

FAST satellite observations of electric field structures in the auroral zone

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Abstract. Electric field and energetic particle observations by the Fast Auroral Snapshot (FAST) satellite provide convincing evidence of particle acceleration by quasi-static, magnetic-field-aligned (parallel) electric fields in both the upward and downward current regions of the auroral zone. We demonstrate this by comparing the inferred parallel potentials of electrostatic shocks with particle energies. We also report nonlinear electric field structures which may play a role in supporting parallel electric fields. These structures include large-amplitude ion cyclotron waves in the upward current region, and intense, spiky electric fields in the downward current region. The observed structures had substantial parallel components and correlative electron flux modulations. Observations of parallel electric fields in two distinct plasmas suggest that parallel electric fields may be a fundamental particle acceleration mechanism in astrophysical plasmas.

Introduction

Observations of electrostatic shocks by the S3-3 satellite [Mozer *et al.*, 1977] and the Viking satellite [Block *et al.*, 1987] have provided strong evidence of quasi-static, parallel electric fields in the upward current region of the auroral zone. The correlation of anti-earthward ion beams with electrostatic shocks [Mozer *et al.*, 1980; Bennett *et al.*, 1983] and the qualitative agreement between the inferred parallel potential of electrostatic shocks and ion beam energies [Temerin *et al.*, 1981; Redsun *et al.*, 1985] established that parallel electric fields are largely responsible for energizing auroral particles. Further evidence of parallel electric fields has been found in studies of electron distributions [Evans, 1974], observations of ion beams [Shelley *et al.*, 1976], and comparisons of particle observations from two spacecraft [Reiff *et al.*, 1988; Burch, 1988].

One of the most important results of the FAST mission was to identify the "reverse" aurora where electrons are accelerated anti-earthward by quasi-static, parallel electric fields in the downward current region [Carlson *et al.*, 1998a]. In previous works, electrostatic shocks were observed in downward current regions and associated with ion conics [Bennett *et al.*, 1983] and bidirectional electron fluxes were occasionally observed [Klumpar and Heikkila, 1982]. The general belief, however, was that thermal electrons carry the downward current. Downward directed electric fields

were incorporated in an ion heating model [Gorney *et al.*, 1985] and recent observations of large-amplitude, diverging electrostatic shocks [Marklund *et al.*, 1994] at low altitudes were associated with "black" aurora or an absence of precipitating electrons.

We present observations from the FAST satellite of converging electrostatic shocks in the upward current region and diverging electrostatic shocks in the downward current region. The FAST satellite measures electric field waveforms and electron and ion fluxes with unprecedented time resolution, allowing for a detailed comparison between the inferred parallel potentials and the energies of up-going ion or electron fluxes. These comparisons clearly show that parallel electric fields account for the majority of the particle acceleration in both the downward and upward current regions, and that the associated potentials are quasi-static on time scales >10 s.

It has been difficult to explain theoretically how a collisionless plasma supports a parallel electric field. Theories applied to the upward current region include anomalous resistivity [Hudson and Mozer, 1978], weak double layers [Temerin *et al.*, 1982], and magnetic mirror force [Chiu and Schultz, 1978]. Previous observations have not revealed a clear candidate.

Wave observations by the FAST satellite now reveal nonlinear, time-domain electric field structures associated with parallel electric fields. Similar observations have been reported on the Polar satellite [Mozer *et al.*, 1997]. In the downward current region, structures called "fast solitary waves", discussed in detail by Ergun *et al.*, [1998a], may play a key role in supporting parallel electric fields. In the upward current region, we report large-amplitude ion cyclotron waves which develop a substantial parallel component and significantly alter the electron distribution function.

Observations

Figure 1 displays ~ 50 s of high time resolution observations from a near-midnight, Northern auroral crossing by the FAST satellite. The instruments are described elsewhere [Carlson *et al.*, 1998b; Ergun *et al.*, 1998b]. The dashed line separates the downward and upward current regions. The top panel displays the perpendicular D.C. electric field at 10 Hz bandwidth that was nearly along the payload velocity vector (mostly Northward). Electrostatic shocks in the downward current region ($\sim 20:49:37$ UT) had a negative (nearly Southward) electric field followed by a positive (nearly Northward) electric field. The diverging pattern is seen twice. The most visible D.C. electrostatic shock in the upward current region had a positive signal from $\sim 20:50:08$ UT to $\sim 20:50:12$ UT followed by a large negative excursion at $\sim 20:50:12.7$ UT. There was another converging electrostatic shock ($20:50:13.5$ UT - $20:50:15$ UT).

Panel b of Figure 1 shows the same D.C. electric field signal at ~ 4 kHz bandwidth. Large-amplitude (~ 1 V/m pp) waves obscure the electrostatic shocks. Langmuir probe data (not shown) indicate that there were several small-scale density cavities in the downward current region and a broad density cavity in the upward current region. Panel c displays the nearly East-West component of the

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D.C. magnetic field. The steep positive slope in the magnetic field indicates that there was an intense downward current in a narrow region. The negative slope reflects a less intense upward current which extended over a larger region.

Panels d and e display the high- and low-frequency power spectral density of the electric field versus frequency. The downward current region had strong, broadband emissions extending from ~50 Hz to ~20 kHz. The upward current region had auroral kilomet-

ric radiation at ~380 kHz. There were intense ion cyclotron emissions in both regions.

Electron fluxes are displayed as a function of energy in panel f and pitch angle in panel g. In the downward current region, the up-going electrons were confined to very narrow pitch angles (180°) but had a broad energy range. There were also weaker fluxes of earthward, field-aligned electrons seen at the upper and lower edges of panel g at 0° and 360° pitch angles. The upward current region had precipitating electrons (20:49:40 UT to end of plot) with a mono-energetic peak that were mostly isotropic in pitch angle with a loss cone. From ~20:49:46 UT on, there were no electron fluxes below ~1 keV (fluxes <60 eV were spacecraft photoelectrons).

The ion fluxes versus energy and pitch angle are displayed panels h and i respectively. Conical distributions indicative of ion heating were in the downward current region and extended into part of the upward current region (20:49:30 UT - 20:49:46 UT). An up-going, energetic ion beam was in the remainder of the upward current region. The ion conics indicate that the spacecraft was below the (upward current) acceleration region from 20:49:40 UT to 20:49:46 UT and the ion beam indicates particle acceleration both above and below the spacecraft from then to the end of the plot.

Figure 2a shows an expanded view of the perpendicular D.C. electric field in the upward current region. Panel b displays up-going ion fluxes with the inferred parallel potential superimposed. The parallel potential was derived by integrating the product of the observed electric field and the spacecraft velocity from the left edge of the ion beam (20:49:46 UT) where the parallel potential was assumed to be zero. We also assumed the parallel potential was zero at the right edge of the ion beam (20:50:13 UT) and imposed a constant ionospheric electric field.

Except near 20:49:47 UT and 20:49:55 UT, the implied parallel potential and the ion beam energy are within ~25% when the ion beam energy was greater than 500 eV. This detailed, quantitative agreement over a 30 s period implies that the ion beam was energized by a parallel potential that endured for tens of seconds.

A similar analysis was performed in downward current region. The top panel of Figure 3 displays the electric field. Below are the up going electron fluxes with the inferred parallel potential super-

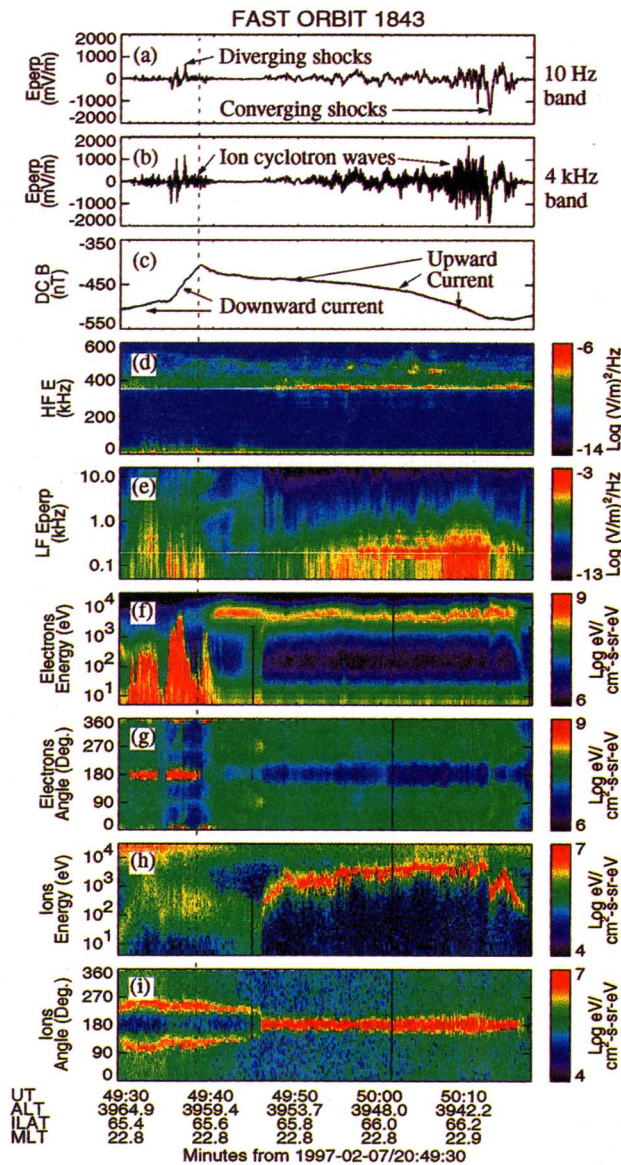


Figure 1. High-resolution observations of the near-midnight auroral zone. The dashed line separates the downward and upward current regions. (a) The D.C. electric field signal filtered to 10 Hz, perpendicular to B_0 and nearly along to the velocity of the satellite. (b) The D.C. electric field signal at ~4 kHz band width. One can see strong ion cyclotron waves. (c) The nearly East-West component of the magnetic field. A positive slope indicates a downward current and a negative slope an upward current. (d-e) The high- and low-frequency power spectral density of the electric field versus frequency. The white lines are the electron and H^+ cyclotron frequencies. (f) and (g) Electron energy flux versus energy and pitch angle. Fluxes near 180° are up-going and those near 0° or 360° are down-going. (h) and (i) Ion energy flux versus energy and pitch angle. Again, fluxes near 180° are up-going.

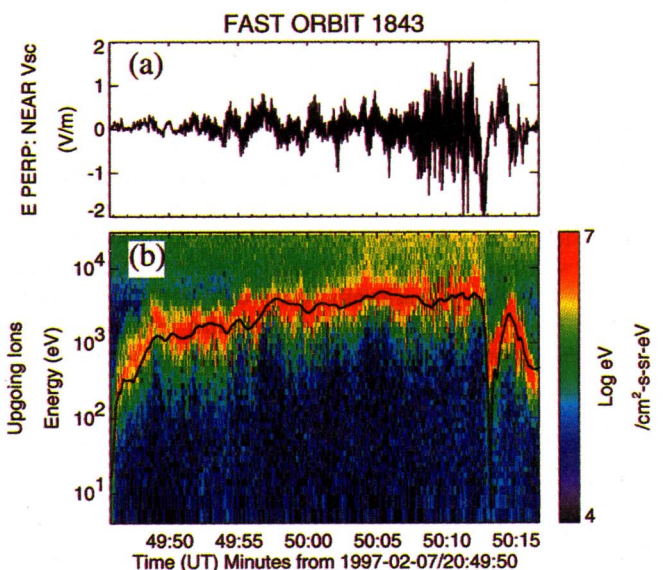


Figure 2. (a) The D.C. electric field perpendicular to B_0 and nearly along to the velocity of the satellite. (b) Up-going ion energy flux versus energy with the inferred parallel potential from the observed electric field superimposed.

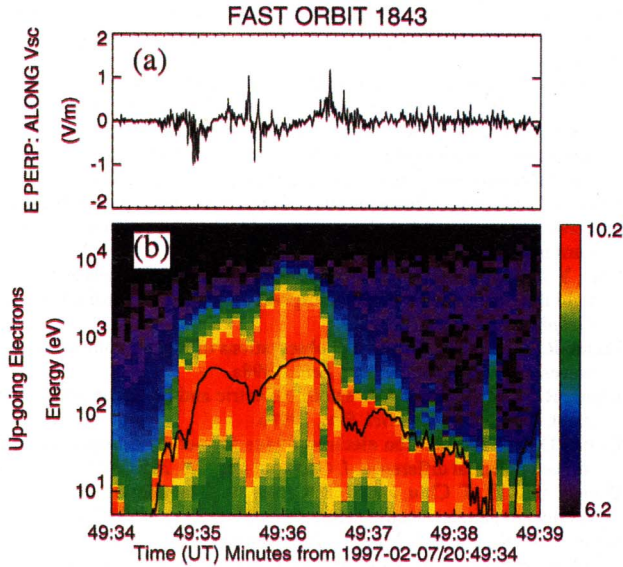


Figure 3. (a) The D.C. electric field perpendicular to B_0 and nearly along to the velocity of the satellite. (b) Up-going electron energy flux versus energy with the inferred parallel potential from the observed electric field superimposed.

imposed. The broad energy peak in the up-going electron fluxes suggest that wave-particle interactions strongly modified the electron distribution. None the less, the inferred parallel potential and the electron energy at the peak fluxes display similar characteristics and are often within a factor of two of each other.

Wave observations are displayed in Figure 4. The time axis is the same as that of Figure 1. The dashed line separates the downward and upward current regions. Figure 4a-b displays the perpendicular

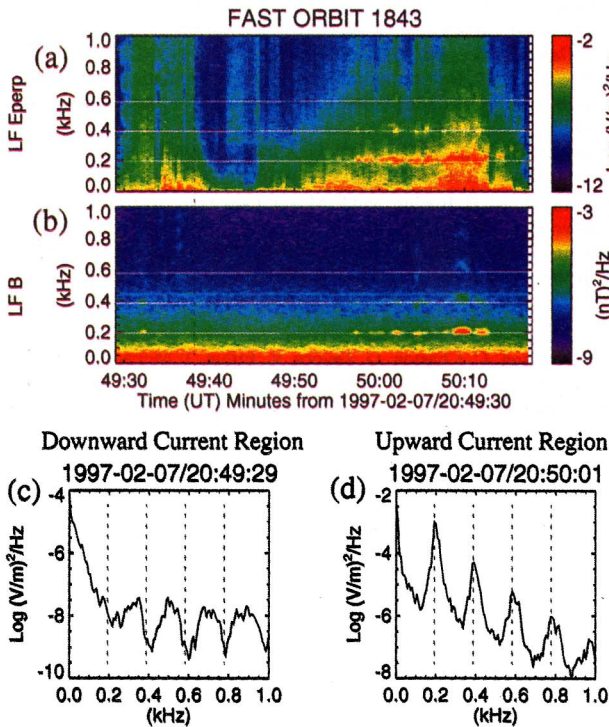


Figure 4. (a-b) The perpendicular electric and magnetic field power as a function of frequency and time. The solid lines are the 1st, 2nd, and 3rd harmonics of the H+ cyclotron frequency. (c-d) Individual spectra. The dashed lines are H+ cyclotron harmonics.

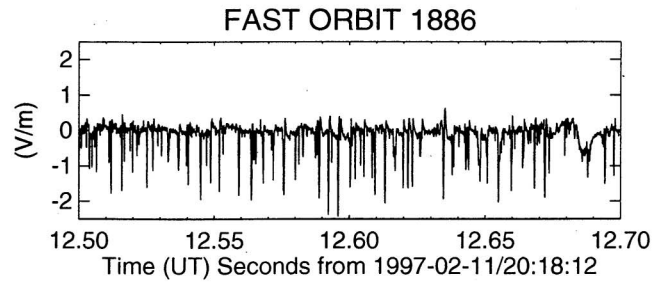


Figure 5. An example of the perpendicular electric field waveform seen in the downward current region.

electric and magnetic field spectral power density below 1 kHz with 4 Hz resolution. Panels c and d show spectra representing the downward (panel c) and upward current regions (panel d). H+ cyclotron harmonics are drawn on all of the plots.

The wave emissions in the downward current region (20:49:29 UT - 20:49:39 UT) were broadband, extending from <4 Hz to ~20 kHz (see also Figure 1d-e). The power spectra (Figure 4c) shows reductions in power at the H+ cyclotron harmonics. These broadband emissions were not random noise, but instead were a series of spiky structures (Figure 5) which reached amplitudes as high as 2.5 V/m. These nonlinear structures are discussed in *Ergun et al., [1998a]* who present evidence that they play a key role in supporting the downward parallel electric field.

The most prominent emissions in the upward current region when the ion beam was present (20:49:50 UT - 20:50:15 UT) were at or slightly above the H+ cyclotron frequency (Figure 4d) and had a significant magnetic component (Figure 4b). The associated electron distributions, the energy source, and the dispersion characteristics of these emissions are discussed in detail in several articles [*McFadden et al., 1998a, Cattell et al., 1998, Chaston et al., 1998*].

Figure 6 shows an example of the nonlinear ion cyclotron waves developing a substantial parallel component, in this case, reaching 700 mV/m. The ratio $|E_{\parallel}|/|B|$ over the period displayed was $\sim 3c$. The structures had negligible phase delays (<200 μ s) between sensors separated by 29 m indicating speeds greater than 100 km/s, wavelengths greater than 0.5 km, and potentials up to or greater than 100 V. Modulations in the electron distributions accompanied this waveform. The relative phasing and the details of the modulations are the subject of future research.

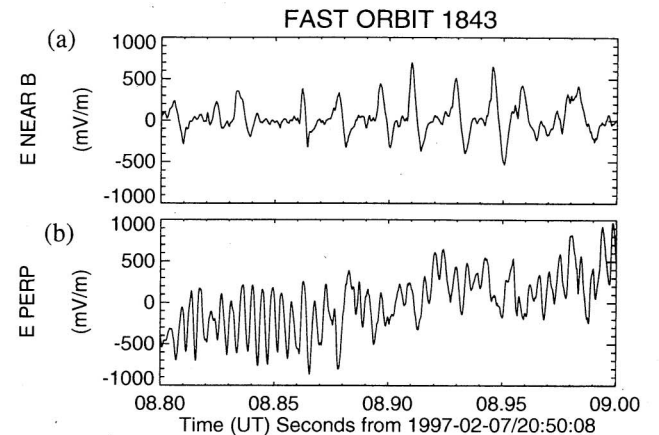


Figure 6. (a) The near-parallel (within 2.25° of B) electric field at high time resolution. The entire plot covers 200 ms. (b) The perpendicular electric field. The large parallel electric fields are observed with waves very near the H+ cyclotron frequency.

Discussion and Conclusions

Twelve electrostatic shocks structures associated with ion beams were studied in detail [see *McFadden et al.*, 1998b, for more examples]. Typically, the inferred potentials from the observed electric fields agree with the ion beam energies, within ~25% when ion energies were greater than ~500 eV. Sources of error include non-uniform ionospheric electric fields, motion or temporal changes of the potential structure, and inaccuracies in the electric field measurement. Inhomogeneities in the ionospheric electric field can cause a large error if the ion energy is less than ~500 eV.

The analysis was repeated for the downward current region for several other orbits with similar results [also see *Carlson et al.*, 1998a]. The good correlation between the inferred parallel potential and the electron energy implies that a parallel electric field energizes the up-going electrons. Unlike to the upward current region, wave-particle interactions play an important role in modifying the up-going particle distributions.

FAST observations reveal nonlinear, time-domain structures associated with parallel electric fields. These nonlinear structures carry large potentials, have significant components parallel to the magnetic field, have coincident electron flux modulations, and are associated with ion cyclotron waves. Similar structures have been observed by the Polar satellite [*Mozer et al.*, 1997]. In the upward current region, large-amplitude parallel electric fields associated with ion cyclotron waves were seen on many of the near-midnight passes which had an ion beam. In the downward current region, the electric field structures were brief (~100 μ s) spikes with both parallel and perpendicular components. The power spectra show depletions rather than enhancements at H^+ cyclotron harmonics. The nonlinear structures in the upward and downward current regions are clearly different suggesting that there are different mechanisms supporting the parallel electric fields.

In summary, FAST observations now show that naturally occurring, quasi-static, parallel electric fields accelerate electrons and ions in two distinct plasma regimes with distinct supporting mechanisms. The detailed agreement between inferred potentials of electrostatic shocks and particle energies in both current regions confirms that particle acceleration in the auroral zone is largely from parallel electric fields. The parallel potentials appear to be stable on time scales of tens of seconds and over distances of tens to hundreds of kilometers. In the upward current region, the electrons flow from a hot plasma into a cold plasma and are accelerated to ~10 times their thermal energy. In the downward current region, electrons flow from a cold, dense plasma into a hot plasma and are accelerated to up to 10^4 times their thermal energy and are strongly modified by nonlinear plasma waves. These observations suggest that quasi-static, parallel electric fields may be a fundamental particle acceleration mechanism in astrophysical plasmas.

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