

The importance of extreme dynamic signatures in the sub-auroral region

B. Gallardo-Lacourt^{1,2}, G.W. Perry³, B. Kunduri⁴, and C. Martinis⁵

¹The Catholic University of America, Washington, DC

²NASA, Goddard Space Flight Center, Greenbelt, MD

³New Jersey Institute of Technology, Newark, NJ

⁴Virginia Tech, Blacksburg, VA

⁵Boston University, Boston, MA

*See attached spreadsheet for additional coauthors

Synopsis

The sub-auroral region is located immediately equatorward from the auroral oval, where important magnetosphere-ionosphere-thermosphere dynamical processes take place. Historically, low-Earth orbit satellites as well as ground-based imagers and radars have provided important information about the region. However, in recent years it has become increasingly clear that there are several unexplored aspects of the region that remain elusive in part due to instrumental and observational limitations. Furthermore, the most commonly used large-scale “state of the art” models and theoretical frameworks of the region rely on a quasi steady-state approach which does not accurately represent the rich sub-auroral electrodynamics underway.

Recent ground-based and in-situ measurements have revealed new and compelling dynamics underway in the sub-auroral region and reinvigorated the community’s interest there. Optical signatures with unusual spectrographic properties, such as SAR arcs, STEVE, and the picket fence, have been associated with extreme and unusual sub-auroral plasma conditions, such as large ion flow velocities (~5-10 km/s) and extreme electron temperatures (>6000 K). Additionally, recent observations have revealed that the transformation of the sub-auroral region into these extreme conditions occurs within minutes. These new measurements pose a significant challenge to our existing theories and available instrumentation, and demonstrate the necessity of new development and deployment of in-situ and remote measurements of the sub-auroral ionosphere.

This white paper highlights some of the open questions in the sub-auroral region that have arisen since the previous decadal survey. It provides recommendations on how science advances can be achieved to help close these open questions, and how new discoveries can be made possible. In short:

1. Establishing new and long-term support for unifying citizen and “traditional” scientists is required to sustain observations and discovery in sub-auroral science.
2. NASA’s Geospace Dynamics Constellation (GDC) mission is required to address and close many outstanding sub-auroral science questions and should be carried-out without delay.
3. New and long-term support for ground-based observations infrastructure is needed to better understand the nature and dynamics of the sub-auroral ionosphere. Existing infrastructure is too sparse in geographic distribution in the sub-auroral region within the United States.
4. In situ measurements of the lower-thermosphere in the sub-auroral region by rockets, low-altitude satellites, and/or some other techniques are required to conclusively identify the source, energetic pathways, and mechanism of the extreme conditions reported at sub-auroral latitudes.

1. Introduction

The sub-auroral ionosphere is located equatorward of the auroral oval and usually involves the mid-latitude plasma density trough. The region usually features a plasma density depletion, significant meridional plasma density gradients, heightened electron temperatures, and fast sunward directed plasma flows. In the magnetosphere, these strong sunward flows are an important manifestation of plasma transport near the inner edge of the plasma sheet and the ring current.

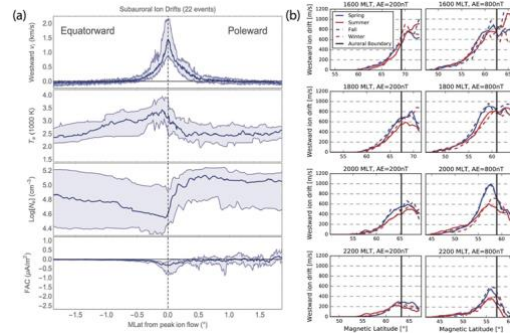


Figure 1: Measurements of SAIDs. (a) Superposed epoch analysis of SAIDs measured by Swarm satellites [modified from Archer and Knudsen, 2018]. (b) SAIDs predicted by empirical model reconstructed from statistical measurements of DMSP and DE satellites [modified from Landry and Anderson, 2018].

[\[Access high resolution Figure 1\]](#)

Sub-auroral plasma flows have been traditionally divided into two categories: the latitudinally narrow flows in the premidnight sector termed polarization jets (Galperin et al., 2002) or sub-auroral ion drifts (SAIDs) (Anderson et al., 1991; Spiro et al., 1979), and latitudinally broad flows on the duskside (e.g., Yeh et al., 1991) named sub-auroral polarization streams (SAPS) (Foster & Burke, 2002). Very often, the term SAPS encompasses latitudinally narrow ($<2^\circ$) and wider westward flows ($4\text{--}6^\circ$), without distinguishing between potentially different generation mechanisms (e.g., Mishin et al., 2017). Typically reported measurements of pre-midnight sub-auroral flows do not exceed ~ 2 km/s. Figure 1 shows examples of statistical analysis of fast sub-auroral flows. Traditionally, SAPS intensifications have been associated with substorms (e.g., Anderson et al. 1993, 2001; Erickson et al., 2002; Foster et al., 2004; Galperin, 2002; Mishin & Mishin, 2007); however, more recent observations have also found a connection between localized SAPS intensification and auroral streamers (e.g., Mishin and Puhl-Quinn, 2007; Gallardo-Lacourt et al., 2017) and showed that the sub-auroral flows have a high degree of variability (e.g., Kunduri et al., 2018). The association of SAPS with auroral streamers and substorm activity has garnered particular interest, and the influence of high-latitude mesoscale phenomena on the sub-auroral ionosphere is still understudied.

Over the last few decades, different mechanisms have been proposed to explain SAPS observations under different geomagnetic conditions. An early generation theory suggested that during periods of enhanced geomagnetic activity, a misalignment between the ion and electron Alfvén layers generates strong poleward-directed electric fields that drive westward $E \times B$ drifts (Gussenhoven et al., 1983). Currently, there are two well-known generation mechanisms for SAPS flows: the *current generator mechanism* and *voltage generator mechanism*. In the current generator mechanism (Anderson et al., 1993), the upward and downward Region-2 Field-Aligned-Currents (R2 FAC) are closed via a poleward directed Pedersen current, to maintain current continuity. This current closure is associated with a poleward directed electric field, which drives the observed westward moving plasma. The sub-auroral plasma recombines with neutrals due to the fast flows; it reduces the conductance of the sub-auroral ionosphere and increases the electric field. The voltage generator mechanism (Southwood and Wolf, 1978) discusses the charge separation observed in the magnetotail between plasma sheet electrons and ions. This charge separation gives rise to the tailward (poleward) directed electric field that produces the duskward (westward) flows in the magnetotail (in the ionosphere).

Both proposed mechanisms have allowed for a better understanding of the sub-auroral region. However, each ultimately falls-short of describing more dynamic sub-auroral events since both mechanisms have been formulated under the assumption of a quasi-static and slow varying magnetosphere-ionosphere system. In contrast, other mechanisms (e.g., Mishin, 2013) do not rely on a quasi-static approach and considers the dynamic nature of the region. Nevertheless, theoretical and modeling efforts have yet to explain many aspects of sub-auroral phenomena. In the following section, we provide examples of phenomena which the current modeling and theory fail to describe.

2. An extremely dynamic sub-auroral region

Within the past decade, optical observations of the sub-auroral region collected by citizen scientists have provided arguably the most compelling evidence that our contemporary understanding of the sub-auroral region is woefully inadequate. Furthermore, their observations, combined with in-situ satellite measurements, inform us that the magnitude and rapid evolution of the westward plasma flows described above are severely underestimated by our ground-based measurements, models, and theories of the region. With the improvement of commercially available optical instruments, many branches of the sciences (such as astronomy, solar science, and aeronomy) have benefited from an active, engaged, and growing community of citizen scientists. Citizen scientists are credited with the discovery of an optical phenomena in the sub-auroral region named

STEVE (MacDonald et al., 2018; Gallardo-Lacourt et al., 2019), which is associated with extreme SAIDs featuring westward plasma flows of the order of orbital speeds (Archer et al., 2019a). The research on this topic has evolved fast, with the first publication being cited almost 80 times in four years, and several papers using a combination of traditional scientific instruments and citizen scientists' observations (e.g., Archer et al., 2019b; Nishimura et al., 2019; Martinis et al., 2021). Although the main focus of this white paper is not centered on citizen scientists' observations in particular, it is important to highlight that many of the recent scientific advancements around the auroral ionosphere have been triggered—or at least supported—by collaborations with citizen scientists. This is not limited to STEVE, major scientific advances have also been made for other types of auroral and sub-auroral phenomena with the aid of citizen scientists' observations (e.g., MacDonald et al., 2015, 2018; Palmroth et al., 2020; Martinis et al., 2021; Nishimura et al., 2022). Therefore, the future research on Heliophysics science needs to fully embrace this synergistic relationship.

Recommendation #1

Since the release of the last decadal survey, some of the most significant and impactful advances in sub-auroral science have been a direct result of the devotion of the citizen science community and their hard work, and the interactions between that community and the “traditional” science community. Indeed, their impact can be quantified: as of August 2022, the original STEVE publication (MacDonald et al., 2018) has been cited almost 80 times and featured in over 120 news stories (sourced from Altmetric). In addition, many of the articles on STEVE cited above have been featured in media articles around the world. Accordingly, *new and long-term support for unifying the citizen and “traditional” science communities are required to sustain observations and discovery in sub-auroral science.*

Equatorward of the auroral oval, the fast and narrow plasma flows and electron temperatures associated with STEVE are an unprecedented observation in the sub-auroral ionosphere, prompting a reexamination of older datasets (e.g., Pfaff and Halford, 2020). STEVE's generation mechanism along with many of its other unique features are still under intense debate. The challenges associated with studying the phenomena are exacerbated by the fact that measurement thresholds and sampling targets for existing and prospective in situ rocket and spacecraft missions are insufficient for fully specifying the *known* values of the flows and temperatures associated with STEVE.

Figure 2 shows Swarm B measurements of a STEVE event with cross-track plasma velocities of the order of 10 km/s and electron temperatures well above 10,000 K. Measurements of such extreme conditions are often limited by the instrument's capabilities which are often designed according to the expected range of measurements. For example,

the Swarm Electric Field Instrument (EFI; Knudsen et al., 2017), which was first to reveal the extreme plasma dynamic underway in the vicinity of a STEVE event, was not calibrated for the extreme temperatures displayed in Figure 2 since those temperatures and flows were not expected to be encountered anywhere in the topside F-region ionosphere.

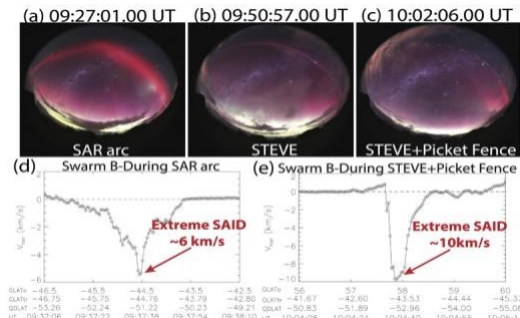


Figure 2: Citizen scientists’ images showing the transition from (a) SAR arc, (b) to STEVE, to a final observation of the (c) Picket Fence. From Swarm data, the (d) SAR arc is associated with a fast SAID of $\sim 6\text{km/s}$ and (e) STEVE with an extreme SAID of $\sim 10\text{ km/s}$ [Modified from Martinis et al., 2022].

These extreme conditions have motivated reevaluations of intense subauroral electric fields measured by decommissioned spacecrafts (e.g., Dynamics Explorer-2), once thought as improbable (e.g., Pfaff and Halford, 2020). Consider, for example, the extreme velocities shown in Figure 2 which could be interpreted as “unrealistic”. However, when these spacecraft measurements are combined with citizen science observations of an optical phenomena (e.g., STEVE) and

determined to be collocated with the spacecraft measured extreme flows, which is done in Figure 2, the previously “unrealistic” flows are re-interpreted as “plausible”.

[\[Access high resolution Figure 2\]](#)

In recent years, spectrographic measurements and particle data have revealed that these optical structures are related to interesting dynamics and chemistry in Earth’s upper atmosphere. Mendillo et al. (2016) reported a stable auroral red (SAR) arc in the sub-auroral ionosphere with multiple emission features. Previously, SAR arcs had been distinguished by their “spectral purity” (Kozyra et al., 1997) compared to other emissions observed in the sub-auroral or auroral zone. Similarly, several studies have reported on STEVE’s continuous emission that appears to be unrelated to particle precipitation (Gallardo-Lacourt et al., 2018a; Gillies et al., 2019; Nishimura et al., 2019). Additional studies noted that the green emissions of the “picket fence” frequently observed with STEVE are too spectrally pure, consistent with the notion that precipitation of magnetospheric origin is not responsible for the green emissions (Mende et al., 2019; Semeter et al., 2020). Reports on the picket fence phenomenon would not have been possible without the use of citizen science data, emphasizing our challenges to study the sub-auroral region. In general, all these observations highlight our limited understanding of the chemistry of the lower-thermospheric region, how it varies with altitudes, and its response to dynamic conditions, pointing to a clear need for a better understanding of the vertical variations of the region.

In-situ measurements of the sub-auroral ionosphere obtained by satellites provide information at a fixed altitude in the sub-auroral ionosphere (e.g., Swarm and DMSP). SAID, originally referred to as polarizations jets, were first reported by Galperin et al. (1973). Key sub-auroral physics results have also stemmed from DMSP (e.g., Anderson et al., 1991) and, more recently, Swarm observations (e.g., Archer et al., 2019a). Some of the important aspects of in situ measurements in the region are the altitude, UT, and MLT dependence of various signatures. For example, DMSP, at 855 km altitude, observes SAID differently than Swarm, at approximately 480 km altitude. This is illustrated in Figure 3 (unpublished, courtesy of W. E. Archer), which shows DMSP F18 and Swarm measurements of an SAID, taken at nearly the same geographic location (but different altitudes), within 1 hour of each other. While the cross-track plasma flow profiles of both spacecraft are very similar, the plasma density profiles are not. DMSP, at a higher altitude,

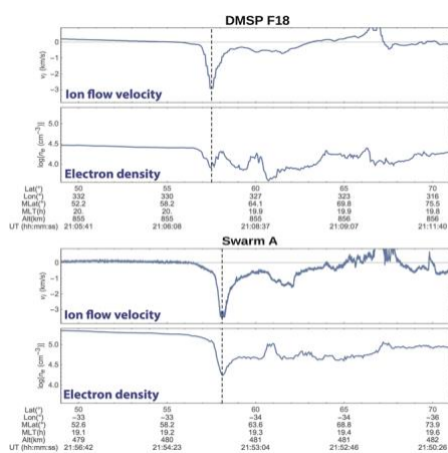


Figure 3: DMSP F18 (upper panels) and Swarm A (lower panels) measurements of the sub-auroral ionosphere. DMSP measured a less prominent plasma density depletion associated with the SAID.

measured a less prominent plasma density depletion associated with the SAID. If this difference is solely due to altitude effects, the larger density depletion at lower altitudes could be due to stronger recombination. In some plasma density altitude comparison cases, an “anti-trough” is observed at the higher altitude measurements (Anderson et al., 1991).

Despite existing in situ measurements of SAID and other sub-auroral dynamics provided by satellites (e.g., DMSP, Swarm), a lack of contemporaneous measurements of electric fields, energetic particles, and magnetic fields at appropriate altitudes (less than 400 km) is still required to advance our understanding of the region and its dynamics.

[\[Access High resolution Figure 3\]](#)

Recommendation # 2

Accurate satellite measurements at altitudes of 400 km or less are essential to understanding the extreme dynamic reported in the sub-auroral ionosphere. *NASA’s Geospace Dynamics Constellation (GDC) mission will provide the measurements required to address and close many outstanding sub-auroral science questions and should be carried-out without delay.*

Ground-based instrumentation in the sub-auroral region—such as all-sky imagers, spectrographs, meridian scanning photometers, radars, among others—has been essential for the scientific development in recent years (e.g., Gallardo-Lacourt et al., 2018b; Gillies et al., 2019; Nishimura et al., 2020). Continuous support of these arrays and facilities is needed to maintain scientific productivity and improve our understanding of the sub-auroral ionosphere. In addition, coherent and incoherent scatter radars have provided a great deal of information, increasing our understanding of the auroral and sub-auroral regions (e.g., Zou et al., 2009; Kunduri et al., 2018;

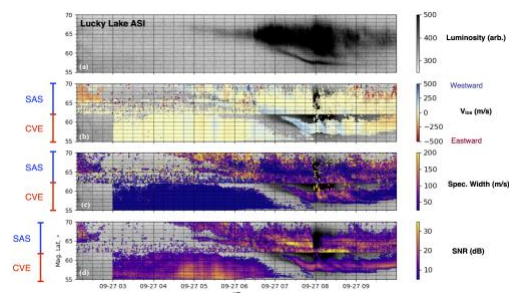
Ae et al., 2020). In particular, incoherent scatter radars (ISR) are excellent at providing localized altitudinal profiles of density, temperature, and velocities (Erickson et al., 2011); however, while very powerful, these instruments are sparsely located and seldomly capture the sub-auroral ionosphere.

On the other hand, coherent scatter radars, such as SuperDARN, provide a comprehensive coverage of the auroral and sub-auroral ionosphere (Nishitani et al., 2019) making them ideal to study the plasma properties during intense sub-auroral events (e.g., Oksavik et al 2011; Perry et al., 2017). However, a recent study notes that radar echoes may disappear when optical signatures of extreme sub-auroral plasma conditions are observed (Perry et al., 2019). Figure 4 shows an observation of STEVE; while the echoes at higher latitudes (Saskatoon; SAS) remained unaltered, the sub-auroral radar (Christmas Valley East; CVE) showed an echo depletion prior to STEVE.

Despite the lack of a comprehensive statistical analysis to conclusively determine if the echo disappearance during STEVE events is a recurrent effect, this phenomenon has been dubbed as the *STEVE effect*. Further analysis is required to understand whether this effect is produced by instrumental limitations (e.g., oversensitive SuperDARN echo rejection algorithm) or a geophysical response (e.g., radio wave propagation conditions). Numerical ray trace modeling supports the latter (Perry et al., 2019). Another unexplored possibility for the disappearance of SuperDARN echoes during STEVE events (e.g., Figure 4) is that the field-aligned irregularities, which are suspected of being the main source of backscatter target for SuperDARN radars, are dampened by the conditions associated with STEVE. Given the extreme gradients expected in the geophysical parameters during STEVE, this is a possibility and could be tested out using models like Rathod et al., (2021). However, due to the sparsity of facilities (ionosondes, incoherent scatter radar, etc.) it is difficult to test any of these theories in regions where STEVE occurs and gain insight into the aforementioned characteristics and effects. Therefore, a combination of ground-base and in-situ measurements, as well as improvements in our theoretical and modeling approaches in the region are needed to make real progress on understanding the dynamic and rapidly changing sub-auroral ionosphere.

Recommendation # 3

The existing capabilities of ground-based infrastructure to remotely sense the ionosphere is too sparse in geographic distribution in the sub-auroral region within the United States. ***New and long term support in ground-based observations infrastructure is needed to better understand***



the nature and dynamics of the sub-auroral ionosphere.

Figure 4: (a) Keogram of STEVE observed at Lucky Lake. (b-d) combined radar echoes from the SAS high-latitude radar and CVE mid-latitude radar. Echoes at high-latitude remained unchanged during the STEVE observation, while the echoes at mid-latitude disappear at the time of STEVE [From Perry et al., 2019].

[\[Access high resolution Figure 4\]](#)

Perhaps one of the most difficult questions to answer while evaluating generation mechanisms for the extreme conditions observed in the sub-auroral region, is the role of the thermosphere and lower atmosphere during these events. Satellite measurements, while fundamental to study the region, cannot provide key measurements of the ionosphere-thermosphere system; however, rockets can easily cover this altitudinal issue. In addition, currently available ISR are often located poleward of the sub-auroral ionosphere and do not measure the region continuously. The challenges and open questions presented above suggest a great opportunity for new and affordable technology to be developed, and the potential implementations of well-known measuring techniques, such as sounding rockets. Sounding rocket campaigns have been instrumental in the understanding of the lower-atmosphere and the ionosphere (e.g., Pfaff et al., 2004). The heliophysics community has gained vast experience on the use of sounding rockets to study the geospace environment (e.g., Lynch et al., 2005; Collier et al., 2015) and the Sun (e.g., Burton & Wilson, 1965). Such expertise, together with the development of new technology and instruments, and the combination of available space and ground-base instrumentation, could provide new insights on the physics of the lower-thermosphere-ionosphere at sub-auroral region, commonly dubbed *the ignosphere* due to the lack of measurements (Palmroth et al., 2020)

Recommendation # 4

In situ measurements of the lower-thermosphere in the sub-auroral region by rockets, low-altitude satellites, and/or some other techniques are required to conclusively identify the source, energetic pathways, and mechanism of the extreme conditions reported at sub-auroral latitudes.

3. Summary

The sub-auroral region is one of the most dynamic regions in the coupled Magnetosphere-Ionosphere-Thermosphere system. Recent measurements and observations highlight the necessity to deploy ground-based instruments with better coverage of the sub-auroral lower-thermosphere-ionosphere region, improving our modeling capabilities, and take advantage of in-situ measuring techniques such as sounding rockets. Our main recommendations can be summarized as the follow:

1. Establishing new and long-term support for unifying citizen and “traditional” scientists is required to sustain observations and discovery in sub-auroral science.
2. NASA’s Geospace Dynamics Constellation (GDC) mission is required to address and close many outstanding sub-auroral science questions and should be carried-out without delay.
3. New and long-term support for ground-based observations infrastructure is needed to better understand the nature and dynamics of the sub-auroral ionosphere. Existing infrastructure is too sparse in geographic distribution in the sub-auroral region within the United States.
4. In situ measurements of the lower-thermosphere in the sub-auroral region by rockets, low-altitude satellites, and/or some other techniques are required to conclusively identify the source, energetic pathways, and mechanism of the extreme conditions reported at sub-auroral latitudes.

References

- Aa et al., 2020, doi: [10.1029/2020JA028584](https://doi.org/10.1029/2020JA028584)
- Anderson et al., 1991, doi: [10.1029/90JA02651](https://doi.org/10.1029/90JA02651)
- Anderson et al., 1993, doi: [10.1029/92JA01975](https://doi.org/10.1029/92JA01975)
- Anderson et al., 2001, doi: [10.1029/2001JA000128](https://doi.org/10.1029/2001JA000128)
- Archer & Knudsen, doi: [10.1002/2017JA024577](https://doi.org/10.1002/2017JA024577)
- Archer et al., 2019a, doi: [10.1029/2019GL082687](https://doi.org/10.1029/2019GL082687)
- Archer et al., 2019b, doi: [10.1029/2019GL084473](https://doi.org/10.1029/2019GL084473)
- Burton and Wilson, 1965, doi: [10.1038/207061a0](https://doi.org/10.1038/207061a0)
- Collier et al., 2015, doi: [10.1016/j.asr.2015.08.010](https://doi.org/10.1016/j.asr.2015.08.010)
- Erickson et al., 2002, doi: [10.1029/2000RS002531](https://doi.org/10.1029/2000RS002531)
- Erickson et al., 2011, doi: [10.1029/2010JA015738](https://doi.org/10.1029/2010JA015738)
- Foster & Burke, 2002, doi: [10.1029/2002EO000289](https://doi.org/10.1029/2002EO000289)
- Foster et al., 2004, doi: [10.1029/2004GL021271](https://doi.org/10.1029/2004GL021271)
- Gallardo-Lacourt et al., 2017, doi: [10.1002/2017JA024198](https://doi.org/10.1002/2017JA024198)
- Gallardo-Lacourt et al., 2018a, doi: [10.1029/2018GL078509](https://doi.org/10.1029/2018GL078509)
- Gallardo-Lacourt et al., 2018b, doi: [10.1029/2018JA025368](https://doi.org/10.1029/2018JA025368)
- Gallardo-Lacourt et al., 2019, doi: [10.1029/2019EO117351](https://doi.org/10.1029/2019EO117351)
- Galperin et al., 1973, Direct measurements of ion drift velocity in the upper ionosphere during a magnetic storm.
- Galperin, 2002, doi: [10.5194/angeo-20-391-2002](https://doi.org/10.5194/angeo-20-391-2002)
- Gillies et al., 2019, doi: [10.1029/2019GL083272](https://doi.org/10.1029/2019GL083272)
- Gussenhoven et al., 1983, doi: [10.1029/JA088iA07p05692](https://doi.org/10.1029/JA088iA07p05692)
- Knudsen et al., 2017, doi: [10.1002/2016JA022571](https://doi.org/10.1002/2016JA022571)
- Kozyra et al. 1997, doi: [10.1029/96RG03194](https://doi.org/10.1029/96RG03194)
- Kunduri et al., 2018, doi: [10.1029/2018JA025690](https://doi.org/10.1029/2018JA025690)
- Landry & Anderson, 2018, doi: [10.1002/2017JA024921](https://doi.org/10.1002/2017JA024921)
- Lynch et al., 2005, doi: [10.1029/2004JA010502](https://doi.org/10.1029/2004JA010502)
- MacDonald et al., 2015, doi: [10.1002/2015SW001214](https://doi.org/10.1002/2015SW001214)
- MacDonald et al., 2018, doi: [10.1126/sciadv.aag0030](https://doi.org/10.1126/sciadv.aag0030)
- Martinis et al., 2021, doi: [10.1029/2020GL092169](https://doi.org/10.1029/2020GL092169)
- Martinis et al., 2022, doi: [10.1029/2022GL098511](https://doi.org/10.1029/2022GL098511)
- Mende et al., 2019, doi: [10.1029/2019GL086145](https://doi.org/10.1029/2019GL086145)
- Mendillo et al., 2016, doi: [10.1002/2016JA023258](https://doi.org/10.1002/2016JA023258)
- Mishin & Mishin, 2007, doi: [10.1016/j.jastp.2006.09.009](https://doi.org/10.1016/j.jastp.2006.09.009)
- Mishin & Puhl-Quinn, 2007, doi: [10.1029/2007GL031925](https://doi.org/10.1029/2007GL031925)
- Mishin, 2013, doi: [10.1002/jgra.50548](https://doi.org/10.1002/jgra.50548)
- Mishin et al., 2017, doi: [10.1002/2017JA024263](https://doi.org/10.1002/2017JA024263)
- Nishimura et al., 2019, doi: [10.1029/2019GL082460](https://doi.org/10.1029/2019GL082460)
- Nishimura et al., 2020, doi: [10.1029/2020JA028067](https://doi.org/10.1029/2020JA028067)
- Nishimura et al., 2022, doi: [10.1029/2022JA030570](https://doi.org/10.1029/2022JA030570)
- Nishitani et al., 2019, doi: [10.1186/s40645-019-0270-5](https://doi.org/10.1186/s40645-019-0270-5)
- Oksavik et al., 2011, doi: [10.1029/2011JA016788](https://doi.org/10.1029/2011JA016788)
- Palmroth et al., 2020, doi: [10.1029/2019AV000133](https://doi.org/10.1029/2019AV000133)
- Pfaff et al., 2004, doi: [10.2514/1.11945](https://doi.org/10.2514/1.11945)
- Pfaff & Halford, 2020, [Enhanced DC Electric Fields Associated with Sub-Auroral Polarization Streams and “STEVE” Auroral Displays within Evolving Sub-Storms](#)
- Perry et al., 2017, doi: [10.1002/2016RS006142](https://doi.org/10.1002/2016RS006142)
- Perry et al., 2019, doi: [10.13140/RG.2.2.30940.05762](https://doi.org/10.13140/RG.2.2.30940.05762)
- Rathod et al., 2021, doi: [10.1029/2020JA029027](https://doi.org/10.1029/2020JA029027)
- Semeter et al., 2020, doi: [10.1029/2020AV000183](https://doi.org/10.1029/2020AV000183)
- Southwood & Wolf, 1978, doi: [10.1029/JA083iA11p05227](https://doi.org/10.1029/JA083iA11p05227)
- Spiro et al., 1979, doi: [10.1029/GL006i008p00657](https://doi.org/10.1029/GL006i008p00657)
- Yeh et al., 1991, doi: [10.1029/90JA02751](https://doi.org/10.1029/90JA02751)
- Zou et al., 2009, doi: [10.1016/j.jastp.2008.06.015](https://doi.org/10.1016/j.jastp.2008.06.015)