The case for a rocket campaign targeting subauroral dynamics

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Abstract

Recent optical observations in the subauroral region highlight the need for better measurements in an area of the ionosphere colloquially termed the "ignorosphere." Examples include STEVE's unusual multi-wavelength emissions (e.g., Gillies et al., 2019; Mende et al., 2019) which have been theorized to be excited in situ and not by precipitation (e.g., Harding et al., 2020; Gallardo-Lacourt et al., 2018; Nishimura et al., 2019). Fundamental questions pertaining to STEVE cannot be closed without in situ measurements of the composition of the neutral and ionized gasses. In addition, direct reports on the temporal and spatial evolution (order of minutes) from bright SAR arcs into STEVE (e.g., Martinis et al., 2022) highlight the rapid and extreme dynamics that take place in the subauroral region. Both of these phenomena have been linked to subauroral ion drifts (SAID).

While several quasi-stationary theories have attempted to explain the formation of such fast subauroral flows (e.g., Anderson et al., 1993; Mishin et al., 2003), they cannot explain the temporal evolution reported in recent years. Moreover, no currently existing models simultaneously capture the plasma dynamics, neutral chemistry, photochemistry, and magnetosphere-ionosphere interactions that are required to reproduce the extreme conditions reported by the new studies. To fully understand the rapid and small-scale dynamics of the subauroral ionosphere and to inform future model development, new in-situ subauroral measurements are required not only in the zonal and meridional components, but also in altitude.

Ground-based measurements and satellite data (e.g., SuperDARN, Swarm, DMSP) currently do not provide the measurements required to fully study the sub-auroral ionosphere. Although Incoherent Scatter Radars could provide the needed vertical profiles in a limited area, most of these instruments are located either poleward or equatorward from the area of interest. However, sounding rockets possess the capability to directly measure the altitudinal profiles of the subauroral region. Sounding rocket campaigns, therefore, present a potential opportunity to help us understand the observed temporal and spatial evolution of phenomena associated with intense subauroral ion drifts.

Introduction

- The recent discovery of new subauroral optical structures highlights the necessity for better understanding of the subauroral ionosphere
- In particular, fast subauroral flows termed Subauroral Ion Drifts (SAIDs) need to be studied carefully

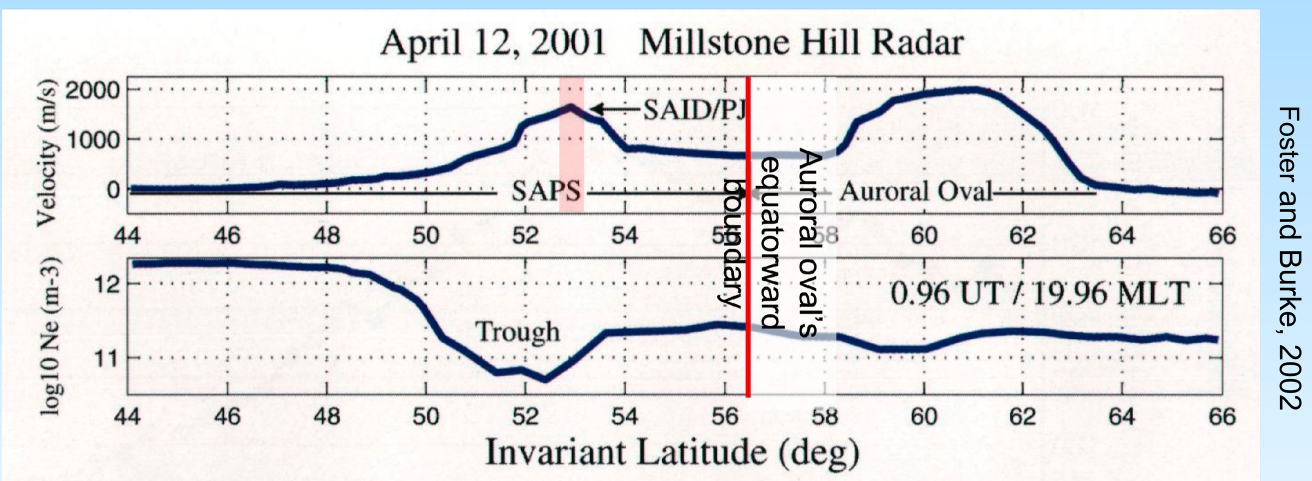

Figure 1: Subauroral polarization streams (SAPS) measured by Millstone Hill Radar (Foster and Burke, 2002). Embedded in the SAPS flows, there is a region of faster flows termed Subauroral ion drift (SAID). SAPS, is collocated with a region of depleted electron density called plasma trough.

- Currently available instruments (e.g., DMSP, Swarm, SuperDARN, ISR, etc) have provided an unprecedented view of the subauroral ionosphere

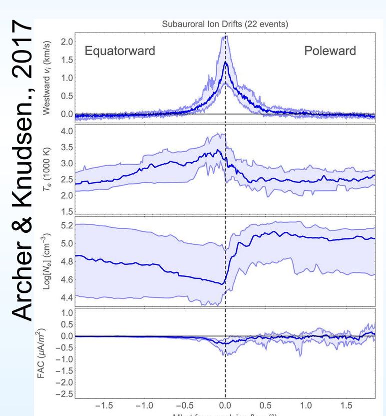

Figure 2: Archer et al. (2017) used the Swarm satellites to study SAIDs and distinguish these flows from BCBFs (Birkeland Current Boundary Flows)

- However, these instruments were not designed to detect and study these extreme dynamics as they were not expected (e.g., MacDonald et al. (2018); Archer et al., 2019; Martinis et al., (2022)).

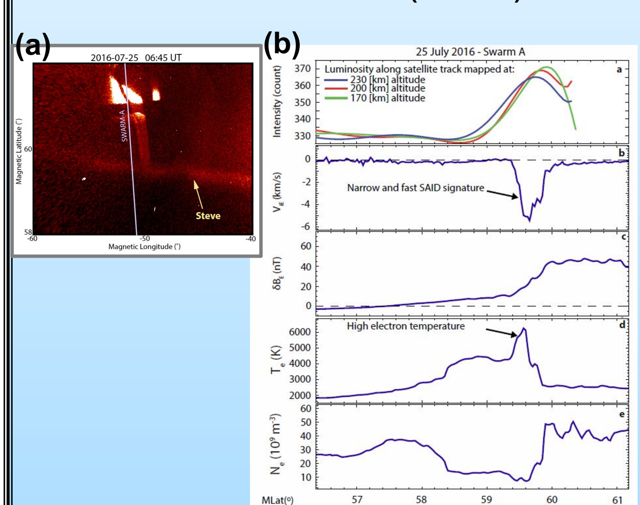

Figure 3: MacDonald et al., 2018. First report of STEVE and SAID extreme conditions. (a) STEVE observation at LUCK-REGO. Swarm-A orbit in purple. (b) Extreme conditions measured by Swarm-A: Fast and narrow SAID and high Te

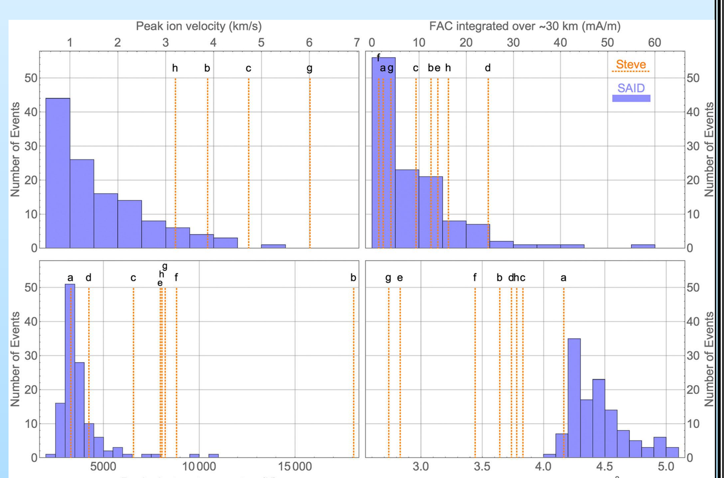

Figure 4: Archer et al., 2019. Statistical study of STEVE's extreme conditions. Extreme plasma parameters measured coincident with Steve events (orange dashed lines), compared to 122 SAIDs measured by Swarm satellites

Recent observations of extreme conditions

- Recent observations have revealed more intense SAIDs
- Martinis et al. (2022) reported a SAR arc evolving into STEVE during the St. Patrick day storm of 2017

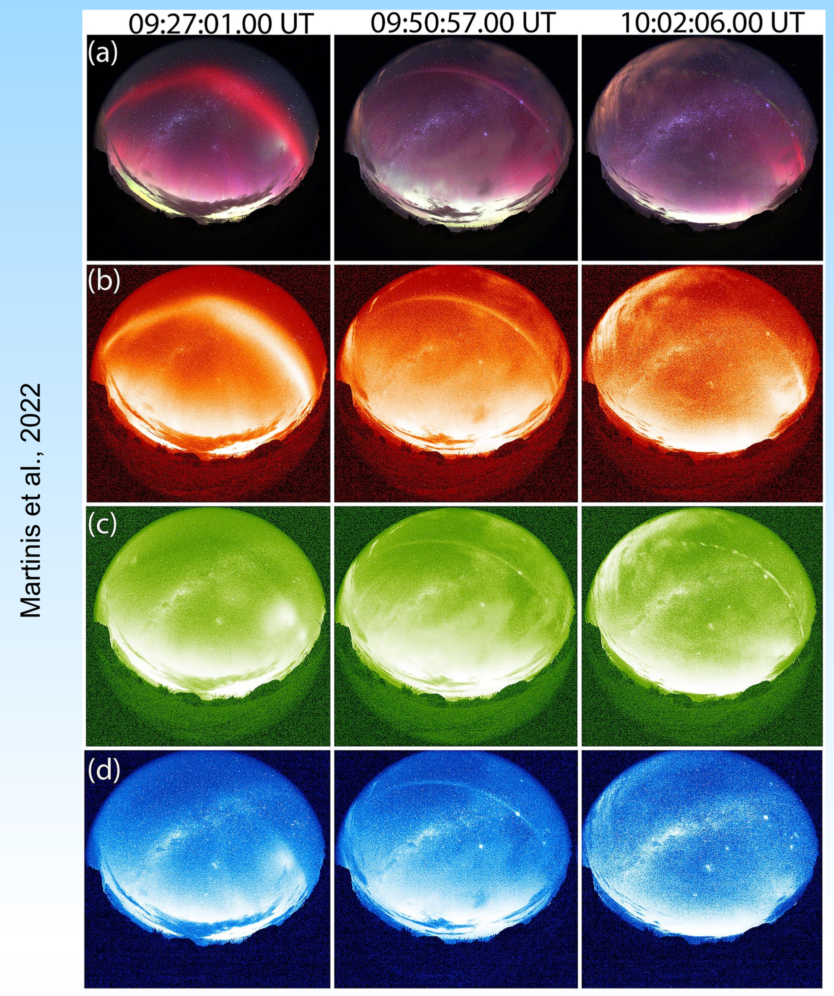

Figure 5: Martinis et al.,(2022) reported the transition of SAR arc into STEVE on 17 March 2015. (a) Temporal evolution of a SAR arc (left), into a STEVE (middle) and Picket Fence observations (right). (b) Temporal evolution on red channel. (c) Temporal evolution in green channel. (d) Temporal evolution in blue channel. The SAR arc is only observed in the red channel (left). STEVE is visible in the three channels (middle); and the Picket Fence is only detected in the green channel. This is consistent with the spectrographic measurements reported by Kozyra et al. (1997) for SAR arcs, and Gillies et al. (2019) for STEVE. However, theoretically there is no apparent link between the SAR arc mechanism (heat conduction) and

- Swarm-B satellite crossed the subauroral region during this event
- Swarm satellite detected a fast (~5.5 km/s) SAID coincident with the SAR arc observation
- Once STEVE developed, the SAID observed was narrower than that observed for during the SAR arc and faster, ~10 km/s
- Interestingly, the bright (6kR) SAR arc during this event is ~10 times brighter than typical SAR arcs and thus appears unlikely to be associated with the *Kozyra et al* (1997) mechanism

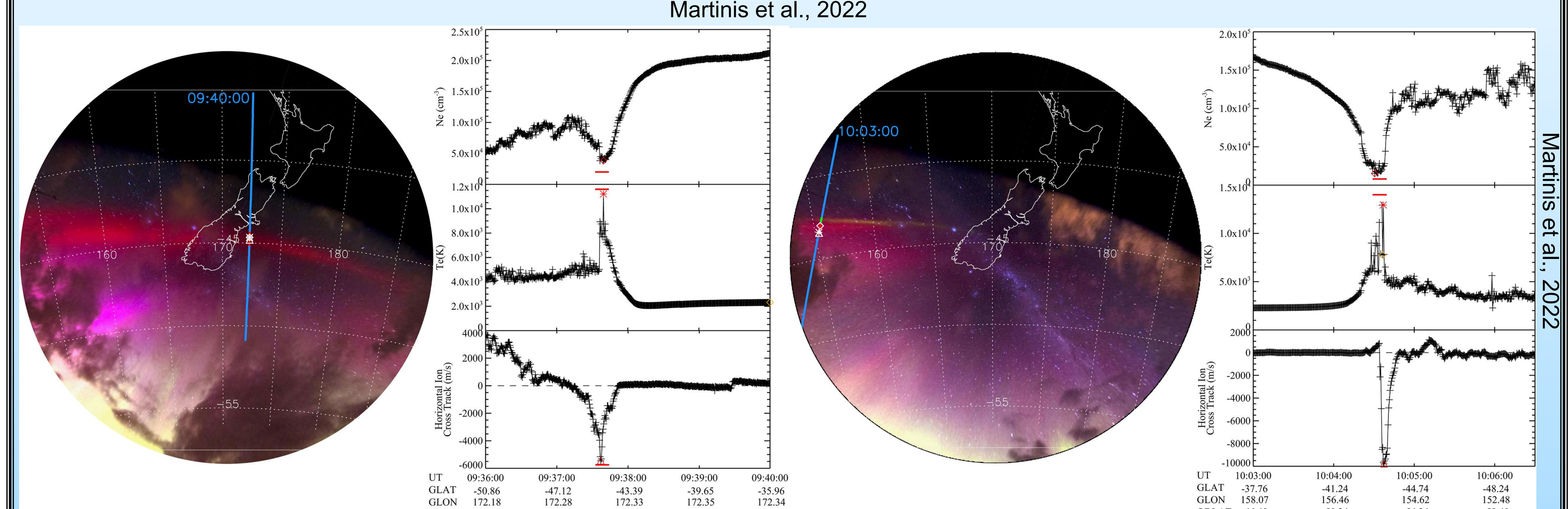

Figure 6: Swarm measurements reported during the SAR arc (left) and STEVE (right).

(left) Fast and narrow SAID of ~5.5 km/s was observed during the SAR arc observations and electron temperature of 12000 K. These measurements were collocated with a depleted plasma trough.

(Righ) During the STEVE observation, the observed SAID was narrower and faster, ~10 km/s. The electron temperature was also higher, ~14000 K. The electron density was also lower during the STEVE event

Open questions

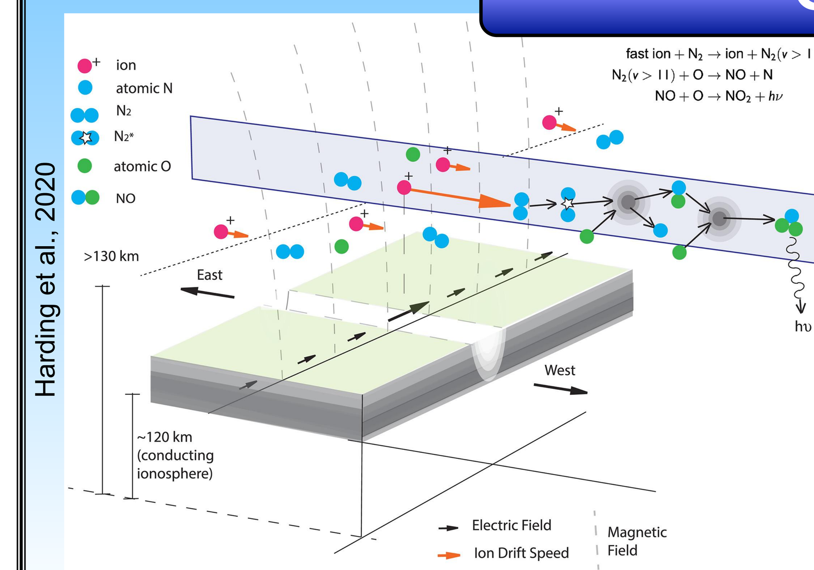

Figure 7: Harding et al. (2020) proposed a theoretical mechanism for the generation of STEVE emissions

- Harding et al. (2020) used a simple photochemical model to produce a theoretical approach for the generation of the unique STEVE optical signature
- In this approach nitrogen molecules are vibrationally excited by collisions with fast ions in SAIDs, overcoming the activation energy of the N_2+O→NO+N reaction
- The resulting NO combines with ambient O, producing NO_2 and spectrally broad light (STEVE)
- This hypothesis needs observational confirmation
- However, several questions remain:
  - What causes the picket fence emission?
  - What is the composition in the lower thermosphere in the subauroral region and how does it change during SAID and extreme SAID events?
  - How do the temporal and spatial characteristics of subauroral electric fields evolve?
  - Are the brighter SAR arcs associated with STEVE generated in the same way as SAR arcs addressed in the literature? (e.g., Kozyra et al., 1997; Fok et al., 1991; Sazykin et al., 2002).
  - Is pre-conditioning required to enable STEVE events; if so, what are requirements?
  - Substorms have been associated with SAIDs and STEVE, however these phenomena are less common than substorms. What's unique to STEVE/SAID related substorms?

Why do we need a rocket campaign?

- A rocket campaign will allow us to analyze in-situ vertical profiles and temporal evolution of the subauroral region in a region of the ionosphere-thermosphere system that is largely inaccessible to other measurement techniques. Parameters of interest include:
  - Electric field
  - Superthermal electron spectrum
  - Plasma and neutral temperatures
  - Neutral composition (e.g., [NO]) and winds
  - Electromagnetic and kinetic energy inputs
- These measurements will allow us to gain insight into the generation mechanism of SAID/SAPS and their extreme plasma dynamics.
- A final important question: where should the rockets launch from?
  - Facilities like Wallops Island may be too far south.
  - Poker Flat's allowable rocket launch corridors may not be suitable for sampling the sub auroral ionosphere-thermosphere system.
  - New facilities in Europe (including France and Scotland) may be suitable.

Summary and Conclusions

- Recent observations of the sub auroral ionosphere-thermosphere system reveal new and compelling plasma dynamics that is not well understood
- A rocket campaign is necessary to obtain a vertical profile of subauroral plasma properties during SAID and/or extreme SAID
- Multiple rockets could allow us for better statistics during different geomagnetic conditions/different SAID magnitudes
- Existing instruments and missions are crucial to complement these in-situ measurements and can help us obtain a complete picture of the subauroral evolution

Acknowledgements

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