

Response to Reviewer 1:

We thank the reviewer for the thorough and constructive assessment of our manuscript. We appreciate the reviewer's recognition of the value of the Skywarden dataset and their detailed suggestions for improving the clarity of the scientific objectives, presentation of the results, and manuscript structure. We have carefully considered all comments and will revise the manuscript accordingly. Our point-by-point responses are provided below.

This study expanded the investigation of auroral fragment occurrence distributions to an unprecedentedly wide range of latitudes and magnetic local times, using the archive Skywarden, which contains aurora images taken by citizen scientists. Aurora researchers verified the images to ensure the academic value of the dataset, and comparisons were made with other measurement data. Each survey topic was carefully examined, and the results are reliable. However, there are aspects of the manuscript structure that require improvement. I have proposed some comments for clearly describing the scientific objectives and focusing the explanation on their elucidation. I hope that the authors will revise the manuscript in line with the comments below.

[Major Comment 1]

The scientific objectives of this study are stated at the end of Section 1: "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." Three scientific objectives were proposed and investigated in 26 fragment events. The distinction between the first and third scientific objectives is not clear, but probably the third is the essential one. To address this, the study examined the relative locations of ground-based observation locations with respect to the auroral oval observed by DMSP/SSUSI. As described in the second paragraph of Section 2.4, a comparison with the auroral oval was made for all events, but results are shown for only three cases (Sections 3.2.1-3). Figure 2b provides the magnetic latitude distribution of the observation locations, but their relative positions with respect to the auroral oval are not provided. The observation that fragments occur both inside and outside the oval can be considered a new finding, but presenting the relative distribution of the oval for all 26 cases would make it an even more scientifically valuable new finding. Relative location is discussed in Section 4.2, but except for the three cases compared with DMSP/SSUSI data, almost no results are introduced. This section should be revised to discuss all events.

We agree that the scope of the different analyses and the distinction between the first and third objectives should be clarified.

We will therefore revise the objectives and Sections 3.2 and 4.2 to distinguish between the occurrence analysis of all events and the targeted case studies relative to the auroral oval. The aim of the oval-relative analysis is to demonstrate that fragments can occur poleward of, equatorward of, and within the auroral oval, rather than to determine how many events occur in each of these regions. This broader range of oval-relative locations extends the previously documented occurrence of fragments and is the main new finding of this analysis. We will revise the objective to state this aim explicitly.

The relation to the auroral oval was assessed for three selected events with suitable DMSP/SSUSI coverage and sufficient optical information. These cases were selected to illustrate fragment observations poleward of, equatorward of, and within the auroral oval.

We assessed whether classification of all events was feasible. However, suitable DMSP/SSUSI coverage and sufficiently close overpass timing are not available for every event. In several cases, the satellite observations do not provide a sufficiently reliable estimate of the event specific auroral oval boundaries.

We also tested the Feldstein–Starkov statistical auroral oval model, following the formulation and coefficients presented by Sigernes et al. (2011), as a possible way to estimate the oval location for events without suitable DMSP/SSUSI coverage. However, comparisons with available DMSP/SSUSI observations for several events showed that the modelled boundaries could be displaced to an extent that could affect the interpretation of an observation's position relative to the oval.

The comparison for Event 22 in Manitoba is shown below as an example. At the event MLT, the modelled equatorward boundary lies at 64.64° MLAT, 5.77° poleward of the observer's location at 58.87° MLAT. The observer is therefore substantially equatorward of the modelled oval. In contrast, the DMSP/SSUSI observations show the observer location at, or very close to, the equatorward boundary of the observed auroral emission. The modelled poleward boundary lies at 72.39° MLAT, giving an oval width of 7.75° MLAT at this MLT. The discrepancy between the modelled and satellite-observed equatorward boundaries is therefore approximately three-quarters of the modelled oval width. A boundary error of this magnitude could for example cause an observation within the actual oval to be incorrectly classified as equatorward or poleward of it, particularly for observations near the oval boundaries.

Although the model provides a useful large-scale statistical estimate of auroral oval location, the comparisons show that its event-specific boundary estimates can differ from

the satellite observations by an amount comparable to the oval width. Such discrepancies are too large for the model to serve as a reliable substitute for satellite observations when classifying individual events relative to the oval. We therefore decided not to use it to classify all events and will limit the oval-relative conclusions to the three case studies supported by satellite and optical observations.

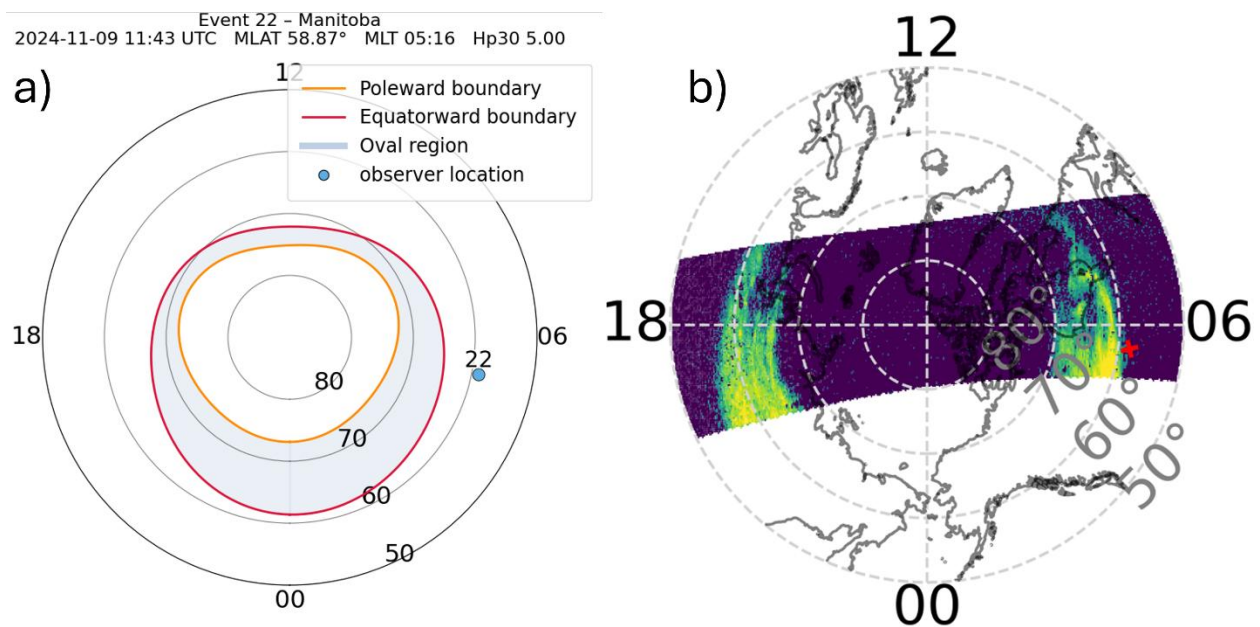


Figure 1: Comparison of (a) the Feldstein–Starkov statistical auroral oval model and (b) DMSP/SSUSI observations for Manitoba on 9 November 2024 (Event 22). The blue dot in panel (a) and red cross in panel (b) mark the observer location at 58.87° MLAT and 05:16 MLT. In panel (a), the model places the observer well equatorward of the modelled oval, whereas in panel (b), the observer is located at, or close to, the equatorward boundary of the auroral emission observed by DMSP/SSUSI.

[Major Comment 2]

This is another comment regarding the scientific objectives. For the second objective, solar wind parameters and geomagnetic indices near the time of event occurrence were examined. However, only three cases (Sections 3.2.1-3) are shown. Of course, it is not realistic to display graphs for all 26 cases, but these three are not presented as representative cases in answering the second objective. It was difficult to obtain an answer to this objective from these three cases, so the answer to this objective is not explicitly stated in Section 5 (Conclusions). If further analysis is necessary, one option would be to remove this topic from the research objectives. However, in that case, it would be necessary to significantly revise the figures and content.

We agree that the three detailed case studies were not selected as representative examples of the solar wind and geomagnetic conditions across the full event set. Their purpose was to provide the solar wind and geomagnetic context for the selected case studies relative to the auroral oval, rather than to answer the second objective for all 26 events.

We will revise the manuscript to distinguish more clearly between the descriptive analysis of all events in Section 3.1 and the contextual time series for individual events in Sections 3.2.1-3.2.3. In particular, we will clarify that the solar wind and index plots for the case studies are not intended to be representative of all events.

We will also revise the second objective and the Conclusions to clarify that the analysis describes the range of solar wind and geomagnetic conditions associated with the observations, rather than identifying a specific solar wind driver or causal dependence.

The analysis of background conditions for all events is instead provided in Figure 2. Figure 2b shows the distribution of all events in MLAT and MLT, colour coded by hp30, and Figure 2c shows the relation between MLAT, one hour mean AL, and one hour mean IMF B_z for all events. These results show that fragment observations occurred across a broad range of geomagnetic activity levels and background conditions.

[Minor Comments]

Line 30: “Dayton-Oxland et al., 2025”

We will correct the citation for Dayton-Oxland et al. (2025) in the revised manuscript.

Line 109–111: “Events located between ... as poleward.”

These results are not provided in the text and figures. Please add the breakdown of the 26 events to Table A1. Also, for “subauroral” and “poleward” cases, calculate and provide the relative magnetic latitude in degrees to the poleward/equatorward edge of the auroral oval. For “auroral” cases, set the relative magnetic latitude to 0°. By comparing these results with the magnetic latitudes of fragments reported in previous studies, explain the progress since their results.

The suggested approach would be an effective analysis to investigate the offset of fragments from the edges of the auroral oval. However, as explained in our response to Major Comment 1, we cannot provide a reliable classification relative to the auroral oval or a boundary offset for the complete event set because suitable DMSP/SSUSI coverage and

sufficiently reliable event specific oval boundaries are not available for every event. We will therefore revise the objectives and manuscript text to clarify that the analysis relative to the auroral oval is limited to the three selected case studies.

We will also add a brief discussion of this limitation and note that future studies with additional fragment events and suitable satellite conjunctions could enable a larger statistical analysis of fragment locations relative to the auroral-oval boundaries.

In terms of discussing and comparing the magnetic latitudes of the fragments, we have some discussion on this in section 4.2. Specifically, we compare our Antarctica event with the observations reported by Li et al. (2025) at a similar magnetic latitude and discuss how the present observations extend the occurrence range beyond the previously reported high-latitude cases.

Lines 126–127: “... with links provided in the event list in Appendix A.”

The link in the event list appears to be just plain text, which means there is no direct link to the website.

We thank the reviewer for identifying this issue. Direct hyperlinks to the corresponding Skywarden observations were included in the submitted manuscript but were not retained when the manuscript was processed into the preprint version. We will ensure that Table A1 contains direct, clickable hyperlinks to all Skywarden event records in the revised manuscript.

We will also provide 1024-pixel quicklook images for all events as indexed supplementary material, labelled by event number and UTC time. Where feasible, we will also include downscaled versions of the associated videos. In addition, all observations included in the revised study will be tagged with *#fae2026MielkeEtAl* in the Skywarden database, allowing readers to retrieve the complete set of study observations through the Skywarden search function independently of individual hyperlinks.

These complementary access routes will make the material easier to inspect while preserving access to the original observations, metadata, and descriptions on Skywarden.

Lines 141–143: “Figure 2c shows ... colour-coded to IMF B_z .”

Events #10, 11, and 12 might have been missed.

Please change the colour map so that $B_z = 0$ is recognizable.

We thank the reviewer for pointing this out. Events 10, 11, and 12 are not visible in the current version of Figure 2c. We will revise the figure to ensure that all events are shown and identifiable.

We will also replace the current colour map with a diverging colour map centred on $B_z = 0$, using a distinct neutral colour at zero. This will make the sign and magnitude of IMF B_z clearer.

Lines 142–143: “The mean values ... each fragment event.”

For solar wind parameters, it is understandable to use the mean value over 1 hour before the event as a representative value, considering the travel time from the satellite measurement point to the front side of the magnetosphere and magnetospheric/ionospheric response delays. On the other hand, what is the reason for also using the mean AL index in the hour before the event as an indicator of ionospheric current conditions? Furthermore, what is the reason for not using IMAGE magnetometer index instead of AL and AU?

We thank the reviewer for this comment. We agree that averaging AL over the preceding hour can smooth out short-timescale variations and does not necessarily represent the electrojet activity close to the fragment observation time. We will therefore replace the preceding one-hour mean AL with a 10-minute mean immediately preceding each event. We use a shorter interval to better represent activity close to the observation time but retain averaging because AL can fluctuate rapidly.

We considered the IMAGE magnetometer index. However, the dataset contains events from several longitude sectors and both hemispheres, including North America, Greenland, Svalbard, Scandinavia, and Antarctica, whereas IMAGE is a regional index. For the Antarctica case, we additionally checked the SuperMAG SML/SMU indices and found variations similar to those in AL/AU. We will therefore retain AU and AL as consistent descriptive activity indicators across the event set, while clarifying their limitations.

Figures 3 and 6: I do not understand the academic rationale for adding constellations and star names. Please state in the text the reason why their inclusion is considered to aid understanding of the research topic. If there is no specific reason, please remove them from the figures. Note that direction can be sufficiently understood from the symbols (e.g., S) annotated in the photos.

We agree that the direction symbols shown in the images are sufficient for the reader to understand the viewing direction. We will remove the constellation names and star labels from Figures 3 and 6 to improve figure clarity. We will retain a brief statement in the Methods section that visible stars and constellations were used during the analysis to estimate camera pointing direction where this information was not available from the observation metadata.