The Mysterious Green Streaks Below STEVE

Joshua Semeter\textsuperscript{1,}*, Michael Hunnekuhl\textsuperscript{2,}*, Elizabeth MacDonald\textsuperscript{3,}*, Michael Hirsch\textsuperscript{1,}*, Neil Zeller\textsuperscript{4,}*, Alexei Chernenkoff\textsuperscript{5,} and Jun Wang\textsuperscript{5}

\textsuperscript{1}Department of Electrical and Computer Engineering and Center for Space Physics, Boston University, Boston, MA, USA, \textsuperscript{2}Independent Researcher, Gehrden, Germany, \textsuperscript{3}Goddard Space Flight Center, NASA, Greenbelt, MD, USA, \textsuperscript{4}Neil Zeller Photography, Calgary, Canada, \textsuperscript{5}Alberta Aurora Chasers, Calgary, Canada

Abstract  Strong thermal emission velocity enhancement (STEVE) is an optical phenomenon of the subauroral ionosphere arising from extreme ion drift speeds. STEVE consists of two distinct components in true-color imagery: a mauve or whitish arc extended in the magnetic east–west direction and a region of green emission adjacent to the arc, often structured into quasiperiodic columns aligned with the geomagnetic field (the “picket fence”). This work employs high-resolution imagery by citizen scientists in a critical examination of fine-scale features within the green emission region. Of particular interest are narrow “streaks” of emission forming underneath field-aligned picket fence elements in the 100- to 110-km altitude range. The streaks propagate in curved trajectories with dominant direction toward STEVE from the poleward side. The elongation is along the direction of motion, suggesting a drifting point-like excitation source, with the apparent elongation due to a combination of motion blur and radiative lifetime effects. The cross-sectional dimension is \(<1\) km, and the cases observed have a duration of \(\sim20–30\) s. The uniform coloration of all STEVE green features in these events suggests a common optical spectrum dominated by the oxygen \(557.7\)-nm emission line. The source is most likely direct excitation of ambient oxygen by superthermal electrons generated by ionospheric turbulence induced by the extreme electric fields driving STEVE. Some conjectures about causal connections with overlying field-aligned structures are presented, based on coupling of thermal and gradient-drift instabilities, with analogues to similar dynamics observed from chemical release and ionospheric heating experiments.

Plain Language Summary  STEVE is a recently identified atmospheric phenomenon caused by supersonic plasma jets flowing at altitudes \(>100\) km. STEVE appears as a whitish pink arc extending in the magnetic east–west direction, which is often accompanied by an adjacent region of green features. In some cases, the green features appear as periodic vertical columns resembling a “picket fence”. These features were thought to be caused by the same mechanism as the aura, but the color is wrong. This article examines these features from a morphological perspective. We use time lapse images recorded by citizen scientists to examine fine-scale structures in STEVE’s green emission region. We focus particular attention on a narrow streak of emission commonly observed underneath the picket fence. These streaks have width of just a few hundred meters and propagate horizontally. They have identical coloration to other green objects in the field, suggesting a common source. Although we cannot state conclusively what that source mechanism is, they are most likely excited by turbulent heating related to the extreme plasma flows of STEVE. Our initial analysis suggests a physical connection between these tiny streaks and the extended picket fence features above them. Advancing this physics will benefit greatly from continued involvement of citizen scientists.

1. Introduction

Strong thermal emission velocity enhancement (STEVE) is a recently identified optical feature in the subauroral ionosphere appearing within a narrow channel of extreme westward ion drifts (MacDonald et al., 2018). The phenomenon was identified by citizen scientists using consumer camera equipment. In true-color photography, STEVE appears as a diffuse arc extended in the east–west direction with color ranging from mauve to gray white, which is often, but not always, accompanied by ephemeral green features nicknamed “the picket fence”. Multipoint triangulation has placed the mauve component at an altitude range of \(130–270\) km, with picket fence features extending below to as low as \(\sim95\) km (Archer, St.-Maurice, et al., 2019). Conjugate measurements by the Swarm satellites at \(\sim400\)-km altitude have detected \(B_z\) ion velocities approaching...
6 km/s in the STEVE channel, with evidence for electron temperatures approaching ~1 eV near the edges (Archer, Gallardo-Lacourt, et al., 2019). Initial spectroscopy of STEVE has revealed the mauve color to arise from the oxygen 630-nm red line emission superimposed on a continuum spectrum from ~400 to ~700 nm (Gillies et al., 2019). The whitish color is attributed to lower-altitude events, where the metastable O(¹D) state responsible for the red line component is collisionally quenched (Liang et al., 2019). The companion picket fence region has been found to be predominantly oxygen 557.7-nm green line, with a trace contribution from N₂ first positive emissions (Mende et al., 2019). The lack of emissions from higher energy N₂⁺ transitions has argued against precipitating magnetospheric electrons as a source of the green features (Mende et al., 2019), although the role of precipitation in STEVE remains a subject of debate (Nishimura et al., 2019).

This paper considers STEVE’s green companion from a morphological point of view. Particular attention is placed on ephemeral “streaks” of green emission that have been observed underneath, and conjugate to, field-aligned structures comprising the picket fence. Several examples of this feature are shown in Figure 1, as captured in true-color imagery by citizen scientists. The streaks do not appear with every picket fence occurrence. But, once recognized, the phenomenon is readily discoverable in many images. In all cases, we have examined the streaks formed on the poleward side of STEVE and propagated with dominant component directed toward the main STEVE channel. Similar streaks to those shown in Figure 1 have also been found embedded in more dynamic displays (e.g., Figure 5), where their motion is more complicated and their relationship to the magnetic field topology less clear. Notably, the lifetime of these features is sufficiently long (>20 s) to enable tracking through multiple images, allowing for deconvolution of finite exposure time effects (motion blur) and spatiotemporal correlation with other features in the images.

Our findings are based on a critical analysis of time-sequential imagery of the streaks. The complete image sequences used in this work are summarized in the following time-lapse movies.

**Movie 1.** Time lapse, 4-seconds per frame, corresponding to the event presented in Figures 1a, 2, and 3. The full-text HTML version of this article includes video content. To view this version, please visit https://doi.org/10.1029/2020AV000183.

**Movie 2.** Time lapse, unknown frame period, corresponding to manuscript Figure 1c. The full-text HTML version of this article includes video content. To view this version, please visit https://doi.org/10.1029/2020AV000183.
In the remainder of this work, we provide an initial examination of the altitude, trajectory, orientation, and dimensions of this feature, followed by some conjectures about its origin and connections to broader questions of the picket fence source and the modes of energy dissipation represented by the STEVE phenomenon. This work also suggests new opportunities for the use of photometric imaging as a diagnostic of ionospheric turbulence under extreme conditions.

2. Analysis Results

The experimental results in this work were all derived from imagery recorded by citizen scientists using commercially available equipment. The unfamiliar nature of this phenomenon and the unusual views obtained by the photographers make interpretation with respect to physical hypotheses challenging. Observer
Figure 1. Sample images highlighting STEVE’s green component and the mysterious green streaks appearing below the “picket fence”. (a) 6 May 2018, 11:20:05 MDT (05:20:05 UT), 4-s exposure, 51.255°N, 114.701°W (credit: Alexei Chernenkoff). (b) 13 September 2018, Isle Royale National Park, MI (credit: Shawn Malone). (c) 27 March 2017, 15-s exposure, Fortrose, New Zealand (credit: Stephen Voss). (d) 6 May 2018, ~11:19 MDT (05:19 UT), 33-ms exposure (NTSC video), Southern Alberta, CA (credit: Alan Dyer).

Perspective, camera exposure times, magnetic field topology, and radiative lifetime effects must all be considered carefully in drawing physical conclusions from these observations. We endeavor to discuss these issues in the context of our analysis. The features of interest are often faint, and the images displayed in this work have been adjusted to enhance contrast. Our findings do not rely on absolute photometric calibration, although that will undoubtedly become an important consideration in future studies.

2.1. Altitude Determination

Knowledge of the height of the features provides an important constraint for assessing physical mechanisms. Direct triangulation on the basis of time-synchronized images from two locations allows the calculation of the height of aurora, STEVE, or airglow structures. Archer, St.-Maurice, et al. (2019) and Palmroth et al.
Figure 2. (a) STEVE image from the location (51.255°N, 114.701°W) on 6 May 2018, 11:20:14 MDT (05:20:14 UT) (credit: Alexei Chernenkoff). (b) Time-synchronized image of the same event recorded from location (51.267°N, 114.328°W) (credit: Jun Wang). This pair of images was used for triangulation of the low-altitude streak with the end points labeled R1 and R2. The altitudes were determined to be 104.6 ± 1.6 km for R1 and 106.4 ± 1.6 km for R2.

(2020) present algorithms for this purpose in their works. In standard optical triangulation, the position of an object (latitude, longitude, height) is calculated from the observer locations and object bearing using standard trigonometric relations. The bearing (elevation and azimuth) of a point in the night sky may be determined with high precision via analysis of the background star field (Lang et al., 2010). Limiting the analysis to a neighborhood of stars near the feature minimizes potential lens distortion effects.

Figures 2a and 2b show the images used in our triangulation analysis, recorded from locations (51.255°N, 114.701°W), and (51.267°N, 114.328°W), respectively (about 50 km WNW of Calgary, Alberta). For this study, we used natural triangulation points defined by the leading edge and trailing edges of the streak, labeled R1 and R2. The triangulation geometry is shown to scale in Figure 2c. This triangulation problem exemplifies both the opportunities and the challenges in using citizen science imagery for precision analyses. The method developed for this study is described in detail in the supporting information and presented in overview here.

The first challenge is to establish the timing. The time stamps recorded into the image metadata may contain substantial errors and cannot, in general, be relied on. For wide-field images such as these, we can estimate the correct time by analyzing star positions with respect to prominent topographical landmarks on the horizon. Through this analysis, we were able to establish absolute time of the image in panel (a) to within an uncertainty of ±2 min. The star field is a slowly varying background, and this level of uncertainty translates to a height uncertainty of ~1 km for objects in the lower ionosphere.

The more significant source of error is the relative time offset between the images. The fine-scale features varied rapidly in these images. The triangulation result may thus be highly sensitive to a small synchronization offsets between the images. This is especially true for this geometry (Figure 2c), where the observer separation was small (25.9 km) relative to the target distance (~230 km). Fortunately, the observer at the location of Figure 2a captured a contiguous time sequence of images of this event. The sequence is shown in Figure 3, highlighting the two prominent streaks in Figure 2. Comparing fine-scale features in the image sequence with features in single frame observation of Figure 2b yielded a near perfect match to the frame displayed in Figure 2a. We conclude that the time offset between the images is <2 s.
We then applied a modified triangulation method that exploits the unique one-dimensional geometry of these features (see supporting information for full details). The streaks in Figure 3 are seen to move along a line corresponding to their direction of elongation (the significance of this is further discussed in section 2.2). We therefore assume that the streaks were moving in a straight line through three-dimensional space during the exposure and that the images represent two-dimensional projections of this line. We next let R1 and R2 in Figure 2a be fixed reference points. The projections of these points in Figure 2b are unknown, but they are assumed to lie along a line defined by the streak (depicted in red in Figures 2b (inset) and 2c). The geophysical coordinates of points R1 and R2 were found by testing points along the red line for consistency with both projections. Specifically, for each test point, the position of the ground intersection was computed from the elevation and azimuth information, and the corresponding altitude was computed independently for each observer. The solution is the position at which the altitudes agree. The logic of the method is that there is only one line in three-dimensional space that is consistent with a line in two-dimensional space observed from two locations.

The optimal positions of R1 and R2 in Figure 2b are labeled R1* and R2*. It is interesting to note that R1 and R1* both lie on the leading edge of the streak in their respective images, where the edge is well defined, while R2* lies a bit behind the trailing edge, which is somewhat broader and more diffuse. For R1, the optimized mean height is 104.6 ± 1.6 km, and for R2, it is 106.4 ± 1.6 km. Uncertainties were estimated using a Monte Carlo method. Histograms of triangulated heights were constructed based on 10,000 trials distributed uniformly over the range of pointing uncertainties defined by uncertainties in timing, feature dimensions, and observer location (minor). The uncertainty ranges reported above are the interdecile ranges of the resulting histograms. Further detail is presented in the supporting information.

We conclude that the streak R1–R2 resides in the lower ionospheric E-region in the altitude range of 103–108 km, with some evidence for a slight downward orientation of the streak toward the main STEVE arc. This is consistent with observations of trajectories in other events, as discussed in sections 2.2 and 3.3.

2.2. Trajectory

Figure 3 shows a sequence of cropped images at 4-s cadence, documenting the formation and evolution of the two streaks highlighted in Figures 1a and 2a. The streaks initially appeared as point-like features (white arrow in panel a, yellow arrow in panel c), which subsequently elongate along their direction of motion. The trajectory has a dominant component toward the main STEVE channel in these observations. The elongation of the features is influenced by at least three effects. The first is simple motion blur caused by the 4-s exposure. The second is emission afterglow. As suggested in prior work (Gillies et al., 2019; Mende et al., 2019), the green color is predominantly due to the 557.7-nm line,
produced by the metastable \( \text{O}(^{1}S \rightarrow ^{3}P) \) transmission of atomic oxygen, with radiative lifetime 0.74 s. A moving source of \( \text{O}(^{1}S) \) will produce a luminous tail in the 557.7-nm emission due to the finite radiative lifetime. The third effect is spatiotemporal variability in the excitation source itself.

In order to better quantify the effects described above, we turn to an event that was far more dynamic while also exhibiting greater dynamic range in the image sensor. Figure 4 was recorded on 20 May 2017 at 00:32 MDT (06:32 UT) from location 51.66° N, 112.91° W at 15-s exposure. In this display, a series of coherent green structures are observed to extend away from the main STEVE channel. The two structures toward the top of the image are composed of periodically spaced bands, each aligned approximately parallel to the main STEVE channel. The local vertical zenith direction lies just outside the field of view, as indicated by the red circle. The mauve-white arc is stretched out along the magnetic east–west direction. The orientation of the green features in Figure 4 is difficult to establish in this projection. Accounting for the geometric point of view is particularly important in the subauroral region, where the field lines are not vertical, and the features are not easily reconciled with intuition developed from auroral observations.

This event was captured by a second colocated camera with narrower field of view and higher image cadence (3.5 s). The full image sequence is shown in Movie 4. Figure 5 shows four selected images from this sequence. Figure 5 shows four selected images from this camera, with local time as indicated. The field of view corresponds to the rectangular region in Figure 4. Blue contours indicate geographic azimuth and elevation as

---

**Figure 5.** Sample images of dynamic green emissions observed within the rectangular region of Figure 4. Azimuth and elevation contours are shown in blue. The magnetic zenith direction is indicated by the yellow star.
The image samples in Figure 5 were selected to give a sense of how these features varied as they moved westward from near zenith (panel a) to lower elevation (panel d). The individual features changed substantially from frame to frame, indicating that this phenomenon was not fully resolved at 3.5 s. Dynamic features in the high-latitude aurora exhibit orientations and motion that are clearly organized with respect to the magnetic field, with the local magnetic zenith serving as the point of convergence (e.g., Dahlgren et al., 2013). The features in Figure 5 exhibit no definitive or stable orientation with respect to the magnetic field.

The yellow star in each frame indicates the magnetic zenith direction (inclination 73.5°, declination 14°), calculated using the International Geomagnetic Reference Field (IGRF) model (Thébault et al., 2015).

determined from star field fitting using the Astrometry.net package (Lang et al., 2010). The yellow star in each frame indicates the magnetic zenith direction (inclination 73.5°, declination 14°), calculated using the International Geomagnetic Reference Field (IGRF) model (Thébault et al., 2015).

Figure 6. Image sequence at 3.5-s cadence corresponding to the rectangular region in Figure 5d, showing the evolution of an emission streak that persisted in five contiguous frames (feature within the white oval). In panel (f), the length, orientation, and direction of motion of the streak are shown as a series of vectors. The red line shows the magnetic field-aligned direction superimposed on features that formed above the streak.

Figure 7. Normalized brightness as a function of distance along the trajectory of the streak feature in Figures 6a–6e. The behavior is consistent with a drifting point source. An asymmetry develops as the object moves, consistent with an “afterglow” tail due to the 0.74-s radiative lifetime of the O(1S) state.
One feature that remained coherent across multiple frames is the small streak within the dashed box of Figure 5d. This streak has characteristics similar to the streaks in Figures 1 and 3—that is, it is the smallest object within the field, it appears below the other features (i.e., lower elevation), and, unlike other features in this sequence, it persisted as a coherent drifting object across several frames.

Figures 6a–6e show the evolution of this feature through five consecutive 3.5-s frames. The field of view corresponds to the dashed box in Figure 5d. Figure 6f duplicates the image of Figure 6e with fiducial marks inserted: the white arrows show the location, length, and direction of motion of the streak as extracted from each of panels (a)–(e). The streak is seen to be contiguous from frame to frame (i.e., tip of one arrow lines up with tail of the next). This suggests that it is produced by a drifting point-like source and that the observed elongation is primarily caused by motion blur and afterglow effects previously discussed. The trajectory is also seen to be slightly curved in this perspective. The curvature is consistent with bending toward the main STEVE channel. This trajectory may have similarities to Figure 1c, where the trace emission behind the streak suggests a drift path that bent into the horizontal plane. The red line inserted in panel (f) indicates the magnetic field-aligned direction. Its significance will be discussed in section 2.3.

2.3. Dimensions and Velocity

The high fidelity of Figure 6 allows for a quantitative examination of dimensions and velocities of the streak. Figure 7 shows the relative brightness of the camera's green channel versus distance along its trajectory for each panel (a–e) of Figure 6. The distance scale was computed in the following manner. First, the plate scale, \( p = 0.0257 \) radians/pixel, was determined for the region of interest (Figure 5d, inset) using the star field calibration. Next, we select as the origin a pixel \((x_0, y_0)\) corresponding to the tail of the first arrow in Figure 6f. The selection of this point is somewhat arbitrary, as it is the relative motion between frames that is of interest. The range to this point is given by \( R_0 = z_0 / \sin(\theta_0) \), where \( \theta_0 \) is the elevation and \( z_0 \) is an assumed feature altitude, taken to be 100 km. The pixel coordinates \((x_p, y_p)\) of a cut through the feature are then converted to physical distance \( d \) using the small angle formula,

\[
    d = R_0 p \sqrt{(x_p - x_0)^2 + (y_p - y_0)^2} \quad \text{(km)}.
\]

For this event, observations were only available from a single location, and so the streak trajectory through three-dimensional space is unknown. The distance scale so derived corresponds to a projection of the actual distance scale into the image plane under the stated assumptions. If we assume a point-like object that elongates in the direction of motion, this scale approximates the projected distance in kilometer along the trajectory traced by the white arrows in Figure 6f. At its initial appearance, the full width at half maximum (FWHM) is similar to the separation between peaks. This result is consistent with a moving point source subject to motion blur. The streak can also be seen to broaden and develop an asymmetric “tail” behind its trajectory. This is qualitatively consistent with the afterglow effect due to the finite radiative lifetime of the \( O(1S) \) state. If the actual trajectory has a component orthogonal to the image plane, the widths and peak positions extracted from Figure 7 would be compressed by a common scale factor.

Figure 8 shows the evolution of this feature in the direction transverse to its propagation. The curves have been manually shifted to align the lower-altitude edge of the streaks, in order to compare relative changes in width during its lifetime. When first observed (curve a), the streak has a cross-sectional width of \( \sim 350 \) m. This streak is thus among the smallest optical aeronomical features observed at any latitude in the aurora or airglow (Borovsky & Susczynsky, 1993; Semeter et al., 2008). As it evolves through subsequent frames (curves b–e), an extended region of emission is seen to develop to the left (i.e., at higher elevation angle). Some context for this can be obtained by returning to Figure 6. The new region of emission corresponds
to a developing magnetic field-aligned feature in the upper part of the encircled region, above the streak. In Figure 6f, a red bar has been inserted to show the magnetic field-line direction projected into the image plane. Magnetic conjugacy of low-altitude streaks and field-aligned features is also observed in the wide-field image samples of Figure 1. The analysis of Figure 8 provides possible evidence for the contemporaneous development of the low-altitude streaks of emission and magnetic field-aligned features above it.

3. Discussion

True-color images of selected STEVE events obtained by citizen scientists have been used in a critical examination of small-scale features in the green “picket fence” region. Image sequences acquired at 3.5- and 4-s cadence have revealed dynamic subkilometer features with varying orientations, dimensions, and motions (Figures 5 and 6). Unlike the quasiperiodically spaced green columns that inspired the “picket fence” designation, these features are not extended along magnetic field lines and are thus inconsistent with production via energetic particle precipitation. Readers are encouraged to view Movies 1–4 in order to develop their own impression of these unusual features and the unique perspectives obtained by citizen scientists.

This work has focused on a particular repeatable feature: a narrow “streak” of emission appearing below the picket fence that propagates toward STEVE from the poleward side. This feature is noteworthy for several reasons: (1) it is the lowest-altitude and smallest-scale optical feature associated with STEVE; (2) it has been observed in many STEVE events; (3) when contiguous image sequences are available, the feature has been observed to persist for >20 s as a coherently propagating object (Figures 3 and 6 and Movies 1–4); and (4) it is magnetically conjugate to, and sometimes optically connected with, overlying field-aligned emission structures. The following sections present some conjectures based on the initial analysis reported herein.

3.1. Source of Green Line Excitation

The magnetic field elongation often observed in the green emissions adjacent to STEVE (e.g., Figure 1) has naturally led many to assume production via usual auroral mechanisms—that is, penetration of magnetospheric electrons with kinetic energy >1 keV (e.g., Gillies et al., 2019; Mishin & Streltsov, 2019; Nishimura et al., 2019). However, initial spectroscopic measurements reported by Gillies et al. (2019) are inconsistent with this hypothesis. A careful analysis by Mende et al. (2019) found the spectrum to be dominated by the metastable oxygen 557.7-nm line (4.19-eV excitation energy, 0.74-s radiative lifetime) but with a trace contribution from prompt $N_2^{1P}$ emissions (7.35-eV excitation energy). Entirely absent, however, were contributions from higher energy emissions of $N_2^{1N}$, often represented in auroral studies by the band head of the $N_2^{1N}$ first negative (1N) group at 427.8 nm (18.75-eV excitation energy). This emission, produced by collisional ionization and excitation of ambient $N_2$, must be present for particle penetration to these altitudes. The presence of $N_2^{1P}$ without $N_2^{1N}$ has argued for a lack of primary electrons with the requisite >1-keV energy range, rather than a depletion of ambient $N_2$ (Mende et al., 2019). This finding supported earlier conjectures based on color comparisons (Mende et al., 2019) that the source of the green companion to STEVE is likely direct excitation of oxygen $O(1S)$ by superthermal electrons energized locally in the ionosphere.

For the features examined in this work, the particle precipitation hypothesis is excluded based on morphological considerations. Analyses of the streak in Figures 6 and 8 are consistent with a drifting point-like source, with cross-sectional size <350 m. Triangulation of a similar feature in Figure 2 has placed it in the lower ionospheric E-region, in the 100- to 110-km range. Penetration of a magnetospheric electron to <110 km requires an initial energy >10 keV (Semeter & Kamalabadi, 2005). The attenuation process will produce visible emissions that extend >10 km along the magnetic field line, with variations in intensity and color dictated by the altitude-dependent energy deposition rate and atmospheric composition (Lummerzheim & Haerendel, 2001; Semeter & Diaz, 2007). The small field-aligned dimensions and variegated orientations of the features examined herein suggest excitation by non-auroral mechanisms.

3.2. Superthermal Electron Production

In seeking a source of free energy able to excite oxygen green line features at subkilometer scales, it should be noted that the ion drift speeds within STEVE exceed 6 km/s (Archer, Gallardo-Lacourt, et al., 2019; MacDonald et al., 2018). The patterns and intensities of turbulent heating caused by such supersonic plasma jets in the outer atmosphere are not well known. Additional complexity arises from the entanglement of chemistry and electrodynamics: ion velocities in this range are known be associated with rapid conversion
from atomic ($O^+$) to molecular ($NO^+$) ions (Anderson et al., 1991), which would impact momentum balance in the channel in a highly nonlinear manner. Under these conditions, it is not surprising to find pockets of extreme electron heating.

Some evidence for this has been found in conjugate satellite measurements. Nishimura et al. (2019) and Archer, Gallardo-Lacourt, et al. (2019) have reported measurements from the Swarm satellites of a narrow channel of electron heating conjugate to STEVE, with $T_e$ exceeding 8,000 K, as well as a single-point measurement approaching 12,000 K ($>1$ eV). These measurements occurred in a region of depleted plasma densities and large upward ion velocities, consistent with expected signatures of low-altitude heating. The measured electrons are certainly nonthermal, but a distribution with average energy $\sim$1 eV would be expected to include a significant population at the requisite 4.19-eV energy for green line excitation. Candidate mechanisms for superthermal electron production in the low-altitude ionosphere include the modified two-stream (Farley-Buneman) instability (Farley, 1963; Oppenheim & Dimant, 2013) and the electron and ion thermal instabilities (Dimant & Sudan, 1997). These instabilities have the lowest threshold in the 100- to 120-km altitude range (Dimant & Oppenheim, 2004), which is consistent with the altitude range found via triangulation in section 2.1. The kilometer cross-sectional dimensions found in section 2.3 are consistent with scale sizes of irregularities produced in simulations (Oppenheim & Dimant, 2013). Electron temperatures as high as 6,000 K have been observed in association with plasma heating by Farley-Buneman waves (Bahcivan & Cosgrove, 2010). Using the linear relationship of Foster and Erickson (2000), this would correspond to an electric field of $\sim$300 mV/m, corresponding to ion drifts of $\sim$6 km/s. This is consistent with initial measurements of STEVE ion drifts (MacDonald et al., 2018), with some observations suggesting that the parameter set may be even more extreme (Archer et al., 2019).

Manifestations of such turbulent processes in airglow or auroral signatures have not yet been theoretically predicted. The hypothesized photochemical model for the production of the 557.7-nm emission is

$$O(^3P) + e(E) \rightarrow O(^1S) + e(E - 4.19\text{eV}) \quad (2)$$

$$O(^1S) \rightarrow O(^3P) + h\nu_{557.7} \quad (3)$$

(Itikawa & Ichimura, 1990). Note that the metastable $O(^1D)$ state, responsible for the oxygen 630-nm red line, is excited through the same collisional reaction but at lower energy (1.96 eV). However, it is quenched at lower ionospheric altitudes due to its long ($\sim$120 s) radiative lifetime. Extracting spatiotemporal information about electron heating from images of this emission requires careful consideration of source dynamics and radiative lifetime effects, as represented in the space-time perspective of the sensor. It must also be borne in mind that the images only provide information about electrons with energy $>4.19\text{eV}$ (45,000 K). Lower energy superthermal populations are important and presumably present, but invisible in green line imagery. A full treatment of these effects is beyond the scope of this work, but a qualitative consideration is useful for evaluating evidence from citizen science imagery.

### 3.3. Relation to Magnetic Field-Aligned Features

The initial examples examined in this work provide evidence for a connection between the low-altitude streaks and overlying magnetic field-aligned features comprising the picket fence. The evidence is summarized in Figure 9. In each panel, the grayscale image depicts the green channel of the camera, displayed as a negative for ease of annotation. The red arrows highlight features aligned with the magnetic field; the blue arrows indicate the orientation and, where known, trajectory of the streaks. Figure 9a corresponds to Figure 3c. At this point in time, the upper streak has developed a visible tail extending behind the trailing edge, which is qualitatively consistent with the afterglow effects discussed in section 2.2. This streak has also developed a faint emission column extending above it in the magnetic field-aligned direction. The combination of these effects forms an intriguing “L” shape in the image (see Movie 1).

Figure 9b is from Figure 1b. Here, multiple horizontal streaks are observed at the base of field-aligned aurora-like structures, with an apparent gap in between. In panel (c) (from Figure 1c), the streak and the faint emissions connecting to the field-aligned feature above form a bent feature, taking on a “J” shape. The temporal development of this morphology was not resolved in this image sequence (see Movie 2). However, the streak studied in Figure 6 was well resolved and exhibited a similar dynamic. In Figure 9d, the blue
Figure 9. Relationship between magnetic field-aligned features (red), streak orientation, and streak motion (blue) for examples used in this study. The images show the green channel of the cameras, displayed as a negative (emissions are dark). (a) From Figures 1a and 3c. Blue arrows show the horizontal equatorward direction of motion, as observed in Figures 3a–3f. (b) From Figure 1b. Blue arrows show the orientation of the streaks in relation to magnetic field direction. (c) From Figure 1c. The blue curve highlights the curved shape of the airglow feature which appears to bend into the field-perpendicular equatorward direction. (d) From Figure 5c (rotated 90°). Blue curve shows the complete trajectory as extracted from the image sequence in Figures 5a–5e.

One speculation that could account for a continuous transition between magnetic-aligned features at higher altitudes and narrow horizontal features at lower altitudes involves collisions. If we assume that the green emission is excited by a cloud of superthermal electrons, then the drift would be constrained to the $E \times B$ direction at higher altitudes, but develop an increasing component in the direction opposing $E$ at lower altitudes, as increasing collisions allow the electrons to respond directly to the poleward electric field. This explanation would require that the electrons become demagnetized due to collisions in the $\sim 100$- to 110-km altitude range (based on triangulation results). This is higher than what is expected under quiescent conditions (Brekke, 2013). However, we note that the effective collision frequency can be modified substantially in the presence of extreme electric fields (Bahcivan & Cosgrove, 2010; Milikh & Dimant, 2003), which are expected to be highly variable in space and time within the picket fence region.

3.4. Formation of Field-Aligned Features From Point Sources

One question that arises naturally from the evidence assembled thus far is whether field-aligned “aurora-like” optical features can evolve from point-like sources created through turbulent heating. Preferential expansion of an isolated plasma population along the magnetic field direction is expected considering the difference in field-parallel versus field-perpendicular mobility (Rishbeth & Garriott, 1969). A possible structuring mechanism lies in the coupling between the Farley-Buneman and gradient-drift instabilities, which arise from a common dispersion relation (Fejer & Kelley, 1980). The coupling effects can be amplified in regions of extreme density gradients (Haldoupis et al., 2005), such as those found on the poleward edge of an extreme Sub-auroral Ion Drift (SAID) channel.

The evolution of a plasma cloud into aurora-like features has been well documented in artificial plasma release experiments (Haerendel & Lüst, 1968), where a cloud of ionized barium (Ba$^+$) released in the ionospheric $F$-region striates across magnetic field lines and diffuses along the magnetic field, forming structures reminiscent of rayed aurora within just a few seconds (Simons et al., 1980). The cross-field striation is thought to be caused by the gradient drift instability (Linson & Workman, 1970; Simons et al., 1980). This mechanism is also plausible here due to the presence of extreme electric fields and extreme density gradients on the edges of the STEVE channel (Nishimura et al., 2019). In chemical release experiments, the destabilized plasma was a cold and long-lived barium ion (Ba$^+$) cloud illuminated by sunlight fluorescence. In the present situation, the illuminating agent would be superthermal electrons with energy $>4.19$ eV exciting the oxygen O($^1S$) state. In the image sequences of Figures 3 and 6, the excitation source persisted for $>10$ s, which is long compared with time scales for field-line elongation observed in Barium releases (Simons et al., 2019).
et al., 1980). A full theoretical assessment will require considering collisional effects on the development of the instability at these lower altitudes.

However, based on the limited evidence thus far obtained, it is also possible that the streaks and the picket fence are not causally connected but, rather, represent two distinct responses to the same free energy source. Mende et al. (2019) conjectured that the magnetic field-aligned features could be produced by wave heating induced by the extreme electric fields in the SAID region (Streltsov & Mishin, 2003). Fine-scale green emissions at lower conjugate altitudes could be excited by these same extreme fields.

4. Conclusions

Thus far, nothing about the optical phenomenology associated with STEVE is conveniently explained in terms of our historical understanding of auroras and airglow (Gillies et al., 2019; Harding et al., 2020; Mende et al., 2019). The reason for this may be generally traced to the extreme nature of the driving electric fields and attendant supersonic ion drifts. This regime of ion-neutral interaction has not been systematically treated in aeronomical models. The mauve-white emission of the main STEVE channel is likely related to the continuum nightglow emission that has been known for decades (Bates, 1993). Our understanding of its origin remains incomplete, but STEVE has attracted renewed attention to the topic (Harding et al., 2020). The green features accompanying STEVE often exhibit elongation in the magnetic field direction, suggesting that they are produced by precipitation of magnetospheric electrons (Nishimura et al., 2019). But initial spectroscopic measurements are inconsistent with this hypothesis (Mende et al., 2019). The green phenomena accompanying STEVE also include a variety of blobs, streaks, and curved bands of emission (Figure 5) that are irreconcilable with the precipitation hypothesis on morphological grounds alone.

This work has focused on a particular repeatable feature of the STEVE green line phenomenology: a narrow streak of emission observed below, and connected with, the field-aligned features comprising the picket fence. An initial analysis has been presented using time lapse imagery and multistation observation, revealing the following characteristics.

1. Formation is poleward of STEVE and in the lower ionosphere (100–110 km).
2. Movement follows a curved trajectory, with dominant component toward the main STEVE arc.
3. Elongation is along the direction of motion, suggestive of an unresolved moving point source.
4. Lifetime of an individual streak is \( \sim 20–30 \) s.
5. Location is conjugate to, and sometimes optically connected with, field-aligned features above it.
6. Dimension in the field-aligned direction is \(<1 \) km and thus irreconcilable with production via magnetospheric particle precipitation.

The origin and significance of these unusual features is currently subject to speculation. The similarity in coloration with, and magnetic conjugacy to, other overlying green features suggests a common optical spectrum dominated by the oxygen 557.7-nm emission. The point-like nature of the emission suggests excitation via turbulent electron heating, rather than variations in neutral oxygen density. Prior work on radar backscattered from ionospheric regions impinged by extreme electric fields has implicated an interplay among Farley-Buneman, ion-thermal, electron-thermal, and gradient-drift instabilities in creating small-scale irregularities in density and temperature in the lower ionospheric E-region (Dimant & Oppenheim, 2011). The evidence in these studies has been derived from radar backscatter and in situ plasma measurements. The extreme electric fields, and attendant extreme velocities, observed within STEVE have not been fully treated in theoretical or simulation studies. The question is whether under extreme conditions such mechanisms could produce an electron population exceeding the 4.19-eV threshold for green line excitation, creating an observable optical diagnostic while also providing a mechanism to explain the point-source nature of these objects.

5. Next Steps

STEVE has elevated the role of citizen scientists in primary research. In their quest to obtain beautiful imagery of the natural world, photographers have serendipitously discovered a phenomenon overlooked by professional scientists. References to the optical phenomena of STEVE have since been uncovered in historical literature (Hunnekuhl & MacDonald, 2020), but without its current appreciation as a phenomenon distinct from the typical aurora and airglow (Liang et al., 2018).
Specific gaps in our understanding of STEVE can be filled through enhanced partnerships with citizen science community. First, we cannot yet state with certainty that the optical spectra of all green features are the same. Needed are collaborative observations from high frame-rate broad-band cameras of the type employed herein and high-resolution imaging spectrographs of the type employed by Gillies et al. (2019). Second, there is a need for higher-cadence observations; the 3.5-s cadence of the image sequences used herein (Figure 6) has not fully resolved STEVE phenomena. Third, carefully coordinated multisite measurements are needed for better triangulation of orientations and trajectories of these features. This requires that precise geolocation and timing information be recorded into image metadata. And fourth, continued documentation and sharing of observations with the global community is needed—for example, through the AuroraSaurus project (MacDonald et al., 2015).

Progress will also require new collaborations within the Heliophysics community. If the fine-scale features described herein are a consequence of extreme electric fields, then they present a new diagnostic for understanding ionospheric instabilities and turbulence. Advancing this capability requires that we bridge the gap between theoretical research on plasma heating and observational research on thermally excited optical phenomena. This will require collaborative efforts that conjoin regional transport modeling (e.g., Semeter, 2012), kinetic plasma simulation (e.g., Oppenheim & Dimant, 2004), and aeronomical modeling of optical emissions (e.g., Solomon, 2017).

Conflict of Interest
The authors declare no conflicts of interest relevant to this study.

Acknowledgments
This work was supported by NASA under grant 80NSSC18K0659 and by the NSF under grant AGS-1821135. The authors are grateful to Stephen Voss (Aurora Australis Facebook group), Shawn Malone (Great Lakes Photography), and Alan Dyer (www.amazingdaysky.com) for providing additional critical photographic evidence for this work. We are grateful to the developers of Stellarium.org for making their outstanding tools freely available to the community. The figures presented herein, along with the movies, constitute the entirety of the new data in this work.

References
Anderson, P. C., Hoelis, R. A., & Hanson, W. B. (1991). The ionospheric signatures of rapid subauroral ion drifts. Journal of Geophysical Research, 96(A4), 5765–5792. https://doi.org/10.1029/90JA02651
Archer, W. E., Gallardo-Lacourt, B., Perry, G. W., St-Maurice, J. P., Buchert, S. C., & Donovan, E. (2019). Steve: The optical signature of intense subauroral ion drifts. Geophysical Research Letters, 46, 6279–6286. https://doi.org/10.1029/2019GL082687
Archer, W. E., St-Maurice, J. P., Gallardo-Lacourt, B., Perry, G. W., Cully, C. M., Donovan, E., & Euirich, D. (2019). The vertical distribution of the optical emissions of a STEVE and picket fence event. Geophysical Research Letters, 46, 10,719–10,725. https://doi.org/10.1029/2019GL084473
Bahcivan, H., & Cosgrove, R. (2010). On the generation of large wave parallel electric fields responsible for electron heating in the high-latitude E region. Journal of Geophysical Research, 115, A10304. https://doi.org/10.1029/2010JA015424
Bates, D. R. (1993). Cause of terrestrial nightglow continuum. Proceedings of the Royal Society of London Series A, 441(1917), 227–237. https://doi.org/10.1098/rspa.1993.0141
Borovsky, J. E., & Suszcynskiy, D. M. (1993). Optical measurements of the fine structure of auroral arcs. In Auroral Plasma Dynamics, Geophysical Monograph (Vol. 80, p. 25).
Brekke, A. (2013). Physics of the upper polar atmosphere. Wiley Praxis Series in Atmospheric Physics. Springer: New York. https://doi.org/10.1007/978-3-642-27401-5
Dahlgren, H., Semeter, J. L., Marshall, R. A., & Zettergren, M. (2013). The optical manifestation of dispersive field-aligned bursts in auroral breakup arcs. Journal of Geophysical Research: Space Physics, 118, 4572–4582. https://doi.org/10.1002/jgra.50415
Dimant, Y., & Oppenheim, M. (2004). Ion thermal effects on E-region instabilities: Linear theory. Journal of Atmospheric and Solar-Terrestrial Physics, 66(17), 1639–1654. 40 years of equatorial aeronomy sparked by the Jicamarca Radio Observatory.
Dimant, Y. S., & Oppenheim, M. M. (2011). Magneto-sphere-ionosphere coupling through E region turbulence: 2. Anomalous conductivities and frictional heating. Journal of Geophysical Research, 116, A09304. https://doi.org/10.1029/2011JA016649
Dimant, Y., & Sudan, R. N. (1997). Physical nature of a new cross-field current-driven instability in the lower ionosphere. Journal of Geophysical Research, 102, 2551–2563. https://doi.org/10.1029/96JA03274
Farley, D. T. (1963). A plasma instability resulting in field-aligned irregularities in the ionosphere. Journal of Geophysical Research, 68, 6083. https://doi.org/10.1029/JZ068i022p06083
Fejer, B. G., & Kelley, M. C. (1980). Ionospheric irregularities. Reviews of Geophysics, 18(2), 401–454. https://doi.org/10.1029/RG018i002p00401
Foster, J. C., & Erickson, P. J. (2000). Simultaneous observations of E-region coherent backscatter and electric field amplitude at F-region heights with the Millstone Hill UHF Radar. Geophysical Research Letters, 27(19), 3177–3180. https://doi.org/10.1029/2000GL000042
Gallardo-Lacourt, B., Liang, J., Nishimura, Y., & Donovan, E. (2018). On the origin of STEVE: Particle precipitation or ionospheric skylight? Geophysical Research Letters, 45, 7966–7973. https://doi.org/10.1002/2018GL078509
Gillies, D. M., Donovan, E., Hampton, D., Liang, J., Connors, M., Nishimura, Y., & Spanoswick, E. (2019). First observations from the TREx spectrograph: The optical spectrum of STEVE and the picket fence phenomena. Geophysical Research Letters, 46, 7207–7213. https://doi.org/10.1029/2019GL083272
Haerendel, G., & Lüdt, R. (1968). Artificial plasma clouds in space. Scientific American, 219(5), 80–92. https://doi.org/10.1038/scientificamerican1168-80
Haldoupis, C., Ogawa, T., Schiegl, K., Koehler, J. A., & Ono, T. (2005). Is there a plasma density gradient role on the generation of short-scale Farley-Buneman waves? Annales Geophysicae, 23(10), 3323–3337. https://doi.org/10.5194/angeo-23-3323-2005
Harding, B. J., Mende, S. B., Triplett, C. C., & Wu, Y. J. J. (2020). A mechanism for the STEVE continuum emission. Geophysical Research Letters, 47, e2020GL087102. https://doi.org/10.1029/2020GL087102
Hunnekehl, M., & MacDonald, E. (2020). Early ground-based work by auroral pioneer Carl Stormer on the high-altitude detached subauroral arcs now known as “STEVE”. Space Weather, 18, e2019SW002384. https://doi.org/10.1029/2019SW002384
Itikawa, Y., & Ichimura, A. (1990). Cross sections for collisions of electrons and photons with atomic oxygen. Journal of Physical and Chemical Reference Data, 19(3), 637–651. https://doi.org/10.1063/1.555857

Lang, D., Hogg, D. W., Mierle, K., Blanton, M., & Roweis, S. (2010). Astrometry.net: Blind astrometric calibration of arbitrary astronomical images. AJ, 137, 1782–2800. (arXiv:0910.2233)

Lang, J., Donovan, E., Connors, M., Gillies, D., St-Maurice, J. P., Jackel, B., et al. (2019). Optical spectra and emission altitudes of double-layer STEVE: A case study. Geophysical Research Letters, 46, 13,630–13,639. https://doi.org/10.1029/2019GL085639

Linson, L. M., & Workman, J. B. (1970). Formation of striations in ionospheric plasma clouds. Journal of Geophysical Research, 75(16), 3211–3219. https://doi.org/10.1029/JA075i016p03211

MacDonald, E. A., Case, N. A., Clayton, J. H., Hall, M. K., Heavner, M., Lalome, N., & Tapia, A. (2015). Aurorasaurs: A citizen science platform for viewing and reporting the aurora. Space Weather, 13, 548–559. https://doi.org/10.1002/2015SW001214

MacDonald, E. A., Donovan, E., Nishimura, Y., Case, N. A., Gillies, D. M., Gallardo-Lacourt, B., & Schodfield, I. (2018). New science in plain sight: Citizen scientists lead to the discovery of optical structure in the upper atmosphere. Science Advances, 4, 3. https://doi.org/10.1126/sciadv.aag00930

Mende, S. B., Harding, B. J., & Turner, C. (2019). Subauroral green STEVE arcs: Evidence for low-energy excitation. Geophysical Research Letters, 46, 14,256–14,262. https://doi.org/10.1029/2019GL086145

Milikh, G. M., & Dimant, Y. S. (2003). Model of anomalous electron heating in the E region: 2. Detailed numerical modeling. Journal of Geophysical Research, 108(A9), 1351. https://doi.org/10.1029/2002JA009927

Mishin, E., & Streltsov, A. (2019). STEVE and the picket fence: Evidence of feedback-unstable magnetosphere-ionosphere interaction. Geophysical Research Letters, 46, 14,247–14,255. https://doi.org/10.1029/2019GL085446

Nishimura, Y., Gallardo-Lacourt, B., Zou, Y., Mishin, E., Knudsen, D. J., Donovan, E. F., & Raybell, R. (2019). Magnetospheric signatures of STEVE: Implications for the magnetospheric energy source and interhemispheric conjugacy. Geophysical Research Letters, 46, 5637–5644. https://doi.org/10.1029/2019GL082460

Oppenheim, M. M., & Dimant, Y. S. (2004). Ion thermal effects on E-region instabilities: 2D kinetic simulations. Journal of Atmospheric and Solar-Terrestrial Physics, 66(17), 1655–1668. https://doi.org/10.1016/j.jastp.2004.07.007

Oppenheim, M. M., & Dimant, Y. S. (2013). Kinetic simulations of 3-D Farley-Buneman turbulence and anomalous electron heating, Journal of Geophysical Research: Space Physics, 118, 1306–1318. https://doi.org/10.1002/jgra.50196

Palmroth, M., Grandin, M., Helin, M., Koski, P., Oksanen, A., Glad, M. A., & Verronen, P. T. (2020). Citizen scientists discover a new auroral form: Dunes provide insight into the upper atmosphere. AGU Advances, 1, e2019AV000133. https://doi.org/10.1029/2019AV000133

Rishbeth, H., & Gariotti, O. (1969). Introduction to ionospheric physics. New York: Academic Press. Retrieved from https://cmc.marmot.org/EsboAcademicCMC/ocn689060279

Semeter, J., & Kamalabadi, F. (2005). Determination of primary electron spectra from incoherent scatter radar measurements of the auroral E-region. Radio Science, 40, RS2006. https://doi.org/10.1029/2004RS003042

Semeter, J., Lummerzheim, D., & Haerendel, G. (2001). Simultaneous multispectral imaging of the discrete aurora. Journal of Atmospheric and Solar-Terrestrial Physics, 63(18), 1981–1992.

Semeter, J., Zettergren, M., Diaz, M., & Mende, S. (2008). Wave dispersion and the discrete aurora: New constraints derived from high-speed imagery. Journal of Geophysical Research, 113, A12208. https://doi.org/10.1029/2008JA013122

Simons, D. J., Pongratz, M. B., & Gary, S. P. (1980). Prompt striations in ionospheric barium clouds due to a velocity space instability. Journal of Geophysical Research, 85(A2), 671–677. https://doi.org/10.1029/JA085iA02p00671

Solomon, S. C. (2017). Global modeling of thermospheric airglow in the far ultraviolet. Journal of Geophysical Research: Space Physics, 122, 7834–7848. https://doi.org/10.1002/2017JA024314

Streltsov, A. V., & Mishin, E. V. (2003). Numerical modeling of localized electromagnetic waves in the nightside subauroral zone. Journal of Geophysical Research, 108(A8), 1332. https://doi.org/10.1029/2003JA009858

Thébault, E., Finlay, C. C., Beggan, C. D., Aubert, J., Barrois, O., et al. (2018). International geomagnetic reference field: The twelfth generation international geomagnetic reference field—The twelfth generation. Earth, Planets and Space, 70(2), 79. https://doi.org/10.1186/s13063-015-0228-9

Zettergren, M., & Semeter, J. (2012). Ionospheric plasma transport and loss in auroral downward current regions. Journal of Geophysical Research, 117, A12310. https://doi.org/10.1029/2012JA017637

Zettergren, M., Semeter, J., Blelly, P.-L., & Diaz, M. (2007). Optical estimation of auroral ion upflow: Theory. Journal of Geophysical Research, 112, A12310. https://doi.org/10.1029/2007JA012691