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Key Points:
- First study of STEVE event in conjunction with POES satellite suggests ionospheric origin of STEVE
- This STEVE event is not aurora. Particle precipitation is not observed for this event
- STEVE's skyglow could be associated with protons below 50 eV or generated by a fundamentally different mechanism in the ionosphere

Supporting Information:
- Supporting Information S1
- Movie S1

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On the Origin of STEVE: Particle Precipitation or Ionospheric Skyglow?

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Abstract One of the recent developments in ionospheric research was the introduction of a subauroral spectacle called STEVE (Strong Thermal Emission Velocity Enhancement). Although STEVE has been documented by amateur night sky watchers for decades, it is an exciting new upper atmospheric phenomenon for the scientific community. Observed first by amateur auroral photographers, STEVE appeared as a narrow luminous structure across the night sky. Currently, only one scientific study has focused on STEVE, revealing that it corresponds to a narrow (tens of kilometers in north-south extent) and long (thousands of kilometers in east-west direction) structure located in the subauroral region. An important and fundamental question that arises from this study is the origin of STEVE; more specifically, does STEVE correspond to a new ionospheric phenomenon or is it due to particle precipitation? In this letter, we analyze a STEVE event on 28 March 2008 observed by Time History of Events and Macroscale Interactions during Substorms (THEMIS) ground-based All-Sky Imagers and a Polar Orbiting Environmental Satellite (POES). The POES-17 satellite crossed STEVE at the center of the All-Sky Imager field-of-view, allowing us to collect particle data simultaneously. These concurrent measurements show that STEVE might not be associated with particle precipitation (electrons or ions). Therefore, this event suggests that STEVE's skyglow (which we defined to be unrelated to aurora or airglow) could be generated in the ionosphere.

Plain Language Summary Recently, the scientific community stumbled upon a rare atmospheric phenomenon called Strong Thermal Emission Velocity Enhancement (STEVE) that has been well documented by amateur auroral photographers for decades. STEVE appears across the night sky as an extremely narrow ribbon of vibrant purple and white hues. In this letter, we address an important fundamental question: Is STEVE caused by particle precipitation like aurora or is it produced by a new ionospheric phenomenon? We analyzed a STEVE event using a network of ground-based All-Sky Imagers across Canada and energetic particle detectors on one of National Oceanic and Atmospheric Administration's Polar Orbiting Environmental Satellites. Our results verify that this STEVE event is clearly distinct from the aurora since it is characterized by the absence of particle precipitation. Interestingly, its skyglow could be generated by a new and fundamentally different mechanism in the ionosphere.

1. Introduction

The energy that powers the aurora is extracted from the solar wind plasma through its interaction with the Earth's magnetic field. In the aurora, the electrons and protons originate in regions of the Earth's magnetosphere where the magnetic field is not connected to the solar wind. Some particles originate from the solar wind, and others have its source in Earth's upper atmosphere. The relative contributions of both sources to the magnetospheric plasma are still poorly understood. However, the basic mechanism for the aurora is fairly straightforward. In the ionosphere, electrons precipitate along the magnetic field lines and collide and energize particles in the atmosphere that, in turn, emit photons producing what is known as electron aurora (Banks et al., 1974; Berger et al., 1970; Ress, 1963, 1969). For precipitating protons (or proton aurora), they undergo charge exchange collisions with atmospheric particles and produce hydrogen atoms in an excited state (Donovan et al., 2013; Lui & Anger, 1973; McIlwain, 1960, and references therein).

Other optical emissions observed in the Earth's upper atmosphere are collectively known as airglow (and often referred to as dayglow or nightglow; Solomon, 2017, and references therein). Airglow is the emission of light at discrete wavelengths throughout the spectrum and is produced by chemical reactions of incoming solar radiation with atoms and molecules in the upper atmosphere (Silverman, 1970; Solomon, 1991).

Recently, the scientific community stumbled upon an optical phenomenon that was well known to amateur auroral enthusiasts as "Steve." MacDonald et al. (2018) reported one Steve event observed by ground optical data in conjunction with Swarm satellite measurements. In optical data from the Redline Emission Geospace Observatory (REGO) All-Sky Imager (ASI) at Lucky Lake, Steve developed adjacent to and equatorward of the aurora (i.e., in the suburoral region) and was observed for approximately 1 hr across the Lucky Lake imager field-of-view (FOV). Its structure extended length-wise thousands of kilometers in the east-west direction but had a width of only tens of kilometers in the north-south direction. In addition to Steve, MacDonald et al. (2018) reported an unstable green feature resembling a *picket fence* also propagating westward. At the same time that Steve was observed, the Swarm-A satellite crossed the location of the emission, revealing that the observed luminosity was collocated with a very hot stream (~6,000°K) of very fast (>6 km/s) moving ions less than 50 km in north-south extent. In addition, Swarm-A measured a small magnetic field perturbation, which suggests that Steve may not be associated with the upward field-aligned current as in auroral arcs (Baumjohann, 1983; Kamide & Akasofu, 1976, and references therein). Because of these observed characteristics, the name Steve was converted into a backronym and defined as Strong Thermal Emission Velocity Enhancement or STEVE.

The MacDonald et al. (2018) study was the first scientific publication on STEVE. However, it was limited by lack of available particle data to determine if the observed optical structure was generated by particles precipitating into the atmosphere (similar to auroral arcs, i.e., Hultqvist et al., 1971; Lyons, 1980, 1981; Feldstein & Galperin, 1985, and references therein) or the result of a different (and possibly new) ionospheric process.

In this letter, we report a STEVE event measured by Time History of Events and Macroscale Interactions during Substorms (THEMIS) ASIs in conjunction with the Polar Orbiting Environmental Satellite (POES)-17 (also known as National Oceanic and Atmospheric Administration (NOAA)-17 satellite) that passed directly across the ground-based camera's FOV during the event. The particle data presented in this paper were only measured during a STEVE event. The picket fence was not observed at the time POES-17 crossed the structure. The POES satellites are in a Sun-synchronous orbit at an altitude of ~800 km with an orbital period of ~100 min. The POES-17 particle data showed no evidence of particle precipitation (ions and electrons) associated with STEVE, at least within the energy range of the POES instruments. Consequently, this important result suggests that STEVE's emission or skyglow signature might not be associated with aurora (i.e., particle precipitation). As a note, we have used the term "skyglow" to refer to the structured emission of STEVE, which could be unrelated to aurora and airglow. Moreover, skyglow should not be confused with the structureless glow observed associated with light pollution. Based on our results, we assert that STEVE is likely related to an ionospheric process; however, at this point, we are not able to evaluate the magnetospheric contributions responsible for the formation of STEVE.

2. The 28 March 2008 Event

The STEVE event reported in this paper was observed over eastern Canada on 28 March 2008 and detected above the THEMIS ASI Kapuskasing (KAPU) station. THEMIS ASIs are white light charge-coupled device (CCD) imagers with a latitudinal coverage of ~9°, longitudinal coverage of ~2.5 hr magnetic local time, and a time resolution of 3 s. The spatial resolution is ~100 m near zenith (Mende et al., 2008). The temporal resolution of the POES-17 satellite data (2 s) is comparable to the THEMIS ASI.

In this event, STEVE first appeared as a very narrow structure in the eastern region of KAPU ASI and later propagated from east to west, across the entire longitudinal FOV of the camera covering more than 1,000 km in longitudinal extent with only about half a degree in latitudinal width (~tens of kilometers). Figure 1 shows the sequence in which STEVE was observed in the THEMIS ASIs at KAPU and Sanikiluaq (SNKQ) located in eastern Canada. The white contours in the panels correspond to 65° and 55° magnetic latitude (MLAT). Our observation transpired in the premidnight sector (midnight in KAPU ~4 UT). Before STEVE was observed in the KAPU FOV, we observed auroral activity at higher latitudes as indicated by the presence of several auroral streamers in SNKQ (not shown). This activity was the remainder of a substorm auroral expansion that occurred about 1 hr prior to the observation of STEVE. At approximately 02:15:00 UT, STEVE was observed in the eastern region of KAPU. It rapidly (within ~5–6 min, Figure 1a) traversed the camera FOV to the western edge of the KAPU ASI as a bright and extremely narrow structure (~0.5° in latitude). At

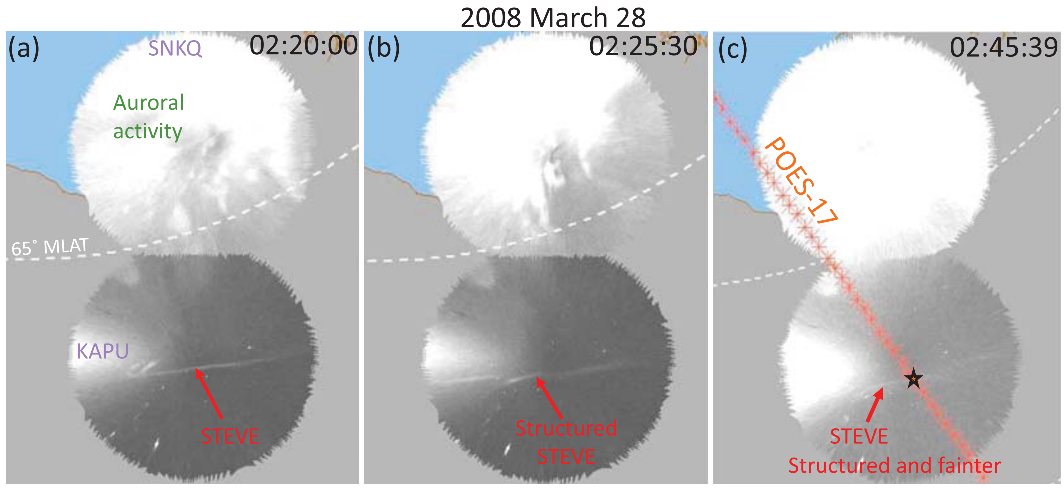

Figure 1. (a–c) Observation of a Strong Thermal Emission Velocity Enhancement (STEVE) event, 28 March 2008 in Kapuskasing (KAPU) Time History of Events and Macroscale Interactions during Substorms (THEMIS) All-Sky Imager. The white contours correspond to 65° and 55° magnetic latitude (MLAT). (c) The asterisks in Figure 1c indicate Polar Orbiting Environmental Satellite (POES)-17 satellite track. The orange star represents the location and time when the satellite crosses STEVE.

about 02:25:30 UT (Figure 1b), STEVE displayed several small-scale structures that also propagated westward. Afterward, STEVE became fainter and more structured until ~03:10:00 UT. A movie with the complete sequence of this event has been added to the supplemental material of this paper.

Concurrent with the observation described above, the magnetic footprint of the POES-17 satellite crossed STEVE in the center of the camera FOV. The orange asterisks in Figure 1c indicate the satellite track across KAPU. At 02:45:39 UT, POES-17 (highlighted by a star in Figure 1c) crosses a faint and structured STEVE in the middle of the KAPU FOV. For technical details on the particle instruments onboard the POES satellites, see Liang et al. (2015).

Figure 2 represents the POES-17 proton (left) and electron (right) fluxes across all energy ranges. Particle data from two different instruments onboard the POES-17 satellite were used in Figure 2. Low-energy particles (50–1,000 eV) and high-energy particles (30 keV to more than 200 MeV) were measured using the total electron detector (TED) and the solid-state medium energy proton and electron detector (MEPED), respectively. The trapped particle population (90° view angle) and precipitating particles (0° view angle) are illustrated by the black and blue curves, respectively (except for Figure 2j). The green vertical line indicates the time when POES-17 crosses STEVE. For protons, there is no clear evidence of precipitating particles at the time of STEVE. Proton aurora for this event is likely to be observed by POES after ~02:46:00 UT and several degrees poleward of STEVE. For electrons, the scenario appears a little more complicated. For electrons with energies between 30 keV and 2.5 MeV, there is no clear evidence of particle precipitation. However, for low-energy particles (50 eV–1 keV, 0° and 30° view angle), we see a significant increase in the precipitating flux (several orders of magnitude) at the time of STEVE. Nonetheless, this increased flux is several orders of magnitude smaller than the flux level observed when POES later crosses the auroral oval (not shown).

In a previous study, Vickrey et al. (1982) estimated the height-integrated energy deposition from precipitating electrons using data from the Chatanika incoherent scatter radar. The study showed that the height-integrated energy deposition during a positive bay event exceeded 10 [ergs/cm^2/s]. During a substorm event, the energy deposition was higher than 30 [ergs/cm^2/s]. More recent studies suggest that energy fluxes of tens of erg/cm^2/s are typically observed for bright auroral structures and a threshold of ~1 [erg/cm^2/s] for visible aurora (e.g., Newell et al., 2010; Zhang & Paxton, 2008).

Figure 3 shows the integrated energy flux for protons (left) and electrons (right) for the 28 March 2008 STEVE event. For protons, the integrated energy flux between 50 eV and 20 keV is almost zero. For electrons, the integrated energy flux is only ~0.06 [erg/cm^2/s] at the time of STEVE. In terms of the data reliability for the TED, total energy flux measurements $>$0.01 [erg/cm^2/s] (here called TED lower reliability limit) are usually considered as trustworthy measurements; values lower than this limit have larger relative uncertainties

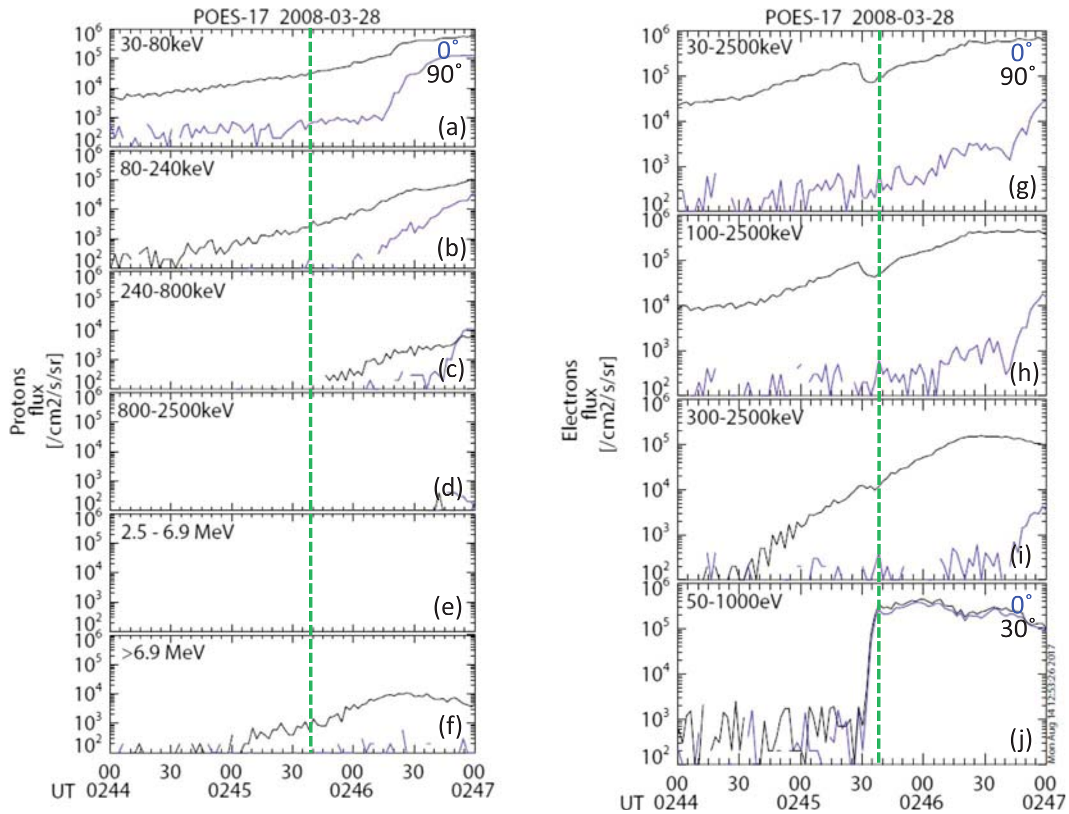

Figure 2. Polar Orbiting Environmental Satellite (POES)-17 data measured during Strong Thermal Emission Velocity Enhancement (STEVE) event. The panels represent (a–f) proton and (g–j) electron flux for all energies.

(D. Evans, private communication, 2015). Therefore, we consider the total integrated electron energy flux measured by POES-17 during our STEVE event as a significant increase in the subauroral region. However, this enhanced flux is at least 2 orders of magnitude smaller than the average energy fluxes reported for auroras in previous studies. We assert that such low precipitating energy fluxes (for protons and especially for electrons) cannot be responsible for the luminosity observed in STEVE.

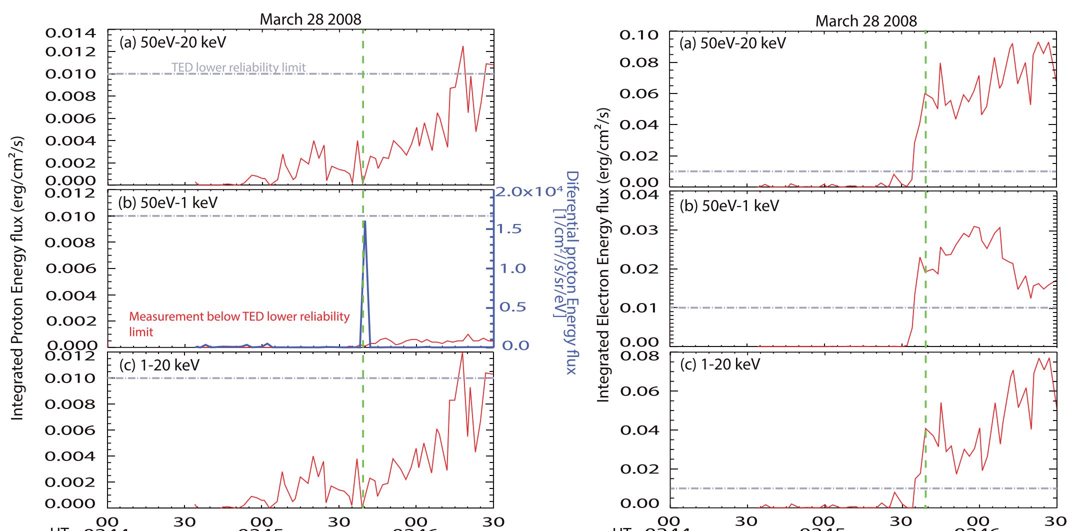

Figure 3. Integrated energy flux for (a) protons and (b) electrons. The horizontal gray dashed line corresponds to the total electron detector (TED) lower reliability limit; under this limit uncertainties in the measurements are too large and energy flux is not considered reliable.

When we searched for specific precipitation features that could be associated with STEVE, we made an interesting observation. The TED onboard of the POES-17 satellite scans 16 energy bins in 2-s intervals. The sensor does not record the differential fluxes from all energy bins; it only saves the maximum value and its corresponding energy channel in order to determine which energy bin yields the largest differential flux. This methodology is applied to evaluate the characteristic energy of precipitation from TED data (Liang et al., 2015), as well as the actual differential flux level at the maximum flux energy channel.

In Figure 3b on the left side (protons) the blue curve corresponds to the maximum differential flux from the TED 0° view angle sensor. During most of the interval, the proton fluxes are almost negligible. However, TED registered a fairly strong differential flux during the observation of STEVE. This maximum flux originates from the lowest energy channel of TED, 50–73 eV centered at ~61 eV. As a result, this corresponds to an energy flux of 9.8E + 5 [ev/cm^2/s/sr/eV], which is a fairly strong differential proton flux at this energy level compared to typical $<$100 eV ion differential fluxes in the subauroral region reported in the literature (e.g., Anderson et al., 2001). Additionally, we examined the 30° view-angle TED sensor and confirmed that its maximum flux also shows a singular peak (~8.0E + 5 [ev/cm^2/s/sr/eV]) at the STEVE traversal epoch. This maximum flux is again associated with the ~61-eV energy bin. As a note, because the satellite was in dark shade with no substantial electron precipitation during the time interval of interest, an instrumental glitch due to spacecraft charging seems unlikely. We currently believe that the maximum fluxes recorded by TED at the traversal epoch of STEVE are most likely real. This indicates that both the proton differential flux peaks at the lowest TED energy bin and the TED total energy fluxes are essentially negligible. Therefore, it seems reasonable to assume that within the flux tubes tied to STEVE, a significant population of proton precipitation with energies $<$50 eV (i.e., lower than the TED energy range) exists. It is beyond the scope of this letter to further discuss the possible origin and role of those low-energy ions in the formation of STEVE. However, we shall briefly mention the following possibility: While those low-energy protons are unlikely to excite visible aurora directly, they might give rise to substantial heating in the upper atmosphere (Eather, 1967). Consequently, this process may substantially affect the ionospheric dynamics and the auroral excitation.

3. Conclusions

In this paper we reported a STEVE event observed using THEMIS ASI at KAPU station. Simultaneously, POES-17 crossed STEVE in the center of the camera's FOV. In the POES-17 data, we did not observe protons and high-energy electron precipitation. For low-energy electrons (50 eV to 1 keV), we observed an increase in the flux. However, the integrated electron energy flux at that time was too low to be responsible for any optical structure and therefore not associated with STEVE. We assert that this observed STEVE event is not directly produced by particle precipitation at 800 km altitude. However, we cannot rule out the possibility that STEVE might be associated with low-energy ($<$50 eV) proton precipitation. We are currently evaluating two other possibilities for the emission. First, the observed skyglow could have its origin in the ionosphere, similar to weak stable auroral red (SAR) arcs in the subauroral region. SAR arc model calculations by Sazykin et al. (2002) indicate that ion-neutral frictional heating in the *F* region ionosphere could provide enough energy to create the weak emission observed in SAR arcs. Even though particles associated with the formation of SAR arcs originate in the magnetosphere, SAR arcs are the result of an ionospheric process. The second possibility involves a process unknown by the authors that could produce electron precipitation below 800 km. The current results do not allow us to conclude definitely whether or not STEVE originates in the ionosphere or magnetosphere. In general, to determine with confidence if STEVE's formation is driven by an ionospheric process or precipitation, particle measurements for a statistically significant number of STEVE events are required. Overall, further analysis is necessary to illuminate the dynamic processes responsible for the emission associated with STEVE.

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