

Statistical properties of small-scale auroral spots near magnetic local noon

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Key Points:

- We identify 65 small-scale auroral spot (SsAS) events near magnetic local noon, observed only in the green line, with two morphological types: sporadic SsAS and fence-like SsAS.
- The occurrence of SsAS is closely associated with southward interplanetary magnetic field (IMF) B_z . It also shows a clear dependence on westward IMF B_y , with their drift motion strictly controlled by IMF B_y polarity.
- European Incoherent Scatter Scientific Association data show density gradients, suggesting that Alfvén waves undergo phase mixing within these gradient structures.

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Abstract: Small-scale auroral spots (SsAS) are frequently observed, particularly on the nightside, yet their formation mechanisms remain unclear. Utilizing all-sky imager data from the Chinese Arctic Yellow River Station and radar measurements from the European Incoherent Scatter Scientific Association (EISCAT), we identified 65 SsAS events occurring near magnetic local noon from 2003 to 2009. We found that they are observed only in the 557.7 nm emission band. They can be classified into two types based on their morphology: sporadic SsAS and fence-like SsAS. The occurrence of these events shows clear dependence on the southward interplanetary magnetic field (IMF) B_z , with the fence-like SsAS exhibiting an even more pronounced dependence. Their occurrence also depends on the westward IMF B_y . Additionally, we found that most events (88%) are located on the poleward side of the auroral oval, and the drift motion of these SsAS is consistent with the motion direction of adjacent auroral structures, whose motion is strictly governed by the IMF B_y polarity. These observations indicate that generation of these dayside SsAS may be directly linked to the solar wind energy input through magnetopause reconnection. The EISCAT observations further show that SsAS are accompanied by pronounced electron density gradients. On the basis of these characteristics, we propose that the generation of SsAS may be related to phase mixing of Alfvén waves arising from the density gradients. This study helps elucidate the coupling chain by which solar wind energy is injected into the polar region and subsequently drives ionospheric responses.

Keywords: small-scale auroral spots; magnetic local noon; interplanetary magnetic field; Alfvén waves; density gradient

1. Introduction

Auroras are optical emissions produced by the interaction between the solar wind and Earth's magnetosphere, in which charged particles precipitate along geomagnetic field lines into the ionosphere and collide with atmospheric constituents. Generally, auroral forms include arcs, rays, bands, curtains, and curls. In recent years, however, observations have revealed a variety of small-scale auroral spots (SsAS), such as the “picket fence” (Archer et al., 2019; Mishin and Streltsov, 2019; Gillies et al., 2020; Semeter et al., 2020; Nishimura et al., 2023), auroral beads (Kalmoni et al.,

2015; Lui, 2016, 2020; Nishimura et al., 2016; Ohtani and Motoba, 2024), and fragmented aurora-like emissions (FAEs; Dreyer, 2019; Li B et al., 2025). These distinct auroral spots not only broaden the spectrum of auroral phenomena but also offer new opportunities for probing complex physical processes in magnetosphere-ionosphere coupling.

The picket fence often co-occurs with a Strong Thermal Emission Velocity Enhancement (STEVE; Nishimura et al., 2023; Partamies et al., 2025). A STEVE typically appears as a purple or mauve-colored luminous arc on the equatorward side of the auroral oval, whereas the picket fence manifests as a subsequent green ray-like picket-fence structure that often persists after the STEVE fades away (Nishimura et al., 2023). High-speed imaging reveals that the picket fence exhibits fine-scale wave-like structures, frequently accompanied by green streaks below it. When the picket fence drifts westward along a STEVE, these green streaks usually appear

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on the poleward side of the STEVE and move toward it (Gillies et al., 2020; Semeter et al., 2020; Nishimura et al., 2023). Up to now, the picket fence has only been detected at night, and its specific formation conditions, wavelength, drift speed, and duration remain unclear.

Auroral beads are a common auroral structure during the initial brightening phase of substorms, appearing as east–west elongated auroral rays with periodic azimuthal modulation. Statistical studies indicate that more than 90% of substorm onset events are accompanied by such structures (Kalmoni et al., 2015; Nishimura et al., 2016). Currently, no consensus exists on their formation mechanism. The leading hypotheses fall into two categories: magnetospheric instabilities and feedback instability (Lui, 2016, 2020; Ohtani and Motoba, 2024).

Additionally, the FAEs reported by Dreyer (2019) manifest as small green luminous fragments that do not extend along magnetic field lines. They can be categorized into randomly distributed structures and wave-like structures that align with auroral arcs at regular intervals. Subsequent research by Li B et al. (2025) further revealed that FAEs can propagate in directions opposite to the overall motion of the auroral oval, not only expanding toward higher latitudes but also drifting eastward along auroral arc trajectories. This phenomenon is also referred to as “auroral ripples” (Li B et al., 2025).

In summary, the above-mentioned spot-like auroral forms, including the picket fence, auroral beads, and FAEs, are each associated with specific large-scale activities (e.g., a STEVE, onset of a substorm) or instabilities (e.g., gradient drift instability). To date, the formation mechanisms of these isolated luminous structures remain unresolved. Furthermore, existing research has predominantly focused on the nightside, leaving a systematic investigation into whether similar structures occur in the high-latitude region near magnetic noon largely absent. To address this gap, this study provides a detailed analysis of SsAS observed in the vicinity of magnetic local noon, aiming to uncover their characteristics and potential drivers, thereby offering new insights into dayside auroral dynamics and the underlying magnetospheric processes.

2. Dataset and Methodology

This study is based on observational data from the all-sky imager (ASI) at the Chinese Arctic Yellow River Station (geographic coordinates: 78.92°N, 11.93°E) between 2003 and 2009. The ASI system is equipped with three narrowband filter channels with central wavelengths of 427.8 nm (blue), 557.7 nm (green), and 630.0 nm (red), which are used to characterize electron precipitation at different energy ranges. Each imager is fitted with a CCD camera with a resolution of 512×512 pixels, and the data have a temporal resolution of 10 seconds, consisting of a 7-second exposure time and a 3-second readout time (Han DS et al., 2015).

We focus on the time interval from 08:00 to 11:00 universal time (UT), corresponding to magnetic local time (MLT) from 11:00 to 14:00. Within this interval, we manually screen all available ASI images to identify events characterized by specific isolated spot-like morphologies. To ensure data consistency and validity, the following selection criteria are applied: (1) exclusion of abnormal

data caused by instrument malfunction or weather interference; (2) sufficient image clarity to unambiguously identify the structure; (3) an event duration of no less than 30 seconds to avoid misidentification caused by transient noise or imaging artifacts. These criteria ensure the objectivity and statistical reliability of event identification.

This study also utilizes the National Aeronautics and Space Administration's OMNI dataset and European Incoherent Scatter Scientific Association (EISCAT) radar observations corresponding to the event periods. The OMNI dataset integrates solar wind measurements from multiple satellites and has been time-shifted to the Earth's bow-shock nose. It provides standardized solar-wind magnetic field and plasma parameters, as well as global geomagnetic indices such as SYM-*H* (symmetric disturbance index in the *H*-component) and AE (auroral electrojet; Fredrick et al., 2025). The EISCAT radar, located in Ramfjordmoen near Tromsø, Norway (69.58°N, 19.23°E), operates in both ultra-high frequency (UHF) and very-high frequency (VHF) bands. By analyzing backscatter signals, it can derive ionospheric parameters, including electron density, electron temperature, ion temperature, and line-of-sight ion velocity (Reidy et al., 2025).

To comprehensively examine the correlation between SsAS and the interplanetary magnetic field (IMF), we use a 30-minute interval (spanning from 15 minutes before to 15 minutes after the event start time). To examine the correlation between SsAS and geomagnetic activity, we use the minimum value of SYM-*H* during the 48 hours preceding the event. These parameters provide the basis for subsequent quantitative analysis.

3. Observational Results

3.1 Two Types of SsAS in the Green Line

On the basis of ASI data from the Yellow River Station during magnetic local noon from 2003 to 2009, we identified a total of 65 independent SsAS events. The duration of these events varied substantially, ranging from as short as 20 seconds to as long as 740 seconds, indicating significant diversity in their lifetimes. Notably, all events were observed only in the 557.7 nm emission band (Figures 1a and 1b), with no corresponding signal detected in the 630.0 nm emission band (Figures 1c and 1d).

We noticed that the SsAS could be classified into two morphological types: sporadic SsAS (Figure 1a) and fence-like SsAS (Figure 1b). The sporadic SsAS consisted of irregularly distributed bright spots with nonuniform spacing and inconsistent orientations, showing no clear periodicity in their spatial distribution. In contrast, the fence-like SsAS exhibited a highly ordered arrangement, with uniform spacing and consistent alignment of the bright spots, forming a distinct picket-fence pattern. This morphological difference not only reflects the diversity of these events on spatial scales but also suggests that their formation mechanisms may be influenced by complex local magnetosphere–ionosphere coupling processes.

3.2 Local Time Distribution of SsAS

Figure 2 shows the local time distribution of the occurrence of SsAS. It demonstrates an occurrence peak at 09:30 UT (corre-

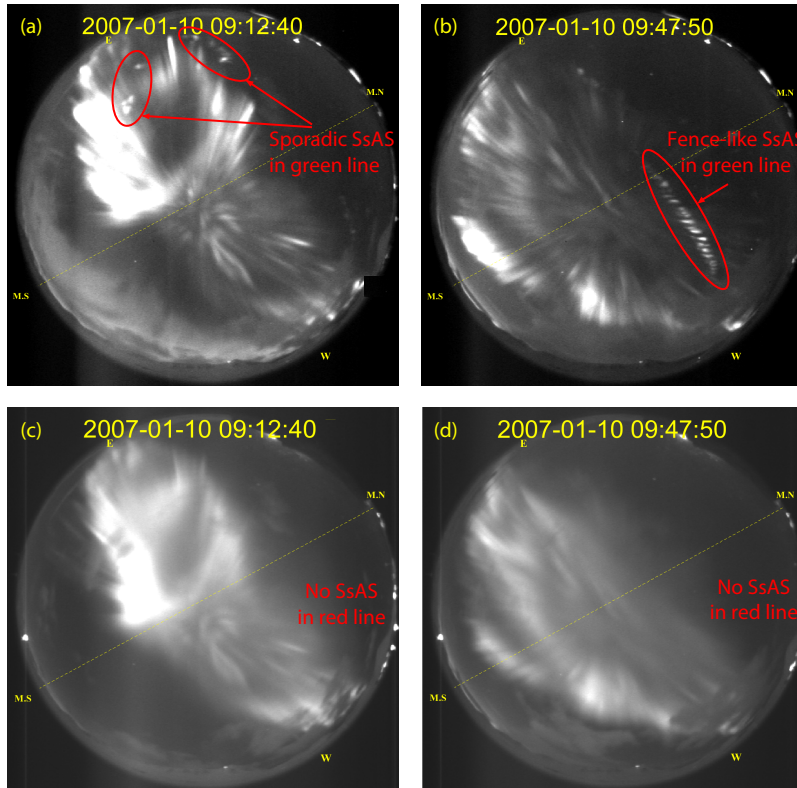


Figure 1. Examples of two typical SsAS observed at the Yellow River Station. (a) Sporadic SsAS in the green line (2007-01-10 09:12:40 UT). The red circles outline the irregularly distributed SsAS. (b) Fence-like SsAS in the green line (2007-01-10 09:47:50 UT), characterized by a fence-like alignment. (c, d) Corresponding images in the red line at the same time as (a) and (b), showing the absence of SsAS.

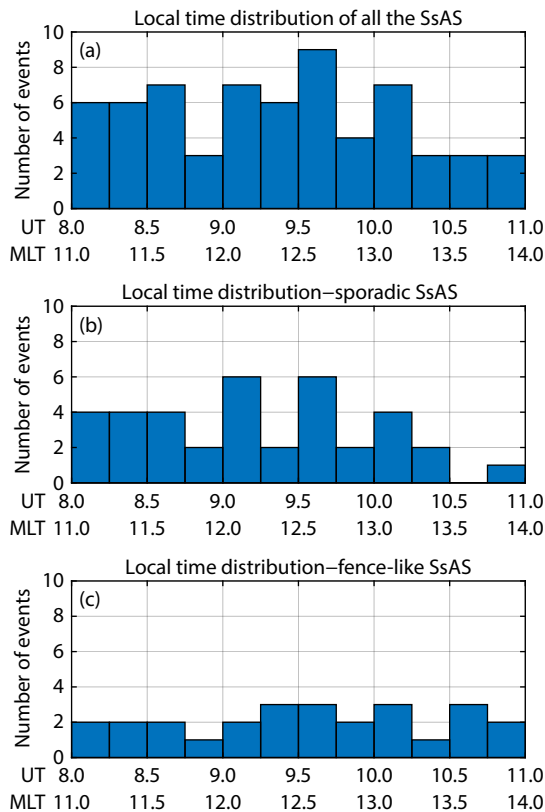


Figure 2. Local time distribution of the SsAS. (a) All the SsAS; (b) sporadic SsAS; (c) fence-like SsAS.

sponding to approximately 12:30 MLT). Further analysis of the two subtypes indicates that both sporadic SsAS (Figure 2b) and fence-like spots (Figure 2c) predominantly occur around magnetic noon, and their temporal distributions resemble that of the overall event set. This result implies that the direct solar wind and magnetopause interaction may be a possible driver for these events.

3.3 Dependence of SsAS on IMF Conditions

Figure 3 presents the dependence of the SsAS on the IMF, showing the average values of each IMF component over a 15-minute window centered on each event occurrence time for all the SsAS and their two subtypes (sporadic SsAS and fence-like SsAS). In each panel, the histograms from left to right show the distributions of IMF B_x , B_y , and B_z , respectively. Figure 3a shows that for all SsAS events, more than 85% of the SsAS occurred under southward IMF B_z ($B_z < 0$), with an occurrence peak near -3 nT. At the same time, it also indicates a clear westward IMF B_y ($B_y < 0$) dependence.

Among the two subtypes, the fence-like SsAS exhibited an even stronger dependence on the negative IMF B_z , as well as the negative IMF B_y , whereas the sporadic SsAS showed a weaker dependence. The IMF B_y distribution showed the highest frequency of occurrence (16 events) in the -8 to -4 nT interval, highlighting the dominant role of the westward component in triggering these events. In contrast, the IMF B_x distribution was nearly symmetric without a clear polarity preference, suggesting its limited influence on event excitation. Therefore, the underlying mechanism of SsAS is likely associated with magnetic reconnection, particularly for the fence-like subtype.

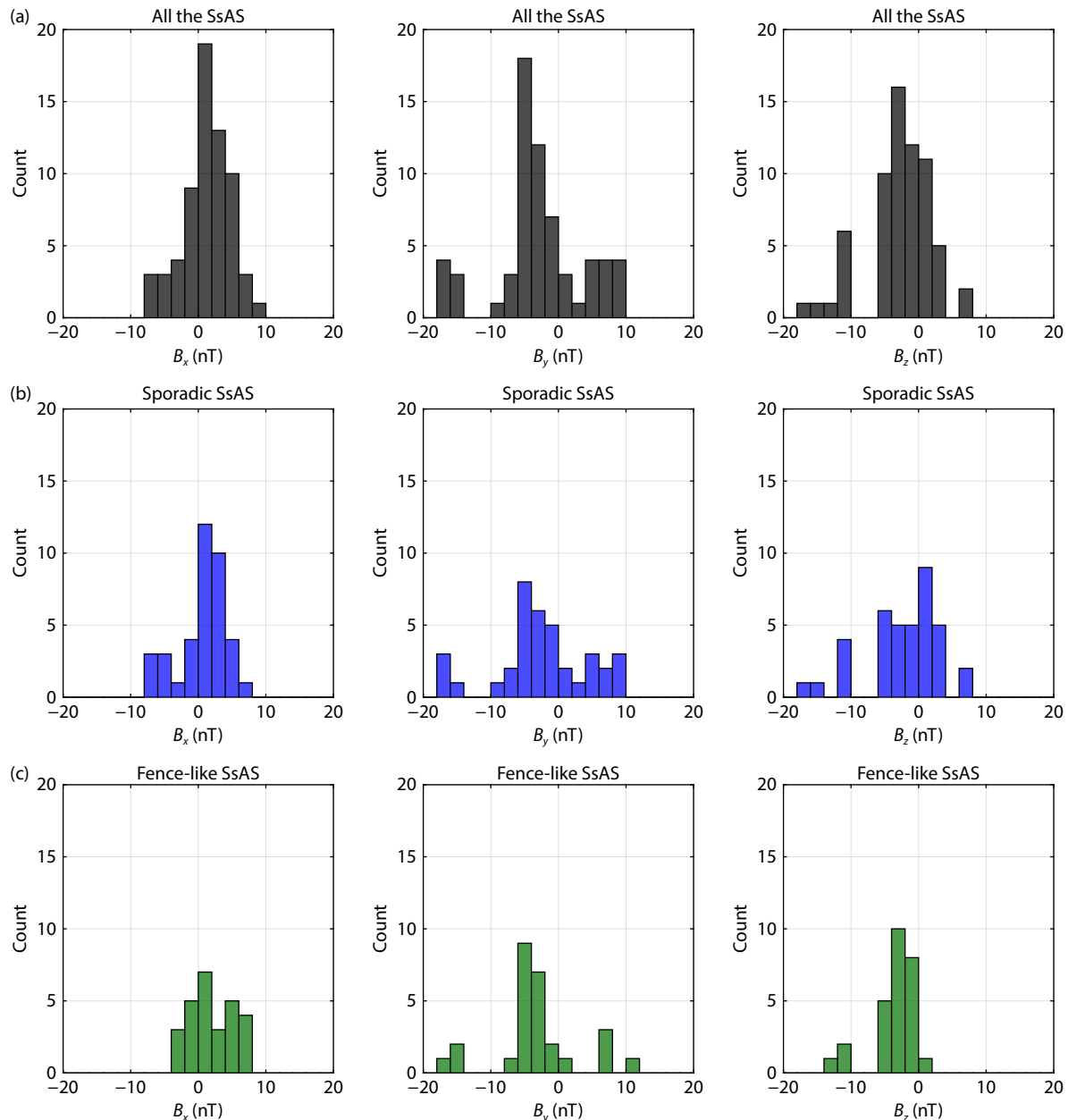


Figure 3. Distributions of solar wind and geomagnetic conditions corresponding to the SsAS. (a) All the SsAS; (b) sporadic SsAS; (c) fence-like SsAS. In each panel, the histograms from left to right show the distributions of IMF B_x , IMF B_y , IMF B_z (bin width 2.0 nT).

3.4 Dependence of SsAS on the SYM- H Index

To examine whether the occurrence of SsAS is associated with intense space environment disturbances, we analyzed the correlation between SsAS and SYM- H . Figure 4 shows the distribution of the minimum SYM- H value within the 48 hours prior to each event for all the SsAS and their two subtypes (sporadic SsAS and fence-like SsAS). We observed that the SYM- H values were mostly distributed between -50 and 0 nT, peaking around -30 nT, except for one fence-like event observed with SYM- H as low as approximately -300 nT. This result indicates that SsAS predominantly occurred during weak to moderate geomagnetic disturbances and did not rely on intense geomagnetic storm conditions.

3.5 Spatial Position and Drift Motion Properties of SsAS

As shown in Figure 5, we noted that SsAS could occur either on

the poleward side, on the equatorward side, or within the auroral oval, and they exhibited clear drift signatures. Therefore, we performed a statistical analysis of their spatial distribution and drift characteristics. Observations indicated that the drift direction of SsAS was generally consistent with that of the auroral oval. As shown in Table 1, the spatial distribution of these events exhibited distinct characteristics: the vast majority (57 events, $\sim 88\%$ of the total) were located on the poleward side of the auroral oval, 6 events ($\sim 9\%$) occurred inside the oval, and only 2 events ($\sim 3\%$) appeared on its equatorward side.

Further analysis revealed that the motion direction of all SsAS was consistent with the drift direction of their adjacent auroral structures, indicating that their dynamics were governed by the local large-scale ionospheric convection field. Specifically,

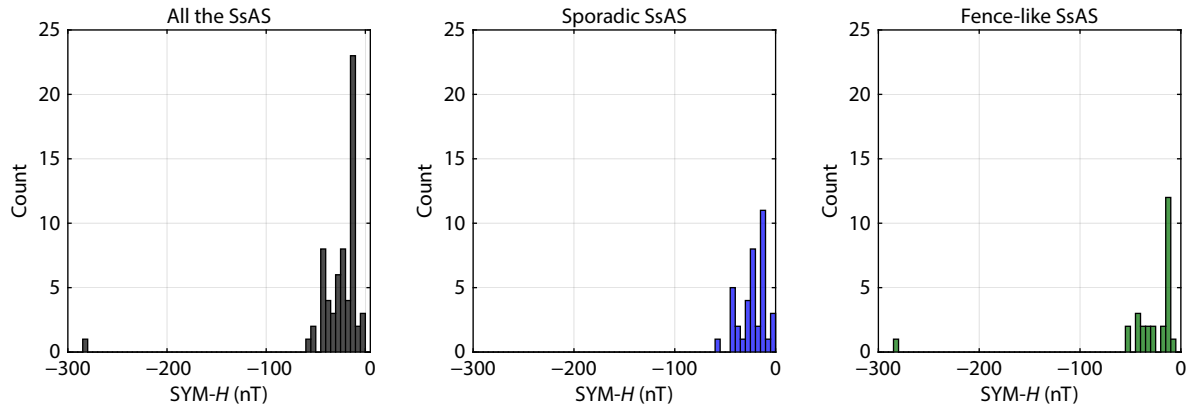


Figure 4. From left to right, distribution of the minimum SYM- H for all the SsAS, sporadic SsAS, and fence-like SsAS (bin width 5.0 nT).

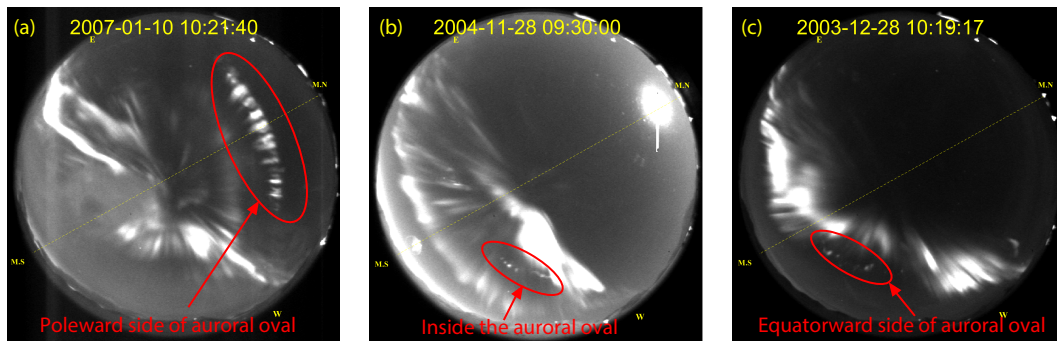


Figure 5. Examples of SsAS at different locations relative to the auroral oval. (a) On the poleward side of the oval; (b) inside the oval; (c) on the equatorward side of the oval. The red circles outline the SsAS.

Table 1. Spatial distribution and drift motion properties of SsAS.

Position to the auroral oval	Total	Motion of adjacent aurora	Number	$B_y > 0$	$B_y < 0$
Poleward side	57	East	50	7	43
		West	7	7	0
Inside	6	East	2	0	2
		West	4	4	0
Equatorward side	2	East	1	0	1
		West	1	1	0

(1) Among the 57 events on the poleward side, 50 were accompanied by eastward-drifting adjacent auroral structures, 43 of which (86%) corresponded to IMF $B_y < 0$; the remaining 7 events were associated with westward-drifting adjacent auroral structures, all of which corresponded to IMF $B_y > 0$.

(2) Of the 6 events inside the auroral oval, the 2 with eastward drift occurred under IMF $B_y < 0$, whereas the 4 with westward drift all occurred under IMF $B_y > 0$.

(3) The 2 events on the equatorward side exhibited eastward and westward drift, corresponding to IMF $B_y < 0$ and IMF $B_y > 0$, respectively. Although the sample size here is small, the trend aligns with the above pattern.

In summary, for all cases in this study, events with eastward-drifting adjacent auroral structures (53 in total) predominantly (44 events) occurred under IMF $B_y < 0$ conditions, whereas all events with

westward-drifting adjacent auroral structures (12 in total) occurred under IMF $B_y > 0$ conditions. This highly systematic correspondence indicates that the local convection environment in which SsAS are embedded is directly regulated by the polarity of IMF B_y and that their drift direction follows the B_y -driven large-scale convection pattern.

3.6 EISCAT Observations

To investigate the relationship between SsAS and the local plasma environment, we conducted a single case study using simultaneous auroral and EISCAT radar observations on November 27, 2011, as shown in Figure 6. As shown in the right panel of Figure 6, we observed that the radar beam was located very close to the SsAS at 08:10:10 UT. At that moment, a distinct feature was observed: a significant increase in electron density (N_e) over the altitude range of 300–600 km, accompanied by an increase in electron tempera-

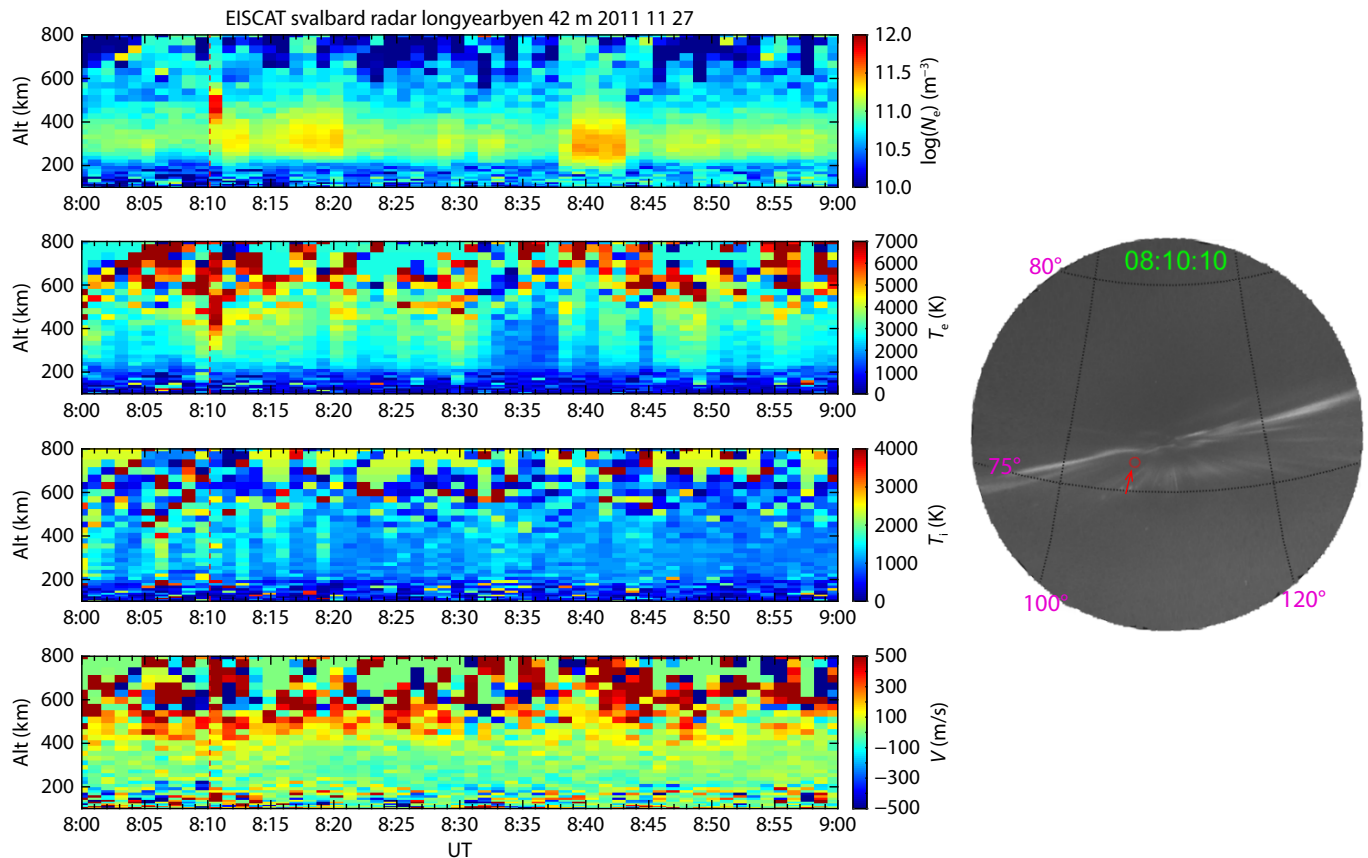


Figure 6. The left panels show the height–time variations of ionospheric parameters observed by the EISCAT Svalbard radar (42 m) on November 27, 2011. From top to bottom, the left panels display electron density [$\log(N_e)$], electron temperature (T_e), ion temperature (T_i), and vertical velocity (V). The right panels show the corresponding auroral images observed by the ASI at the Yellow River Station. In the left panels, the vertical dashed lines mark the occurrence time of the SsAS. In the right panel, the red arrow points to the red circle marking the location of the EISCAT radar beam.

ture (T_e). This increase indicates the presence of a pronounced plasma density gradient around the SsAS.

Notably, radar measurements conspicuously revealed no significant electron density enhancement at E-region altitudes. This result aligns with established auroral physics, as the acceleration region responsible for particle precipitation typically resides well above the E-region. Consequently, sharp density gradient structures are inherently unlikely to form within the E-region itself.

It should be noted that this analysis is limited to the specific conditions of the observed event and cannot be generalized to all SsAS events in our statistical sample. This limitation arises from the stringent spatiotemporal matching requirements for identifying ideal SsAS cases that are simultaneously observed by both the ground-based observatory at the Yellow River Station and the EISCAT radar. Such ideal conjunctions are inherently difficult to obtain because of the strict spatiotemporal matching requirements.

4. Summary and Discussion

According to ASI observations from 2003 to 2009, 65 SsAS events were identified near magnetic noon (MLT 11:00–14:00). The main observational findings include the following:

- (1) All events were observed only in the 557.7 nm green line, with no detectable signal in the 630.0 nm red line.
- (2) Two morphological types were identified: sporadic SsAS and fence-like SsAS.
- (3) More than 85% of events occurred under southward IMF B_z , with fence-like SsAS showing an even stronger dependence; no clear association with geomagnetic storms was found.
- (4) The events also showed a negative IMF B_y dependence.
- (5) Most events (88%) were located on the poleward side of the auroral oval, and their drift direction was consistent with adjacent auroral structures and strictly controlled by IMF B_y polarity.
- (6) EISCAT observations revealed distinct ionospheric density and temperature gradients near the SsAS.

4.1 Precipitating Electrons Responsible for SsAS Underwent Acceleration

The SsAS events share some morphological and spectral features with previously reported nightside structures, such as the picket fence, auroral beads, and FAEs, yet potential commonalities in their underlying physical processes warrant discussion. For the picket fence, its emission is thought to involve direct excitation of

O(¹S) by suprathermal electrons, with its formation closely tied to the flow and density structure of a STEVE and subauroral ion drift (SAID; Archer et al., 2019; Mende et al., 2019; Semeter et al., 2020; Nishimura et al., 2023). For auroral beads, the proposed mechanisms include magnetospheric instabilities (ballooning instability and cross-field current instability; Lui, 2016, 2020; Ohtani and Motoba, 2024) and feedback instability in magnetosphere–ionosphere coupling, where conductivity gradients generate polarization electric fields that, together with Alfvén waves, accelerate electrons and enhance precipitation (Lysak and Song Y, 2003; Lui, 2016, 2020; Watanabe, 2020; Ohtani and Motoba, 2024). For FAEs, their formation is likely associated with gradient drift instability, which produces localized periodic electric fields that accelerate electrons at wave crests and troughs (Li B et al., 2025). Despite their differences in morphology and geophysical context, a common theme among these structures is the modulation of electron acceleration by local electric fields or feedback mechanisms, which may share similarities with the internal physical processes of SsAS.

Turning to the optical characteristics of SsAS events, the exclusive occurrence of SsAS in the green line (557.7 nm) but absent in the red line (630.0 nm) indicates that the precipitating electrons should be monoenergetic and have high energies, implying that they have undergone acceleration. In other words, SsAS are generated by precipitating particles rather than being a process confined solely to the ionosphere (Li B et al., 2025). Studies on auroral particle acceleration mechanisms (Wu J et al., 2020; Shi R et al., 2023) suggest that the physical process underlying auroral particle acceleration involves the following sequence: disturbance energy from the source region is transported by Alfvén waves to the near-Earth acceleration region, where localized acceleration structures form; these structures then accelerate electrons to produce auroras. Therefore, it is necessary to consider what physical processes drive these SsAS.

4.2 Potential Role of Magnetopause Reconnection in Powering Dayside SsAS

Our results also show that SsAS are closely associated with negative IMF B_z and negative IMF B_y . The observed strong dependence of SsAS on negative IMF B_z and B_y can be understood in the context of dayside magnetospheric dynamics. Under southward IMF conditions, enhanced solar wind energy input triggers dayside magnetic reconnection, transferring energy into the magnetosphere–ionosphere coupling system and intensifying magnetospheric convection within 10–20 minutes (Dai L et al., 2023, 2024; Zhu MH et al., 2024). This process creates the energetic environment in which SsAS occur. Meanwhile, although a negative B_y does not directly correlate with the total energy input, it regulates the spatial distribution of electrons with different energy fluxes and shifts the location of the reconnection site (Liou and Mitchell, 2019; Shen HW et al., 2022). Such modulation by IMF B_y may explain the observed polarity control of SsAS motion and spatial distribution. This explanation is also consistent with the fact that the azimuthal motion of poleward-moving auroral forms is highly controlled by IMF B_y . The underlying physical mechanism may be that IMF B_y drives plasma flow through magnetic tension, thereby controlling the azimuthal motion of magnetic flux ropes. Such flux

ropes facilitate the transport of solar wind energy and particles into the Earth's magnetosphere, thereby further affecting the coupling between the magnetosphere and ionosphere systems (Guo J et al., 2022). This may explain why the occurrence of SsAS is closely related to negative B_y . Together, these IMF conditions (southward B_z for enhanced energy input and westward B_y for spatial modulation) create the driving environment that gives rise to the observed characteristics of SsAS.

4.3 Phase Mixing of Alfvén Waves Caused by Gradient Drift Instability May Be Responsible for SsAS Generation

Finally, the EISCAT radar observation in Figure 6 indicates that the SsAS are associated with distinct temperature and density increases. The observed density gradient offers a critical clue. In the ionosphere, such a sharp gradient can excite the gradient drift instability, which naturally generates periodic density structures along the gradient boundary (Tsunoda, 1988). These structures can extend along magnetic field lines, explaining their detection by EISCAT from 300 to 600 km. We propose that when Alfvén waves generated by magnetopause disturbances propagate earthward and encounter these preexisting density variations, they undergo phase mixing (Hasegawa and Chen L, 1975). This process can spatially modulate the Alfvén wave energy, creating alternating, periodic acceleration regions that manifest as the fence-like SsAS (Wygant et al., 2000, 2002; Lysak and Song Y, 2011; Lysak, 2023).

However, the formation mechanism of density gradient structures within sporadic SsAS remains unclear, suggesting that different SsAS categories or events with distinct characteristics may not share a common physical mechanism. Moreover, more events with simultaneous observations from both the Yellow River Station and the EISCAT radar are required to further analyze the underlying mechanisms. Further detailed investigations are therefore necessary to address these issues.

5. Conclusions

On the basis of 65 SsAS events observed only in the 557.7 nm emission band identified from ASI observations, this study reveals that SsAS represent a dayside auroral phenomenon with two distinct morphological types. Our conclusions are as follows.

First, SsAS are observed only in the green line and not in the red line, suggesting that the responsible precipitating electrons have undergone acceleration; thus, SsAS arise from precipitating particles rather than being an ionosphere-only process. Second, the dependence of SsAS on southward IMF B_z indicates that magnetopause reconnection may power these dayside SsAS. Third, we propose, based on EISCAT-observed pronounced density gradients, that phase mixing of Alfvén waves driven by gradient drift instability from such density gradients may generate SsAS.

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