17-12-2020 02:32	Sisimiut, Greenland	66.93° N	53.66° W	I & II	Event 12
13	04-11-2021 11:53	04-11-2021 12:41	Plumas, Manitoba, Canada	50.39° N	99.09° W	I & II	Event 13
14	03-12-2021 07:32	03-12-2021 07:32	Fairbanks, Alaska, USA	64.79° N	147.61° W	I	Event 14
15	23-04-2023 19:54	23-04-2023 19:58	Kouvola, Finland	60.89° N	27.17° E	I	Event 15
16	14-10-2023 00:11	14-10-2023 00:23	Samuelsberg, Norway	69.55° N	20.53° E	I & II	Event 16
17	21-10-2023 05:31	21-10-2023 06:06	Guesthouse Brekka, Iceland	65.84° N	17.34° W	I & II	Event 17
18	01-12-2023 14:51	01-12-2023 15:15	Longyearbyen, Svalbard	78.23° N	15.65° E	I & II	Event 18
19	04-10-2024 09:15	04-10-2024 09:20	Fairbanks, Alaska, USA	64.79° N	147.61° W	II	Event 19
20	11-10-2024 05:14	11-10-2024 05:14	Glen Arbor, Michigan, USA ^b	45.13° N	86.06° W	I	Event 20
21	11-10-2024 05:14	11-10-2024 05:14	Glen Arbor, Michigan, USA ^b	45.13° N	86.06° W	I	Event 21
22	09-11-2024 12:18	09-11-2024 12:20	Plumas, Manitoba, Canada	50.39° N	99.09° W	I	Event 22
23	01-01-2025 16:30	01-01-2025 16:40	Chugach, Alaska, USA	60.68° N	147.19° W	II	Event 23
24	01-01-2025 19:23	01-01-2025 19:28	Abisko, Sweden	68.35° N	18.83° E	II	Event 24
25	01-02-2025 03:30	01-02-2025 03:30	Arjeplog, Sweden	66.05° N	17.88° E	I & II	Event 25
26	19-03-2025 21:00	19-03-2025 21:05	Karlskrona, Sweden	56.17° N	15.66° E	I	Event 26

^a Event 4 combines two Skywarden submissions from the same observer, separated by approximately 10 minutes, and treated here as one fragment episode.



^b Events 20 and 21 are listed separately because they were reported by two different observers, although they captured the same
400 fragment occurrence at the same time.

Code and data availability. The fragment observation dataset, including the associated images and event metadata, is available on the Skywarden platform at <https://www.taivaanvahti.fi/>. Auroral-oval reference data were obtained from DMSP/SSUSI observations, which were downloaded and plotted using the Lompe Python package (<https://doi.org/10.3389/fspas.2022.1025823>; Hovland et al., 2021). Solar wind data were downloaded from OMNIWeb (OMNI 1-min Data, <https://doi.org/10.48322/45bb-8792>; Papitashvili and King, 2020). The Hp30
405 geomagnetic index was obtained from GFZ Potsdam (Hpo Data Service, <https://doi.org/10.5880/Hpo.0002>; Matzka et al., 2022). The AE index (AU, AL) was obtained from the World Data Center for Geomagnetism, Kyoto (Geomagnetic AE index, <https://doi.org/10.17593/15031-54800>; World Data Center for Geomagnetism, Kyoto et al., 2015). The basemap used in Fig. 2a was created with National Geographic MapMaker (<https://www.arcgis.com/apps/instant/atlas/>).

Video supplement. The supplementary videos for the Iceland and Antarctica case studies are available on Zenodo (<https://doi.org/10.5281/zenodo.20811717>; Mielke et al., 2026)
410

Author contributions. LM led the study, performed the data analysis, generated plots, and wrote most of the manuscript. KH contributed substantially to the analysis, generated plots, provided text input, and helped shape the manuscript. NP contributed through intensive discussions and feedback during the development of the paper and helped shape the manuscript. MG, EB, DL, MS, RDO, EK, and VL contributed to the discussions leading to the paper and assisted with event selection from the Skywarden database. DL and MS contributed their own images,
415 while EB and EK helped encourage submissions to Skywarden and tag images as potential fragment candidates. MG, EB, and AS provided feedback on the manuscript. RDO also provided text input. BE and OS provided data/images and assisted with their analysis through raw data, photographic insight, and metadata.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This research was supported by the International Space Science Institute (ISSI) in Bern, Switzerland, through ISSI
420 Working Group project ARCTICS. Financial support is provided to Lena Mielke and Katie Herlingshaw by the Research Council of Norway under contract no. 343302. Financial support is provided to Noora Partamies and Katie Herlingshaw by the Research Council of Norway under contract no. 358004. Maxime Grandin acknowledges funding from the Research Council of Finland (grant 360433-ANAON) and from the European Union (ERC Starting Grant, LOUARN, 101161971). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting
425 authority can be held responsible for them. The authors gratefully acknowledge citizen scientists Sophie Cordon, Michele Aucello, Sirpa

<https://doi.org/10.5194/egusphere-2026-3756>

Preprint. Discussion started: 16 July 2026

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Pursiainen, Andreas Steinbach, Tom A. Warner, Terhi Törmälä, Todd Graven, Christina Sharp, and Christian Harris for sharing fragment images, which made this study possible. The authors thank the developers of Stellarium for providing the software used to identify the star constellations visible in the auroral photographs (Zotti et al., 2021).



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