Abstract Utilizing the suprathermal electron imager onboard the e-POP satellite, we performed a statistical study of groups of repetitive suprathermal electron bursts (STEBs) with 52 events (each with ≥3 STEBs) during 21 e-POP orbits. The STEBs are observed on both the day side and night side, and within a wide range of geomagnetic latitudes, from 64° to 78°. We interpret these data as temporally varying signatures; we suggest the repetition is due to the ionospheric Alfvén resonator (IAR), since the statistical time separation of adjacent STEBs in the satellite frame is 0.5–1.5 s, which is consistent with the characteristic period of the IAR. Furthermore, the STEBs are associated with low-frequency magnetic field perturbations. The statistical occurrence of repetitive STEBs shows a preference toward postnoon and midnight sectors at high magnetic latitudes. We also present one example event of four successive STEBs associated with auroral rays in conjugate imagery. The repetition period of STEBs is similar to the oscillation period of magnetic fields observed by Enhanced Polar Outflow Probe (e-POP). One of the STEBs in an example event exhibits “normal” dispersion (high energy particles with field-aligned pitch angle arriving first) and the adjacent STEB exhibits “inverse” dispersion (low energy particles with broad pitch angles arriving first). With a test particle simulation, we propose one possible explanation of inverse dispersion in terms of a suprathermal electron population and a downward-propagating parallel electric field.

Plain Language Summary An ongoing question in magnetospheric physics is how electrons are accelerated to a wide range of energies. We explore this phenomenon by using electron data obtained from the Enhanced Polar Outflow Probe (e-POP) satellite. We observe repetitive accelerated electrons with period similar to the oscillation of the magnetic field. We argue the repetition is due to standing Alfvén waves, which are caused by incident and reflected waves that propagate along the Earth’s magnetic field line. Our electron observations are useful in detecting the structure of standing Alfvén waves and enhance our understanding of the dynamic electron acceleration process due to them.

1. Introduction

Electron precipitation associated with the discrete aurora can produce monogenetic peaks (inverted-V) and broadband acceleration visible in energy-time spectrograms (Newell et al., 2009). Inverted-V precipitation, which causes the most commonly observed green-line auroral arcs, is characterized by a Λ shape in the electron energy spectrograms measured by spacecraft with a peak energy reaching 1–30 keV. Suprathermal electron bursts (STEBs) are characterized by intense fluxes and energies in the hundreds of eV range, and are associated with red-line emissions which tend to be weak and even subvisual. Their energy spectrum is broad in the magnetic field-aligned direction (B) but relatively cold perpendicular to B. STEBs are observed as transient bursts lasting of the order of 1 s in the spacecraft frame, and their energies often demonstrate a time-variable signature during the observation below the acceleration region. Sometimes these dispersive signatures are interpreted spatially (e.g., Liang et al., 2019), but more often, and in this manuscript, they are interpreted as temporal variations. A “normal” dispersion is characterized by electron energy decreasing with time, which in a temporal interpretation usually means that, for a localized source, high-energy electrons travel faster and arrive at the detector sooner (e.g., Andersson et al., 2002; Asamura et al., 2009; Kletzing & Hu, 2001; Su et al., 2004). This energy dispersion often coincides with pitch angle dispersion, in which field-aligned electrons arrive sooner than electrons with intermediate pitch angles (Arnoldy et al., 1999). An “inverse” dispersion with lower-energy electrons arriving first has been reported in previous studies (Cameron & Knudsen, 2016; Liang et al., 2019). The rising energy feature can result from spatial dispersion...
created by a drifting arc (Liang et al., 2019), or from a model in which satellite observations take place a short distance below the boundary of a rapidly moving acceleration region, such as an aurora ray (Cameron & Knudsen, 2016).

The dynamic acceleration process accounting for STEBs usually involves a parallel electric field carried by kinetic or inertial Alfvén waves with short wavelengths perpendicular to B (Goertz & Boswell, 1979; Hasegawa, 1976; Lysak & Dum, 1983). Electrons can be accelerated to twice the Alfvén speed through a Fermi-like process when reflecting off the wavefront (Andersson et al., 2002; Chen et al., 2005; Kletzing, 1994; Watt & Rankin, 2007; Watt et al., 2005). The electric and magnetic fields associated with STEBs frequently demonstrate fluctuations in the Alfvén wave frequency range (Chaston et al., 2002; Knudsen et al., 1998).

One type of STEB, also known as arc-edge precipitation, appears on the edge of inverted-V precipitation (Boehm et al., 1994). Another type appears in repetitive structures with a frequency of the order of 1 Hz. Tanaka et al. (2005) reported “multiple energy-time dispersions” in the cusp, which are characterized by field-aligned electron energy falling from ~200 to ~20 eV at a repetition period of 0.5–1.0 s. Lynch et al. (1999) and Chaston et al. (2002) observed electron energy dispersion having similar repetition frequencies in the nightside auroral region. Arnoldy et al. (1999) observed that field-aligned bursts fluctuating at ~10 Hz coincide with the energetic inverted-V electrons. These are all case studies in which STEBs demonstrate the same normal dispersion feature without inverse dispersion.

One explanation for periodic suprathermal electron precipitation is given by the theory of the Ionospheric Alfvén Resonator (IAR; Trakhtengerts & Feldstein, 1991; Lysak, 1991). When a traveling Alfvén wave is reflected, for example at the ionosphere boundary due to high conductivity, a standing wave pattern is established by the incident and reflected waves (Knudsen et al., 1992). When the wave is also reflected at the upper boundary due to a sharp gradient in the Alfvén speed (at ~7,000 km altitude), a resonant wave structure is built up along the magnetic field line; this is known as the ionospheric Alfvén resonator. For typical parameters in the ionosphere, the characteristic frequency of the cavity is in the 1 Hz range. Chaston et al. (2002) simulated the IAR including parallel electric fields and generated electron energy and pitch angle distributions similar to the repetitive STEBs observed by the FAST satellite.

Although many studies have focused on the simulation of IAR (e.g., Lysak, 1991,1999) and observations of the standing waves (e.g., Belyaev et al., 1999; Grzesiak, 2000; Knudsen et al., 1992), questions remain as to the source of Alfvén waves trapped in the IAR and their role in auroral arc generation. The plasma sheet boundary layer (PSBL) is one possible source for the Alfvén waves observed on the poleward edge of the auroral oval (Wygant et al., 2000, 2002; Keiling et al., 2003). The Ionospheric Feedback Instability (IFI) has also been invoked as a possible mechanism for the excitation of the IAR and the formation of narrow auroral arcs; in this case the wave energy derives from background convection (Atkinson, 1970; Lysak & Song, 2002; Pokhotelov et al., 2001). A numerical simulation from Russell et al. (2013) shows that ionospheric feedback without instability can generate small-scale Alfvén waves in a strong downward current region.

In this paper, we present an auroral arc event associated with four successive STEBs with both normal and inverse dispersion. We also conduct a statistical investigation of 52 repetitive STEB events (each with ≥3 STEBs) during 21 satellite crossings of the auroral zone. We cannot determine with certainty whether the STEBs are temporal or spatial with single satellite measurements. However, we tend to believe the structures are temporal, since the statistical repetition period is consistent with the characteristic period of the IAR. The electron signatures reported in this study yield insights into the structure of the IAR and magnetosphere-ionosphere coupling, and provide information about dynamic electron acceleration processes in the auroral region.

2. Instrumentation and Data

In this study, we use measurements from the Swarm and e-POP (also known as Swarm Echo) satellites. The CASSIOPE Enhanced Polar Outflow Probe (e-POP) satellite was launched on September 29, 2013 and has a perigee of 325 km and an apogee of 1,500 km (Yau & James, 2015). In this study, we focus on measurements from the e-POP suprathermal electron imager (SEI; Knudsen et al., 2015). The SEI measures two-dimensional (energy-angle) distributions of electrons with energies up to 325 eV. The original 100-Hz images are
co-added to 10 Hz to increase the signal-to-noise ratio. Relative units of DN (data number, which is roughly proportional to differential energy flux; [Knudsen et al., 2015]) are used to represent pixel brightness within the SEI image. Absolute flux units are not used here due to large uncertainties relating to a technical issue with the SEI high-voltage monitors. Electron images are also affected by nonuniform gain variations gradually developed over e-POP’s operation period. All images presented have thus been corrected using a gain correction map, which has been detailed in Shen and Knudsen (2020). Electron image gain changes within a single orbital segment are negligible. In any case, our results do not depend on absolute flux values. We also use 160 Hz vector magnetic field measurements from the magnetic field instrument (MGF; Wallis et al., 2015) on board e-POP.

The original Swarm constellation, launched on November 22, 2013, consists of three identical satellites (Friis-Christensen et al., 2008). Swarm A and C fly side by side (Swarm C lags by about 10 s) in near-polar circular orbits with an altitude of 460 km. Swarm B flies at an altitude of 510 km. Each satellite measures vector magnetic fields with time resolution up to 50 Hz (Friis-Christensen et al., 2006) and electric field perpendicular to \(B\) (through ion drift) up to 16 Hz (Knudsen et al., 2017). In this study, the magnetic field data are decimated to 16 Hz to match electric field data to investigate Alfvén waves.

The auroral images are observed by the THEMIS ground-based All-Sky Imager (ASI) array (Donovan et al., 2006; Mende et al., 2008), which consists of 21 cameras covering middle- to high-latitude North America. Each camera from the array captures 256 × 256 pixel “white light” images every 3 s and has a spatial resolution of approximately 1 km at zenith. An emission altitude of 110 km is assumed to map the images to geographic coordinates for comparison with satellite measurements.

3. Observations

3.1. Case Study

Figure 1 shows e-POP observations of an example event of repetitive STEBs. This event occurred in the postmidnight sector and was observed at an altitude of 1,086 km. Figure 1a shows the field-aligned (within ±15° pitch angle) energy spectrogram of electrons in the energy range of 150–320 eV. Electrons with energy less than 150 eV are not included due to the large uncertainty associated with the SEI image gain correction in the lower energy range (Shen & Knudsen, 2020).

Figure 1b shows the pitch angle spectrogram of electrons in the same energy range (150–320 eV). Four successive STEBs occurred between UT 06:10:37 to UT 06:10:41 with similar time intervals of 1 s. Figure 1c shows the magnetic fields observed by MGF with a band-pass filter of 0.2–4 Hz to remove the background magnetic field and high-frequency noise. \(x\) is in the direction of the e-POP satellite trajectory, \(y\) points horizontally and to the right when facing the satellite’s direction of motion, and \(z\) points toward the nadir direction. At high latitudes in the northern hemisphere, Earth’s magnetic field is only a few degrees off the \(z\) direction (≈9.5° in this case). Variations are observed in both the \(B_x\) (red) and \(B_y\) (blue) components with a similar period of 1 s.

The energy and pitch angle spectrograms demonstrate both normal dispersion and inverse dispersion features in this event. Figure 1d shows the sequential electron distributions observed by SEI during STEB2 (the second STEB marked in Figure 1c). The two yellow circles indicate the energy levels of 150 eV and 320 eV. STEB2 demonstrates an inverse dispersion feature: low-energy electrons with broad pitch angles are observed first (UT 06:10:38.5), and a higher-energy electron beam in the field-aligned direction arrives later (UT 06:10:38.7). In contrast, STEB3 displays a normal dispersion with field-aligned high-energy electrons arriving first (UT 06:10:39.6) and followed by electrons with a broader pitch angle distribution (UT 06:10:39.8).

Notice that the lack of signal around −90° pitch angle (where the sign distinguishes particles coming from opposite azimuthal angles in the plane perpendicular to \(B\)) in Figure 1b and on the left bottom side of the images in Figures 1d and 1e is due to a satellite blockage effect, where electrons have gyro-diameters comparable to the SEI boom length (Shen & Knudsen, 2020). A movie of SEI images for this event is provided in Movie S1.

During this event, Swarm A, C and e-POP flew over the ASI located in Kuujjuaq (KUUJ) with e-POP lagging by 10 min. Figures 2a and 2b show observations from the KUUJ ASI during the crossings of e-POP and
Figure 1. e-POP SEI and MGF observations of an example of successive STEBs on August 28, 2014. Panel a shows the field-aligned (−15°–15° pitch angle) energy spectrogram from e-POP SEI. Panel b shows the pitch angle spectrogram of electrons in the energy range of 150–320 eV. Panel c displays the horizontal components of the magnetic field observed by MGF with a band-pass filter of 0.2–4 Hz. The vertical lines indicate the locations of the four STEBs. Panel d and e display sequential electron distributions at 0.1 s time intervals during STEB2 and STEB3. The white line shows the magnetic field direction.
Swarm satellites. The ASI image is mapped to geographic coordinates by assuming an emission altitude of 110 km, which is a typical altitude of green line arcs. The trajectories of e-POP (orange line) and Swarm (white lines) are traced down to 110 km using a dipole model. The location of the four successive STEBs shown in Figure 1 is marked with a yellow thick line in Figure 2a along the e-POP trajectory. The STEBs are observed to be associated with a rayed arc, which is delineated by the green box. Figures 2a and 2b show the observations at the time when e-POP and Swarm enter the green box, about 10 min apart. The satellite locations are indicated by the spacecraft coordinate systems with the satellite trajectories. Figure 2c shows the ewogram (east-west keogram) between UT 05:58:00-UT 06:14:00, which is generated by taking the pixels in the green box, averaging in latitude and stacking up with time. The arc in the green box has a nonuniform brightness along the arc, which intensifies when Swarm and e-POP are flying over. The bright feature is moving eastward at a speed of ∼4 km/s, which is estimated by the inclination of the line of peak brightness in the ewogram (black dashed line). The arc movement is more easily identified in the movie of ASI images, which is provided in Movie S2.

Figures 3a–3d show observations from Swarm C when it was flying across the KUUJ ASI field of view 10 min before e-POP. The data are presented in the spacecraft frame shown in Figure 2b. Figure 3a shows $\delta B_y$, which is calculated by subtracting the International Geomagnetic Reference Field (IGRF) from the measured magnetic field. In the blue-shaded region, $\delta B_y$ has a positive slope, indicating a large-scale quasistatic downward field-aligned current (FAC). In contrast, the red shaded region indicates an upward FAC sheet (precipitating electrons). This large-scale two-sheet FAC pattern is quasistatic, indicated by a similar
two-sheet structure observed by Swarm A (Figure 3e), and is consistent with the statistical Region 1 and Region 2 FAC distribution in this MLT sector (Iijima & Potemra, 1978). Figure 3b shows the horizontal electric field $E_x$ estimated from the cross-track ion drift velocity measured by the Swarm EFI. Figures 3c and 3d show the Fourier spectrogram of $\delta B_y$ and $E_x$ with a 4-s-wide Hanning window and 50% overlapping sample segments.
The green boxes in Figures 3a and 3b indicate the location of the rayed arc. The four repetitive STEBs observed together with the rayed arc are located on the edge of the upward FAC, where Swarm observed enhanced electromagnetic wave power in the frequency range of 0–8 Hz. We also calculate coherency, which measures the phase correlation between $E_x$ and $\delta B_y$ with a normalized value between 0 and 1. The average coherency in the green box region is 0.4 (not shown here), which is larger than the $3\sigma$ level of the coherency between two signals of Gaussian white noise using the same window length and overlap (Figure 13 in Wu et al., 2020).

Figures 4a and 4b show $E_x$ and $\delta B_y$ within the green box region in an expanded view. The electric and magnetic fields demonstrate fluctuations with a similar period of $\sim 1$ s, suggesting the STEBs are associated with Alfvén waves. Figure 4c shows the histogram of phase difference between $E_x$ and $\delta B_y$ in the green box region. The white line shows the median value for each frequency.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Swarm C electric and magnetic fields within the green box region in Figures 3a and 3b in an expanded view. Panel a: residual magnetic field $\delta B_y$ with a band-pass filter of 0.2–4 Hz. Panel b: electric field $E_x$ observed by Swarm EFI. Panel c: histogram of the phase difference between $E_x$ and $\delta B_y$ in the green box region. The white line shows the median value for each frequency.
coefficient (Knudsen et al., 1992; Miles et al., 2018; Pakhotin et al., 2018; Wu et al., 2020), which in turn is determined by the Alfvén impedance ($\mu_0 V_A$) and Pedersen conductance. In this case, the measured impedance magnitude is about 0.25 S, which is smaller than the Alfvén impedance (about 1.3 S) estimated under the assumption of O+ ions using density measured by the Langmuir probes. We do not have measurements to estimate the Pedersen impedance ($\Sigma P^{-1}$), which is usually much smaller than the Alfvén impedance (Paschmann et al., 2003). It’s possible that the electric and magnetic variations in Figures 4a and 4b are a conflation of both temporal (Alfvénic) and spatial signatures.

3.2. Statistics

We searched 67 e-POP orbits with SEI high-resolution electron data for repetitive STEB events (3 or more STEBs with similar time separation in the satellite frame) from August 2014 to March 2015. In total 52 events were collected from 21 orbits, each containing 1–6 independent repetitive STEB events. The time intervals between adjacent STEBs in the satellite frame vary from 0.2 to 4 s, and most of them are in the range of 0.5–1.5 s. The events are observed at different altitudes, ranging from 335 km to 1,439 km, and under various geomagnetic conditions (1 – 4 + Kp index). Table S1 displays the date, time, location and Kp index for each event. Figure 5a shows the distribution of the events (dots) and the associated orbits (gray lines) shown as a function of magnetic local time (MLT) and magnetic latitude (MLat). Figures 5b and 5c demonstrate the histogram of MLT and MLat distribution of all the repetitive STEB events. Figure 5d shows the histogram of the time interval between two adjacent STEBs. Overall, the events tend to occur at high magnetic latitude (72°–74° MLat) in the postnoon and midnight sectors. The MLT distribution of the all 67 e-POP orbits are shown in Figure S1.

Figure 6 demonstrates the $B_y$ spectra measured by e-POP within (a) and outside of (b) STEB events. The $B_y$ spectra in Figure 6a is calculated from the regions within the 52 repetitive STEB events. For comparison, Figure 6b shows the $B_y$ spectra obtained from the regions equatorward of the associated STEBs. The average wave amplitude inside the STEB region shows enhancements within the range 0.5–1.5 Hz and is much larger than the wave amplitude outside of the STEB region. It is clear that the repetitive STEB events are associated with low-frequency magnetic perturbations, which are consistent with an Alfvén wave interpretation.
4. Discussion

4.1. Normal and Inverse Dispersion

Transient suprathermal electron bursts are consistent with acceleration by inertial Alfvén waves with small-scale perpendicular wavelength \( \lambda_\perp \sim c/\omega_{pe} \), which have a parallel electric field that can accelerate electrons to the suprathermal (hundreds of eV) energy range. The characteristics of STEBs reported in this study, such as energy range and repetition frequency, are consistent with previous results (e.g., Chaston et al., 2002; Lynch et al., 1999; Tanaka et al., 2005) except for the inverse dispersion feature. Our example event (Figure 1) demonstrates inverse dispersion in STEB2 and normal dispersion in STEB3. The other two STEBs in the example event do not show clear time-dependent structures. A noteworthy feature in this event is that the peak energy of the STEBs increases from one to the next within the series of bursts. The normal dispersion is usually explained by time dispersion since higher-energy particles with field-aligned pitch angles travel faster and arrive at detector sooner than the lower-energy particles with broad pitch angles. The inverse dispersion reported in previous literature is explained by assuming an electric field parallel to \( \mathbf{B} \), distributed in altitude, and propagating across \( \mathbf{B} \). Ambient electrons originating at higher altitudes are accelerated through a larger potential drop (Cameron & Knudsen, 2016; Liang et al., 2019). Cameron and Knudsen (2016) performed a test particle simulation starting with a cold electron population and a static electric field to explain the observed inverse dispersion: if the altitude difference between the satellite and the bottom of the acceleration region is smaller than the field-aligned length of the acceleration region, the lower-energy electrons are detected sooner since they originate near the bottom of the acceleration region and closer to the satellite. However, the model of Cameron and Knudsen (2016) does not predict pitch angle features of inverse dispersion.

In order to explore possible mechanisms for inverse dispersion in both energy and pitch angle, we performed a test particle simulation with a suprathermal electron population and a downward propagating electric field between 1,000 and 8,000 km altitude. The auroral ionospheric environment includes ambient...
cold electrons (\(\sim 1\) eV), hot electrons (\(\geq 1\) keV) that generate auroral arcs, and secondary electrons that are scattered from the primary beam. To generate a broad pitch angle distribution similar to what we observed, the source electron distribution requires a relatively higher temperature than ionospheric background electrons. The secondary electrons are in the suprathermal energy range and can resonate with Alfvén waves since their velocities are comparable to the local Alfvén speed (several thousand km/s). Figure 7a illustrates the initial electron distribution and wave in the simulation. The initial velocity distribution of electrons is isotropic and Maxwellian with a temperature of 20 eV. A square wave pulse of parallel electric field is assumed to propagate downward with a speed of 2000 km/s toward the satellite altitude. Only electric and mirror forces are considered in the simulation. Panel b and c show the energy and pitch angle of the particle distribution when detected at 1,000 km altitude. e-POP, Enhanced Polar Outflow Probe; STEB, suprathermal electron bursts.

The inverse dispersion feature of energy and pitch angle is similar to the observed STEB2 in Figure 1b. Particles with downward initial velocities experience a short acceleration in the upward electric field, and then enter the downward electric field for deceleration. Since particles with field-aligned pitch angle enter the downward electric field first and experience a shorter acceleration and longer deceleration, they are overtaken by particles with other pitch angle when detected by satellite between 1.7 and 1.8 s. Particles with upward initial velocities are first reflected and then accelerated by the upward electric field. Since the electric field is propagating downward, these particles experience a longer acceleration process before they enter the downward electric field. As a result, they take a longer time to arrive at the satellite altitude due to reflection, and gain higher energy than particles with downward initial velocities. Movie S6 demonstrates the resonant process of particles interacting with the wave.

Conversely, normal dispersion arises if the bottom edge of the electric field region is far above the satellite altitude. In Figure 8, we show results from another test particle simulation in which we force the electric field to be 0 mV/m below 3,500 km without changing other parameters. Since the distance between the
bottom edge of electric field and satellite is long enough for high-energy electrons to overtake low-energy electrons, the energy and pitch angle demonstrate normal dispersion at the satellite altitude.

Through experimentation with our model, we found two types of dispersion depending on the lower boundary of the parallel electric field in altitude. In a realistic ionospheric environment, the magnitude of the parallel electric field is strongly affected by the electron density profile, since for constant field-aligned current the parallel electric field is inversely proportional to the electron inertial length, which is a function of the electron density. The density gradient along the magnetic field line may also result in reflection of Alfvén waves, which can reduce electric fields near the reflection altitude.

This simplified model accounts for the propagating parallel electric field associated with inertial Alfvén waves, but does not treat fields and particles self-consistently. It is intended to show one scenario that can lead to key features of energy-dispersed STEB, and to motivate future research incorporating a proper numerical simulation capable of supporting a more thorough comparison with observations of the type presented here.

4.2. Interpretation of Repetitive Bursts

Since our example event is observed to be associated with a rayed arc, we first consider the STEB source to consist of spatial structures propagating across \( B \), consistent with the spatially periodic rayed enhancements moving along the arc as shown in Figure 2a. This is also consistent with Lynch et al. (2012), who reported a poleward boundary intensification (PBI) curtain of Alfvénic rayed structures, which was traversed by the Cascades-2 rocket. They attributed the observed 2-s modulation in electron energy flux to rays having an along-arc motion of 8.5 km/s and along-arc spacing of 16 km. Throughout our entire data set, four e-POP orbits (include the example event) have clear auroral arc conjunctional observations with THEMIS ASIs. These four e-POP orbits and ASI observations are shown in Movie S2–S5. Frequently the repetitive STEBs are found to be associated with the most poleward arc, where rays are frequently found.

A major caveat for the spatial interpretation is that only a fraction of the repetitive STEB events are observed with rayed arcs. As shown in Movie S5, repetitive STEBs occur not only on the poleward boundary of the auroral oval where rays are more common, but also on the equatorward side. Furthermore, the repetitive STEBs in Figure 2 are associated with a rayed arc moving longitudinally at a speed of ~4 km/s. If we assume the four successive STEBs are spatial structures moving longitudinally along the arc, rays with along-arc separation of 4 km are needed for the STEBs to be observed by e-POP with 1 s period. However, we estimate the separation of rays in the green box in Figure 2a to be ~50 km. This number is associated with a large uncertainty since the arc is observed on the edge of the camera FOV (elevation angle ~15°) where the spatial resolution is compromised. It is also possible that the rayed arc contains some fast-moving small-scale structures that we cannot resolve with the THEMIS ASIs, since the camera has a time resolution of 3 s with 1 s exposure. Multispectral images with higher cadence, spatial resolution and sensitivity are needed to observe the optical features associated with STEBs directly.

It is also worth noting that the auroral rays we observed in Figure 2 cannot be generated by electrons with energies similar to the observed STEBs in Figure 1, since the THEMIS white light cameras are not sensitive to emissions resulting from electrons in the suprathermal energy range (Gillies et al., 2018). Thus, we interpret our event as suprathermal electrons accelerated by Alfvén waves, which are superimposed on “inverted-V” arcs, leading to visible enhancements on top of the background inverted-V emissions. The SEI captures only the lower-energy portion of this process.

Figure 8. Test particle simulation to produce normal dispersion in energy (panel a) and pitch angle (panel b) by setting the electric field in Figure 7 to 0 V/m below 3,500 km.
Another interpretation for the repetition is due to the temporal variation of the ionospheric Alfvén resonator (IAR). The main arguments in favor of this interpretation are the enhanced low-frequency perturbations in the e-POP magnetic field data (Figures 1c and 6a) and the phase difference between electric field and magnetic field from Swarm in the example event (Figure 4c), which varies with frequency between −45 and 45°. In the case of both traveling Alfvén waves and quasistatic spatial structures, electric field \(E\) and magnetic field \(B\) as measured from a moving spacecraft remain in phase. When a standing wave pattern is built up in the IAR, the phase between electric and magnetic fields will oscillate around 0° by an amount that depends on the reflection coefficient. The incident and reflected waves enhance the wave amplitude at characteristic frequencies, which are in the range of 1 Hz (Lysak, 1991). The statistical repetition period of STEBs observed in this study is 0.5–1.5 s (Figure 5d), which supports an interpretation in terms of the IAR.

The interpretations in terms of rayed structure and the IAR are not inconsistent with one another and can work together in some of our events. This can happen when a magnetic field line is oscillating at the IAR characteristic frequency, but the phase of oscillation between neighboring field lines along the arc is determined by the structure of the rays. In other words, rays represent propagation of shear-mode wave packets across \(B\), superimposed on field-aligned resonances within the IAR. Miles et al. (2018) suggested that the IAR affects smaller-scale structures embedded within discrete arcs on 0.2–10 s timescales.

The parallel electric field of inertial Alfvén waves (IAW) requires perpendicular scales comparable to or smaller than the electron inertial length \(\lambda_e\). At the same time, the latitudinal extent of each repetitive STEB event in this study is at least 10–20 km (the distance traveled by the satellite during one burst), which is comparable to the typical width of an auroral arc (Knudsen et al., 2001; Wu et al., 2017) and larger than \(\lambda_e\) in the acceleration region (of the order of 1 km; Stasiwicz et al., 2000). In the scenario where the STEBs are associated with rays having diameters similar to the arc width, electron acceleration by IAW therefore implies finer-scale structure within each ray. One possibility is that the gradient length at the edge of the rays is comparable to \(\lambda_e\). Another is that there is additional fine structure within the ray but not seen in the \(E\) and \(\delta B\) fields by Swarm, perhaps because it occurs only at higher altitude where the electron acceleration occurs, and is attenuated in the process. We note that the rays reported by Lynch et al. (2012) were ∼2 km in diameter, narrow enough to cause electron acceleration by Alfvén waves themselves without requiring substructure.

### 4.3. Sources of Alfvén Waves

One unresolved question relating to the IAR is the source of the Alfvén waves trapped inside the resonator. Both ionospheric and magnetospheric sources have been proposed. Theories such as ionospheric feedback instability (IFI) can generate Alfvén waves in the ionosphere by inducing FACs associated with an upward propagating Alfvén wave from changes in ionospheric conductivity (Lysak, 1991; Sato, 1978). In this case, the IFI requires a convection electric field in the ionosphere as an energy source (Lysak & Song, 2002; Pokhotelov et al., 2001; Streltsov & Mishin, 2018).

Our statistics show a preference for a magnetospheric source of Alfvén waves since the occurrence map (Figure 5a) of our events bears significant similarity to the Poynting flux map of Alfvén waves observed at altitudes of 25,000–38,000 km (Figure 1c in Keiling et al., 2003). Most of our events are found at high magnetic latitudes (72°–74° MLat) near the poleward edge of the auroral oval and large-scale FAC system. As an example, the repetitive STEB event shown in Figure S2 is located on the poleward edge of the three-sheet FAC structure, where the magnitude of the large-scale FAC is insignificant. Previous studies have reported standing Alfvén wave features in the IAR in both the day side (e.g., Chaston et al., 2002; Grzesiak, 2000) and night side (e.g., Miles et al., 2018), especially on the polar cap boundary of the auroral oval, which maps to the cusp and plasma sheet boundary layer (Chaston et al., 2003; Nagatsuma et al., 1996). These regions are on the boundary between open and closed field lines, potentially suggesting a relation with the reconnection process (Chaston et al., 2003).

### 5. Conclusions

We collected 52 events of repetitive suprathermal electron bursts (STEBs) during 21 e-POP orbits. Events are found at various altitudes and under different geomagnetic conditions. We suggest the repetition is due to the Ionospheric Alfvén Resonator (IAR) since the statistical time separation between two adjacent STEBs...
is consistent with typical IAR periods of the order of 1 s, and the STEBs are associated with low-frequency magnetic field perturbations. Most of the events are found at high magnetic latitudes (72°–74° MLat) in the postnoon and midnight sectors, showing a statistical similarity to the Poynting flux map of Alfvén waves observed in the magnetosphere (Keiling et al., 2003). An ionospheric source of Alfvén waves, such as the feedback instability, may also play a role.

The case study presented here demonstrates both normal and inverse dispersion in energy and pitch angle spectrometers. Using a test particle simulation, we provide one possible explanation of inverse dispersion in terms of a broad source distribution of suprathermal particles and a downward propagating electric field. This paper, following a temporal interpretation in the context of our observations, provides new information pertaining to electron acceleration from Alfvén waves in the form of both statistical properties of repetitive STEBs and details of their energy and pitch angle characteristics versus time, which can be used to test models of electron acceleration within the IAR.

Data Availability Statement
e-POP data are accessible through http://epop-data.phy.ucalgary.ca. Swarm data can be accessed online at http://earth.esa.int/swarm. The ASI data used in this study were produced with funding from the Canadian Space Agency and National Science Foundation. THEMIS ASI data can be viewed via http://data-portal.phy.ucalgary.ca/.

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References
Andersson, L., Ivenko, N., Clemmons, I., Namgaladze, A. A., Gustavsson, B., Wahlund, J.-E., et al. (2002). Electron signatures and Alfvén waves. Journal of Geophysical Research, 107(A9), 2424. https://doi.org/10.1029/2001JA900096
Arnoldy, R. L., Lynch, K. A., Austin, J. B., & Kintner, P. M. (1999). Energy and pitch angle-dispersed auroral electrons suggesting a time-variable, inverted-V potential structure. Journal of Geophysical Research, 104(A10), 22613–22621. https://doi.org/10.1029/99JA00219
Asamurara, K., Chaston, C. C., Itoh, Y., Fujimoto, M., Sakaino, T., Ebihara, Y., et al. (2009). Sheared flows and small-scale Alfvén wave generation in the auroral acceleration region. Geophysical Research Letters, 36(5), L05105. https://doi.org/10.1029/2009gl036803
Atkinson, G. (1970). Auroral arcs: Result of the interaction of a dynamic magnetosphere with the ionosphere. Journal of Geophysical Research, 110(A2), 4746–4755. https://doi.org/10.1029/JA075i025p04746.
Belyaev, P. P., Bölsinger, T., Isaev, S. V., & Kangas, J. (1999). First evidence at high latitudes for the ionospheric Alfvén resonator. Journal of Geophysical Research, 104(A3), 4305–4317. https://doi.org/10.1029/1998ja900662
Boehm, M. H., Paschmann, G., Clemmons, J., Haerendel, G., Eliaison, L., & Lundin, R. (1994). Freja observations of narrow inverted-V electron precipitation by the two-dimensional electron spectrometer. Geophysical Research Letters, 21(17), 1895–1898. https://doi.org/10.1029/94GL00370
Cameron, T., & Knudsen, D. (2016). Inverse energy dispersion from moving auroral forms. Journal of Geophysical Research, 121(12), 11896–11911. https://doi.org/10.1002/2016JA023045
Chaston, C. C., Bonnell, J. W., Carlson, C. W., Berthomier, M., Petiolas, L. M., Roth, I., et al. (2002). Electron acceleration in the ionospheric Alfvén resonator. Journal of Geophysical Research, 107(A11), 1413. https://doi.org/10.1029/2002JA009272
Chaston, C. C., Bonnell, J. W., Carlson, C. W., McDadden, J. P., Ergun, R. E., & Strangeway, R. J. (2003). Properties of small-scale Alfvén waves and accelerated electrons from FAST. Journal of Geophysical Research, 108(A4), 8003. https://doi.org/10.1029/2002JA009420
Chen, L.-J., Kletzing, C. A., Hu, S., & Bounds, S. R. (2005). Auroral electron dispersion below inverted-V energies: Resonant deceleration and acceleration by Alfvén waves. Journal of Geophysical Research, 110(A10), A10513. https://doi.org/10.1029/2005JA011168
Donovan, E., Mende, S., Jackel, B., Frey, H., Syrjasuo, M., Voronkov, I., et al. (2006). The THEMIS all-sky imaging array: System design and initial results from the prototype imager. Journal of Atmospheric and Solar-Terrestrial Physics, 68(13), 1472–1487. https://doi.org/10.1016/j.jastp.2005.03.027
Friis-Christensen, E., Lühr, H., & Hulot, G. (2006). Swarm: A constellation to study the earth’s magnetic field. Earth, Planets and Space, 58(4), 351–358. https://doi.org/10.1186/bf03351933
Friis-Christensen, E., Lühr, H., Knudsen, D., & Haagmans, R. (2008). Swarm—an earth observation mission investigating geospace. Advances in Space Research, 41(1), 210–216. https://doi.org/10.1016/j.asr.2006.10.008
Gillies, D. M., Knudsen, D., Rankin, R., Milan, S., & Donovan, E. (2018). A statistical survey of the 630.0-nm optical signature of periodic auroral arcs resulting from magnetosphere field line resonances. Geophysical Research Letters, 45(10), 4648–4655. https://doi.org/10.1029/2018GL077491
Goertz, C. K., & Boswell, R. W. (1979). Magnetosphere-ionosphere coupling. Journal of Geophysical Research, 84(A12), 101–118. https://doi.org/10.1029/JA084iA12p010739
Grzesiak, M. (2000). Ionospheric Alfvén resonator as seen by Freja satellite. Geophysical Research Letters, 27(7), 923–926. https://doi.org/10.1029/99GL036803
Hasegawa, A. (1976). Particle acceleration by mhd surface wave and formation of aurora. Journal of Geophysical Research, 81(28), 5083–5090. https://doi.org/10.1029/JA081i028p05083
Iijima, T., & Potemra, T. A. (1978). Large-scale characteristics of field-aligned currents associated with substorms. Journal of Geophysical Research, 83(A2), 599–615. https://doi.org/10.1029/JA083iA02p0599
Keiling, A., Wygant, J. R., Cattell, C. A., Mozer, F. S., & Russell, C. T. (2003). The global morphology of wave poynting flux: Powering the aurora. Science, 299(5605), 383–386. https://doi.org/10.1126/science.1080073
Kletzing, C. A. (1994). Electron acceleration by kinetic Alfvén waves. *Journal of Geophysical Research, 99*(A6), 11095–11103. https://doi.org/10.1029/94JA0345

Kletzing, C. A., & Hu, S. (2001). Alfvén wave generated electron time dispersion. *Geophysical Research Letters, 28*(4), 693–696. https://doi.org/10.1029/2000gl012179

Knudsen, D. J., Burchill, J. K., Buchert, S. C., Eriksson, A. I., Gill, R., Wahlund, J. E., et al. (2017). Thermal ion imagers and Langmuir probes in the Swarm electric field instruments. *Journal of Geophysical Research: Space Physics, 122*, 2655–2673. https://doi.org/10.1002/2016ja022571

Knudsen, D. J., Burchill, J. K., Cameron, T. G., Enno, G. A., Howarth, A., & Yau, A. W. (2015). The CASSIOPE/e-POP Suprathermal Electron Imager (SEI). *Space Science Reviews, 189*(1–4), 65–78. https://doi.org/10.1007/s11214-015-0151-1

Knudsen, D. J., Clemmons, J. H., & Wahlund, J. E. (1998). Correlation between core ion energization, suprathermal electron bursts, and broadband ELF plasma waves. *Journal of Geophysical Research, 103*(A3), 4171–4186. https://doi.org/10.1029/97ja0096

Knudsen, D., Donovan, E., Cogger, L., Jackel, B., & Shaw, W. (2001). Width and structure of mesoscale optical auroral arcs. *Geophysical Research Letters, 28*(4), 705–708. https://doi.org/10.1029/00GL011969

Knudsen, D. J., Kelley, M. C., & Vickrey, J. F. (1992). Alfvén waves in the auroral ionosphere: A numerical model compared with measurements. *Journal of Geophysical Research, 97*(A1), 77–90. https://doi.org/10.1029/91ja02300

Liang, J., Shen, Y., Knudsen, D., Spanwick, E., Burchill, J., & Donovan, E. (2019). e-POP and red line optical observations of Alfvénic auroras. *Journal of Geophysical Research: Space Physics, 124*, 4672–4696. https://doi.org/10.1029/2019ja026679

Lynch, K. A., Hampton, D., Mella, M., Zhang, B., Dahlgren, H., Disbrow, M., et al. (2012). Structure and dynamics of the nightside poleward boundary: Sounding rocket and ground-based observations of auroral electron precipitation in a rayed curtain. *Journal of Geophysical Research, 117*(A11), A11202. https://doi.org/10.1029/2012ja017691

Miles, D. M., Mann, I. R., Pakhotin, I. P., Howarth, A. D., Knudsen, D. J., et al. (2018). Alfvénic dynamics and fine structuring of discrete auroral arcs: Swarm and e-POP observations. *Journal of Geophysical Research Letters, 45*(2), 545–555. https://doi.org/10.1002/2017gl076051

Nagatsuma, T., Fukunishi, H., Hayakawa, H., Mukai, T., & Matsuoka, A. (1996). Field-aligned currents associated with Alfvén waves in a nightside auroral arc: Auroral turbulence II particle observations. *Geophysical Research Letters, 23*(22), 3361–3364. https://doi.org/10.1029/96ja009005

Watts, C. E. J., & Rankin, R. (2007). Electron acceleration due to inertial Alfvén waves in a non-Maxwellian plasma. *Journal of Geophysical Research, 112*(A7), A07119. https://doi.org/10.1029/2006ja011907

Wu, J., Knudsen, D. J., Gillies, D. M., & Burchill, J. K. (2020). Swarm survey of Alfvénic fluctuations and their relation to nightside field-aligned current and auroral arc systems. *Journal of Geophysical Research, 125*(3), e2019ja027220. https://doi.org/10.1029/2019ja027220
Wu, J., Knudsen, D. J., Gillies, D. M., Donovan, E. F., & Burchill, J. K. (2017). Swarm observation of field-aligned currents associated with multiple auroral arc systems. *Journal of Geophysical Research, 122*(10), 10145–10156. https://doi.org/10.1002/2017JA024439

Wygant, J. R., Keiling, A., Cattell, C. A., Johnson, M., Lysak, R. L., Temerin, M., et al. (2000). Polar spacecraft based comparisons of intense electric fields and Poynting flux near and within the plasma sheet-tail lobe boundary to UVI images: An energy source for the aurora. *Journal of Geophysical Research, 105*(A8), 18675–18692. https://doi.org/10.1029/1999ja900500

Wygant, J. R., Keiling, A., Cattell, C. A., Lysak, R. L., Temerin, M., Mozer, F. S., et al. (2002). Evidence for kinetic Alfvén waves and parallel electron energization at 4-6 RE altitudes in the plasma sheet boundary layer. *Journal of Geophysical Research, 107*(A8). https://doi.org/10.1029/2001ja900113

Yau, A. W., & James, H. G. (2015). CASSIOPE Enhanced Polar Outflow Probe (e-POP) mission overview. *Space Science Reviews, 189*(1–4), 3–14. https://doi.org/10.1007/s11214-015-0135-1