

SPACE SCIENCES

New science in plain sight: Citizen scientists lead to the discovery of optical structure in the upper atmosphere

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A glowing ribbon of purple light running east-west in the night sky has recently been observed by citizen scientists. This narrow, subauroral, visible structure, distinct from the traditional auroral oval, was largely undocumented in the scientific literature and little was known about its formation. Amateur photo sequences showed colors distinctly different from common types of aurora and occasionally indicated magnetic field-aligned substructures. Observations from the Swarm satellite as it crossed the arc have revealed an unusual level of electron temperature enhancement and density depletion, along with a strong westward ion flow, indicating that a pronounced subauroral ion drift (SAID) is associated with this structure. These early results suggest the arc is an optical manifestation of SAID, presenting new opportunities for investigation of the dynamic SAID signatures from the ground. On the basis of the measured ion properties and original citizen science name, we propose to identify this arc as a Strong Thermal Emission Velocity Enhancement (STEVE).

INTRODUCTION

The aurora borealis and aurora australis (commonly known as the northern and southern lights) are the multiscale end result of a complex chain reaction that begins at the sun and is governed by Earth's magnetic and electric fields. A brief description is that the interaction of the solar wind with Earth's magnetic field generates strong electrical currents in Earth's magnetosphere. These, in turn, accelerate and precipitate charged particles into the upper level of our atmosphere where they collide with its constituent gases. This collisional process stochastically transfers energy to atmospheric atoms that later release the energy through a fluorescent emission of photons. At a global scale, the auroral regions form a large oval around the magnetic poles. This annulus is located at high latitudes, ~65° to 80° in magnetic latitude (MLAT), and is generally less than 10° in latitudinal width (1). During the increased energy input from the solar wind, the auroral oval broadens and moves equatorward (2). Although this overall picture is well understood, with a few exceptions (3), it remains remarkably difficult to attribute observable auroral features to specific ionospheric signatures and magnetospheric processes.

Since the 1950s, space physicists have advocated a truly global, real-time network of amateur observers to study the rare and poorly understood middle- and low-latitude aurora (4). In the past, recording observations accurately was difficult for amateur observers, and few satellite observations were available to complement amateur recordings. Over the past ~11-year solar cycle, which peaked in 2014, auroral observations by the public have evolved into using high-resolution, near scientific-grade, digital cameras and smart phones. At the same time, alerts of auroral activity have gone from ad hoc telephone tree-based

systems to sophisticated predictions based on auroral oval models, social media, and reports from aurora enthusiasts such as those contributing to the citizen science project Aurorasaurus (5, 6).

Observations of a subauroral arc

The various forms and types of aurora correspond to boundaries of the different regions in Earth's magnetosphere and the different processes that occur in each region. Descending in latitude from the magnetic poles to the equator, there is a poleward boundary, indicating the last "closed" field line in the magnetotail (1), an equatorward boundary of the discrete aurora, typically consisting of small-scale arcs that are foot points of small-scale upward currents on stretched dipole-like field lines (7), and an equatorward boundary of diffuse aurora (8). The discrete aurora is produced by accelerated electrons colliding with the atmosphere and is characterized primarily by easily visible active arc-like discrete shapes (9), approximately 10 to 30 km wide (10), and embedded in upward current systems of comparable size or larger (11). A diffuse aurora typically relates to the wave-induced particle precipitation on dipolar field lines and has a much dimmer, diffuse glow (9). Further equatorward, and particularly on the dusk side of the night sky, is the boundary of the proton aurora. Proton auroras are the result of charge-dependent magnetospheric drift motion allowing proton precipitation in regions much closer to Earth and, hence, lower latitude (12). During geomagnetically active times, low-latitude (with respect to the auroral oval) aurora signatures, such as the stable aurora red (SAR) arc (13), are also observed. In addition to SAR arcs and detached proton aurora equatorward of the auroral oval, structured 557.7- and 427.8-nm optical emissions have been also reported on the dusk side and attributed to broad subauroral polarization streams (14).

A group of citizen scientist auroral photographers recently reported repeatedly observing a dynamic, very thin, east-west-aligned aurora-like structure (see Fig. 1) significantly equatorward of the auroral oval during enhanced activity (15). These unusual, transient types of subauroral arcs have in the past been called "proton arcs" by amateur photographers and some members of the space physics community (16). However, a proton aurora is subvisual, broad, and diffuse (12, 17, 18), whereas this arc is visually bright, narrow, and structured. The proton

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Fig. 1. An observation of the subauroral arc (purple) known as STEVE, recorded on 25 July 2016 (05:51 to 06:10 UT) from Regina, Saskatchewan. The arc is located $\sim 4^\circ$ equatorward of the main auroral oval [green glow, bottom right in (A) and (B)] and runs across the sky in the east-west direction. Small green auroral features, resembling a picket fence, are also observed in (B) and (C). All images in the sequence can be found in the video linked to in the Supplementary Materials.

aurora is the manifestation of proton precipitation in our atmosphere and is typically observed at auroral latitudes ($\sim 65^\circ$ MLAT); the location of the arc reported here is at lower latitudes. During 2015 and 2016, these independent citizen scientist auroral photographers captured hundreds of images of the subauroral arc on at least 30 dates. In many cases, multiple independent observers recorded the arc, thus increasing data quality. Observations typically corresponded to nights of enhanced auroral activity predicted over Alberta, either strong substorms or geomagnetic storms of any magnitude. The arc is typically observed during pre-midnight hours [in magnetic local time (MLT)], lasting for approximately an hour. With no accurate scientific classification for the arc available, the citizen scientists named the arc “Steve” in place of the misnomer proton arc (15). Later in 2016, Steve was given the backronym “Strong Thermal Emission Velocity Enhancement” (STEVE) because of data obtained from the satellite measurements reported below.

On 25 July 2016, an expert aurora chaser from Regina, Saskatchewan, used a Nikon D810 camera to record a series of time lapse photographs over a period of 19 min. Between each 4-s exposure frame is a 4-s gap. Several key features of STEVE can be observed in Fig. 1 (A to C). The images in Fig. 1 are taken pointing to the WNW (west-north-west). First, in the unfiltered white-light STEVE is a narrow purple band with the strongest emissions saturating to white. Over a several-minute period, unstable green features resembling a picket fence were observed propagating west. Up to six localized structures at a time were observed, typically for only one or two frames (of 4 s per frame). Their appearance suggests an unstable, turbulent, instability driven locally in the ionosphere, although the visibility of these features at these latitudes has rarely been documented. STEVE shows motion westward in both purple and green colors. The active typical aurora is visible in Fig. 1 far to the north in typical well-understood emission lines (9).

The STEVE structure was also observed by one of the University of Calgary all-sky imagers (ASIs) between 05:48 and 07:10 UT on 25 July 2016. The University of Calgary and the University of California, Berkeley, operate more than 40 ASIs across North America that continuously image the night sky (19). This network of ASIs provides the opportunity to examine auroral morphology and characteristics on both local and large scales. In addition, meridian scanning photometers (MSPs) operated by the University of Calgary and Athabasca University provide information on the latitude of the proton aurora (20).

Figure 2 presents simultaneous observations from the Lucky Lake Redline Emission Geospace Observatory (REGO) ASI at 630.0 nm showing a narrow band of emission located just south of 60° MLAT. The observed structure is approximately 0.5° wide in MLAT and lasts for just over 1 hour. Superimposed on Fig. 2 is a band of coincident emission data from the Forty-Eight Sixty-One (FESO) MSP that records proton aurora emission at 486.1 nm (20). These photometer data show that the proton aurora was located at latitudes above 62° MLAT, about 2° poleward of STEVE. Furthermore, previous studies have demonstrated that classical electron auroral arcs are located poleward of the peak brightness of the proton aurora (21). Thus, STEVE cannot correspond to the classical bright proton aurora or discrete electron auroral arcs.

STEVE has a different appearance than traditional electron auroral arcs. A key difference is that STEVE most often appears to be mauve or purplish in color. STEVE is often visible in data from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) ASIs, which take panchromatic (black and white) images formed with light from a wide and continuous spectral window. However, in ASIs that use narrow band-pass filters, such as the redline imager providing the data used here, STEVE is faint compared to typical aurora, even though the redline imager is far more sensitive than the THEMIS ASIs. This different color, and the fact that STEVE is bright in the RGB (red-green-blue) image of a DSLR (digital single-lens reflex) camera and in the panchromatic THEMIS-ASI images, suggests that the dominant purple luminosity in STEVE represents a mixture of exotic emissions that does not include, for the most part, wavelengths that dominate the precipitating electron auroral luminosity.

The ground observations described above established that STEVE is a previously undescribed optical auroral phenomenon. A conjugate and coincident fly-through by a low-altitude spacecraft, such as Swarm, was needed to determine the in situ nature of STEVE. The European Space Agency’s Swarm constellation was launched in 2013 and consists of three identical satellites, each with instruments to measure the variations in Earth’s magnetic field and associated current systems. Swarm A and C are in near-polar, circular orbits at a starting altitude and inclination of 450 km and 87.4° , respectively. These two spacecrafts are separated by 1.5° in longitude and quickly cut through both the northern and southern auroral zones every 96-min orbit (15 orbits per day). Each Swarm spacecraft carries precision magnetometers (22) and

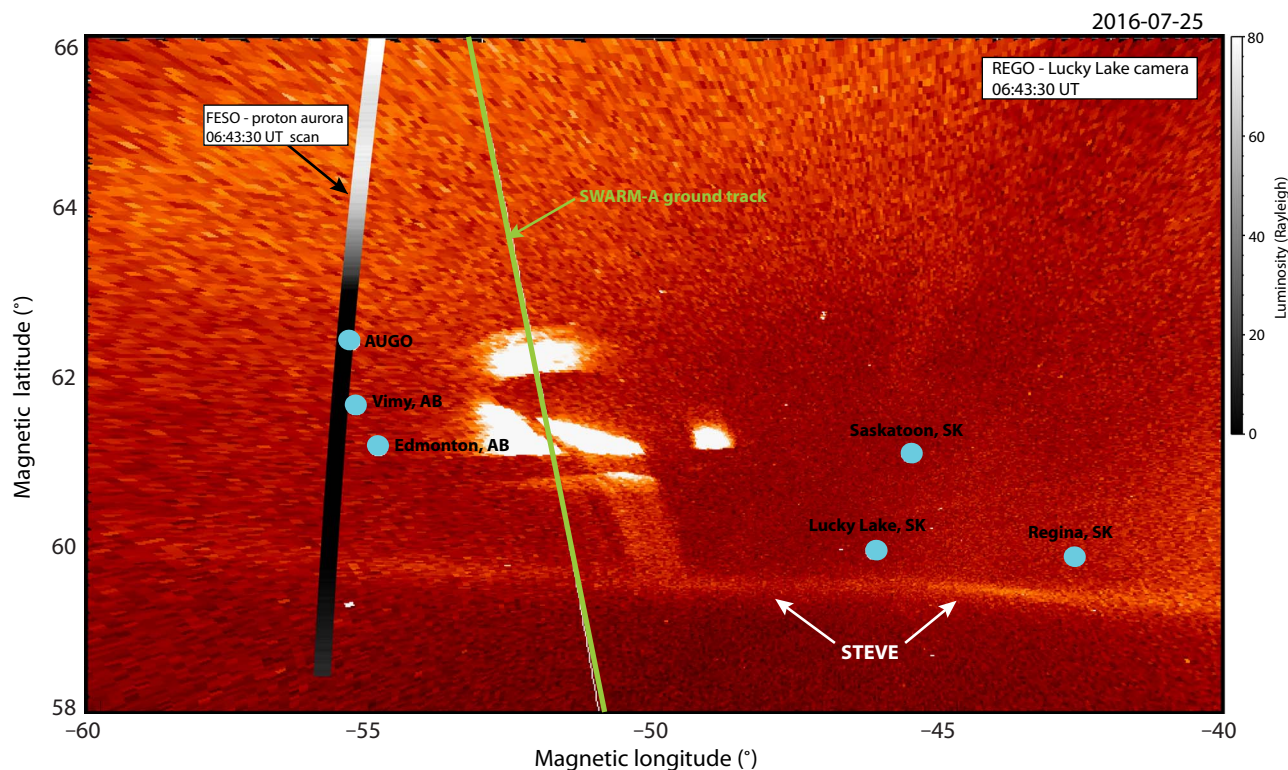


Fig. 2. STEVE event observed on 25 July 2016 by the Lucky Lake REGO ASI at 06:45 UT around 59.5° latitude. As indicated, the STEVE arc is the narrow enhancement spanning nearly the whole field of view. The superposed rectangle corresponds to the Athabasca FESO MSP, located at the Athabasca University Geophysics Observatory (AUGO), data in which the proton aurora is observed at least 2° poleward of STEVE. The blue labels indicate the locations of AUGO, major cities, and the citizen science observations of STEVE. The bright patches in the center of the image are artifacts and not genuine sources of light.

electric field instruments (23), which directly measure ion flow velocity, ion and electron temperatures, and plasma density.

Figure 3A presents the intensity of the STEVE arc measured by the Lucky Lake REGO ASI along the trajectory of the Swarm A satellite (dashed line in Fig. 2). The intensity is mapped-down magnetic field lines to three different altitudes, because the exact altitude of emission of an arc at zenith cannot be determined from a single ground observation. Despite the uncertainty regarding the exact altitude of the emission, the arc was found just below 60° MLAT across the assumed range of emission heights.

The pink region highlights the full width at half maximum of the emission intensity at 170 km. Plotted in Fig. 3B is the ion velocity, which demonstrates a clear westward (negative) flow that reaches 5.5 km/s during the peak STEVE optical emission. The flow's full width at half maximum is less than 0.5° centered on 59.5° (magnetic) latitude. As determined by subtracting the International Geomagnetic Reference Field from the Swarm vector field magnetometer measurements, an increase in the eastward magnetic field perturbation of ~30 nT is observed crossing STEVE (Fig. 3C). By applying Ampere's law, this positive gradient in magnetic field corresponds to a small downward field-aligned current (FAC). Bearing in mind that the measurement corresponds only to the net current per unit area, we cannot resolve the association of STEVE with precipitating electrons (upward FAC). Swarm also measures ambient electron density and temperature with its Langmuir probe. The region of the arc corresponds to an elevated electron temperature of 6000 K (Fig. 3D) and a minimum density of $1 \times 10^{10} \text{ m}^{-3}$ (Fig. 3E). Equatorward of the STEVE arc, an electron density trough of 10^{10} m^{-3} extends for 1° (MLAT), whereas on the poleward side of the

arc, the electron density rapidly increases to around $5 \times 10^{10} \text{ m}^{-3}$. Correspondingly, the electron temperature is enhanced by a factor of ~2 in the equatorward trough and rapidly decreases to background levels on the poleward side of the arc.

Association with SAID

The characteristic strong flow, density depletion, and temperature enhancement shown in Fig. 3 are all indicative of a subauroral ion drift (SAID) (24). We note, however, that the flow speed and temperature measured during this event are much larger than typically reported in this region, including during previous SAID events. For instance, we surveyed 22 SAID events, observed by the Swarm satellites, and found a maximum flow of 2.9 km/s, maximum temperature of 5900 K, and minimum density of $1.6 \times 10^{10} \text{ m}^{-3}$.

SAIDs, previously known as polarization jets, are transient events with supersonic westward flows confined within a narrow region (~1° to 2° MLAT) of space in the evening (near midnight) sector just equatorward of the traditional auroral oval (23–28). They appear following the expansion phase of a substorm. Since their discovery, SAIDs have been investigated extensively by analysis of observational data (primarily from spacecraft and ground-based radar, both statistical and event-based) and numerical modeling (26, 28). The solar cycle, seasonal, and diurnal variations of SAIDs were recently investigated (29) through the analysis of a large collection of SAID events (~18,000) captured by the Defense Meteorological Satellite Program (DMSP) satellites rapidly cutting through these narrow transient structures. Near solar maximum SAIDs tend to occur at a latitude of ~60.1° around 22:30 in MLT with an average half-width of 0.57°. In addition, SAIDs are found to be strongly

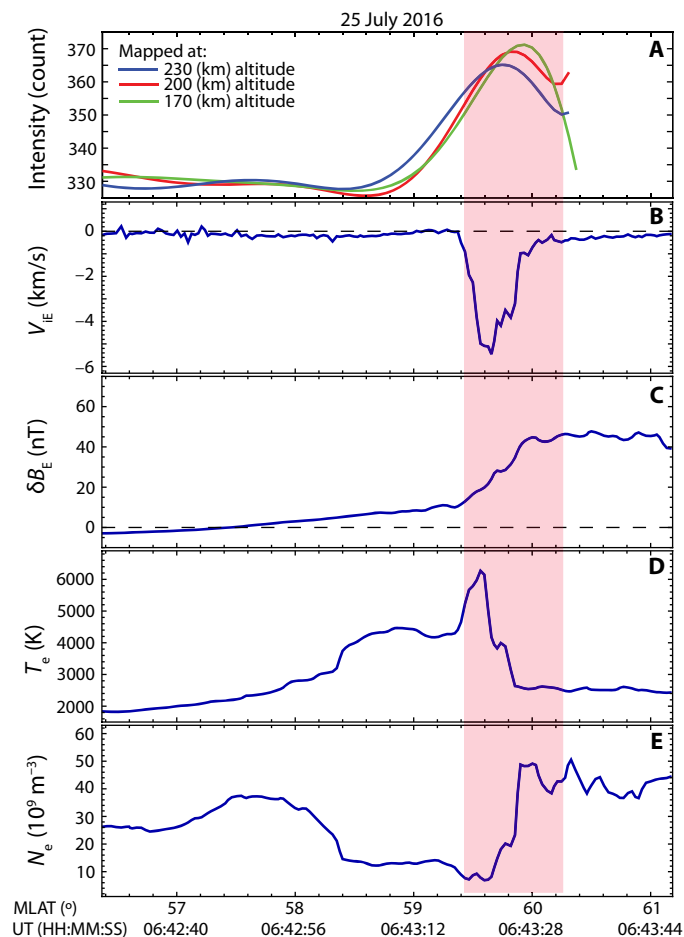


Fig. 3. The conjunction (highlighted in the pink region) of the STEVE optical emission with a pronounced SAID signature at satellite altitudes. A plot of the Lucky Lake REGO ASI intensity along the satellite track mapped at three different altitudes (A), together with Swarm A satellite measurements (B to E). Plotted in (B) is the ion velocity (positive is eastward flow), in (C) is the eastward magnetic field deviation relative to the undisturbed geomagnetic field, in (D) is the ambient electron temperature, and in (E) is the electron number density.

correlated with solar cycle activity. Wider, more equatorward SAIDs occur during high solar activity as opposed to narrower, poleward SAIDs during low activity. SAIDs tend to occur more frequently in spring and fall in comparison to summer and winter, which is consistent with the seasonal distribution of citizen science STEVE reports.

The identification of the STEVE arc with an SAID, and in keeping with the original citizen science name, has led to the backronym of Strong Thermal Emission Velocity Enhancement for STEVE.

However, SAIDs are not typically associated with an optical emission, and any optical emissions produced in association with SAIDs are not yet fully explained. Reports have correlated an SAID with an “anomalous SAR arc” (30, 31), but SAR arcs are dominated by red (630.0 nm) emissions with no or very little green (557.7 nm) emissions and can last 24 hours or more. The STEVE observation, with characteristic purple and green colors evolving within an hour, is distinctly different from a SAR arc. In addition, the green picket fence aurora we report has not been documented in the literature at these latitudes.

During an SAID event observed by Atmosphere Explorer-C (AE-C), the O⁺ density was significantly depleted, whereas the NO⁺ concentra-

tion was enhanced (27). This was due to a strong flow with a significant relative velocity between ions and neutrals increasing charge exchange reaction rates and rapid recombination of O⁺, whereas NO⁺ recombines an order of magnitude more slowly. Recent modeling (31), taking into account temperature enhancement, ion-neutral collisional heating, and composition changes, could potentially explain the red (630.0 nm) emission produced in this type of event as a result of unusual ion composition and fast flows. However, the green (557.7 nm) features cannot be explained from this mechanism and leaves a possibility of contribution by electron precipitation for driving the emissions. The dominant purple color observed in STEVE is also not explained. Further spectral analysis and modeling of STEVE are needed.

The discovery and subsequent investigation of STEVE demonstrate that this subauroral boundary region is a critical magnetosphere-ionosphere coupling region that should now be targeted for further study. STEVE occurs at the boundary of the auroral and subauroral zones, and because SAIDs form in association with auroral substorms, STEVE is likely related to substorm processes such as particle injection and fast flows. In this way, STEVE appears to tie these two separate regions of space together. The narrow north-south but broad east-west extent of STEVE marks a flow region in the magnetosphere that can now be documented by ground-based observers and instrumentation. The strong flows may be directly imaged and measured, possibly by citizen scientists with basic astrometry software tools. Altitudinally, the composition and transient green features require new understanding of coupling between the E and F regions of Earth’s ionosphere.

STEVE has highlighted the importance of citizen science. Although independently observed previously by auroral photographers both amateur and professional, citizen science has proven to be a bridge between amateur observers and traditional aurora scientists. This bridge has facilitated the advancement of our understanding of both the night sky and magnetosphere-ionosphere coupling. We emphasize that this collaboration with the citizen scientists was not simply through crowdsourcing and image analysis of a large data set. Citizen scientists discovered a new category of auroral observation by synthesizing complex information and asked the scientific community for input on these observations. This example can help change the nature of scientific engagement between the scientific community and citizen scientists and move communication from one way to two way, with curiosity transitioning to participation and finally to stewardship (32).

MATERIALS AND METHODS

This study’s aim was twofold: to highlight observations of this new phenomenon and to place it into its geophysical context for a broad range of interested readers. The study included citizen science images, ground optical observations, and in situ satellite observations. The event analyzed was chosen because of the fortuitous conjunction between the availability of simultaneous observations from all three sources. Ancillary data from this event have not been highlighted because they do not quantitatively add to the main goal of this study.

The methods of citizen science that have been used in this study include members of the public participating voluntarily in the scientific process through the auspices of the formal citizen science project Aurorasaurus and citizen-scientists’ own public, online enthusiast groups, collecting and archiving observations, asking questions, interpreting results, making new discoveries, and solving complex problems. The methods and best practices applicable to this approach were further described in the study by MacDonald *et al.* (5). All-sky camera imaging

and photometer data from the University of Calgary and Athabasca University provided quantitative views of optical emissions in specific wavelengths, temporal cadences, and geometries (19, 20). The all-sky and photometer data were mapped into geomagnetic coordinates following standard, calibrated procedures assuming three different altitudes of peak emission ranging from 170 to 230 km. As described in the text, this map was correlated with measurements from the Swarm A satellite as it passed above STEVE's optical emissions at an altitude of 450 km. Electron density and temperature and magnetic field measurements presented in this study were official Swarm Level 1B data products. Ion velocity estimates were from the experimental TII cross-track flow data set (33).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/4/3/eaqa0030/DC1>

movie S1. Link to the YouTube video of STEVE and picket fence aurora: <https://www.youtube.com/watch?v=tH7bVIGNJWU>.

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