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FAST satellite observations of large-amplitude solitary structures

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Abstract. We report observations of "fast solitary waves" that are ubiquitous in downward current regions of the mid-altitude auroral zone. The single-period structures have large amplitudes (up to 2.5 V/m), travel much faster than the ion acoustic speed, carry substantial potentials (up to ~100 Volts), and are associated with strong modulations of energetic electron fluxes. The amplitude and speed of the structures distinguishes them from ion-acoustic solitary waves or weak double layers. The electromagnetic signature appears to be that of an positive charge (electron hole) traveling anti-earthward. We present evidence that the structures are in or near regions of magnetic-field-aligned electric fields and propose that these nonlinear structures play a key role in supporting parallel electric fields in the downward current region of the auroral zone.

Introduction

Auroral zone research has concentrated on the upward current region where electrons responsible for visible aurora are energized by quasi-static, magnetic-field-aligned electric fields [*Mozer et al.*, 1977]. Although up-going and counter streaming energetic electrons have been observed [*Sharp et al.*, 1980; *Klumpar and Heikkila*, 1982], it has been widely believed that auroral currents closed with thermal electron currents originating from the ionosphere. Recent observations by the Fast Auroral Snapshot (FAST) satellite [*Carlson et al.*,1998a], however, show that the downward current is often supported by energetic electrons which also appear to be accelerated by quasi-static, parallel electric fields.

Electrostatic shocks in the downward current region are shown to diverge [*Ergun et al.*, 1998a; *Carlson et al.*, 1998a], implying potential structures similar to those in the upward current region, but with opposite polarity. Anti-earthward electron fluxes have energies that are consistent with the implied parallel potential of the diverging electrostatic shocks. Ions in this region are trapped by the magnetic mirror force and the downward electric field which enhances ion heating [*Gorney et al.*, 1985]. Escaping ions have energies comparable to those of up-going electrons.

One of the most important questions in auroral physics is how quasi-static, parallel electric fields are maintained in a collisionless plasma. In the upward current region, the magnetic mirror force and a dearth of charge carriers could account for some, but not all, of the resistance. The hot (~1 keV), plasma sheet source electrons are energized by about a factor of ten. The downward current region is quite different. Electrons are accelerated by as much as 10^4 times their thermal energy, there is no resistive mirror force, and the cold, dense, ionospheric plasma provides an ample supply of charge carriers. Resistivity must come from collective behavior of the plasma.

In this article, we report observations from the FAST satellite of large-amplitude electromagnetic structures which we shall call "fast solitary waves". These structures travel at speeds far greater than the ion acoustic speed and have amplitudes as high as 2.5 V/m which distinguishes them from previous observations of ion-acoustic solitary waves or weak double layers [*Temerin et al.*, 1982]. We show that they are observed in or near regions where parallel electric fields accelerate electrons and are associated with strong modulations in both up-going and down-going electron fluxes. We propose that these nonlinear structures play a pivotal role in supporting parallel electric fields in the downward current region.

Large-amplitude solitary waves appear in power-frequency-time spectrograms as brief, but intense emissions of broadband, quasi-electrostatic noise. Day side auroral zone observations of broadband electrostatic noise made by the Viking satellite were interpreted as electron acoustic solitons [*Pottelette et al.*, 1990; *Dubouloz et al.*, 1991]. The solitary structures we present have been observed at all local times that FAST has covered. Time domain structures observed in the auroral zone by the Polar satellite [*Mozer et al.*, 1997] and in the plasma sheet boundary layer [*Matsumoto et al.*, 1994; *Omura et al.*, 1994] are very similar.

Observations

The observations are from the FAST satellite electric and magnetic field instrument [*Ergun et al.*, 1998b] and ion and electron electrostatic analyzers [*Carlson et al.*, 1998b]. Figure 1 displays a small portion of a late-evening auroral crossing in the Northern hemisphere. These high-resolution data cover ~25 s.

The entire region had up-going, energetic, field-aligned electron fluxes (Figure 1e,f, 180° indicates up-going) and perpendicular ion fluxes indicative of ion heating (Figures 1g,h). There were weak, down-going, field-aligned electron fluxes as well (Figure 1f, at 0° and 360°). Two bursts of broadband VLF emissions (Figures 1c,d) occurred at ~14:26:11 UT and ~14:26:19 UT. During these two periods, ion energies increased (Figure 1g), ion pitch angles became very close to perpendicular (Figure 1h), and the current to the Langmuir probe decreased indicating a possible density decrease (Figure 1a). There were several visible diverging electrostatic shocks (Figure 1b).

The enhanced VLF emissions appeared in both the perpendicular and parallel electric field. The parallel electric field (Figure 1c) had enhanced broadband noise above 1 kHz. The perpendicular electric field (Figure 1d) had similar enhanced broadband noise but also had lower-frequency (~200 Hz - ~1 kHz) emissions that exhibited depletions in power or "bite-outs" at the H+ cyclotron harmonics (see, *Ergun et al.*, 1998a, Figure 4). There was also a weak perpendicular magnetic component (not displayed).

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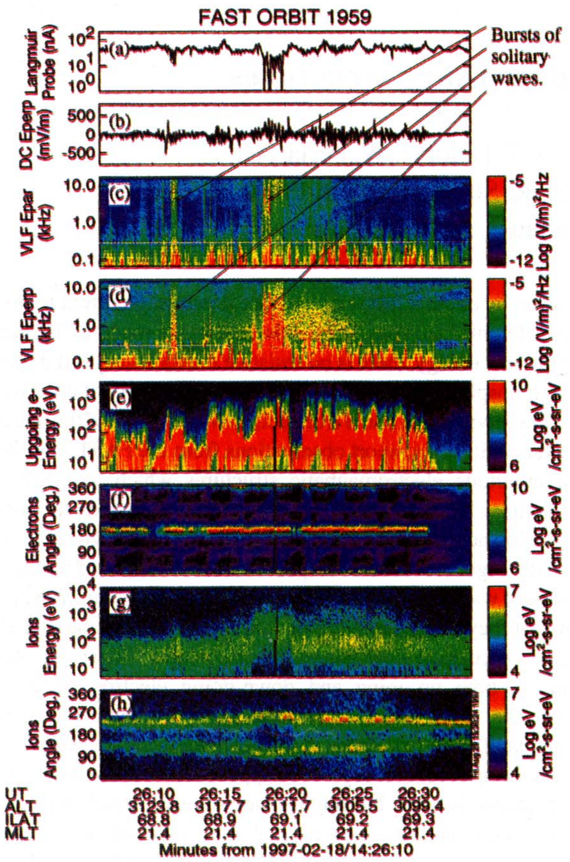

Figure 1. (a) Langmuir probe current reflecting the plasma density. A 2 nA current roughly corresponds to 1 cm^{-3} density. Fast variations may be capacitively induced current from waves. (b) Perpendicular electric field in the spin plane and nearly along the spacecraft velocity. (c-d) Parallel and perpendicular electric field power spectral density. (e-f) Electron energy flux versus energy and time and versus pitch angle and time. (g-h) Ion energy flux.

Figure 2 displays 0.5 s of data covering the first period of enhanced VLF emissions in Figure 1. From the top are electron energy spectra, plasma density, the vector electric field (D.C. to 16 kHz), and an A.C. magnetic field signal. The electric field signal was dominated by a series of large-amplitude, spiky structures rather than random noise. Similar structures have also been observed by the Polar satellite [*Mozer et al.*, 1997]. A close look shows that the structures were spatially coherent and had a period or duration of ~50 μs to ~200 μs. The parallel electric field was bipolar, always in the same sense, first anti-earthward then earthward (Figures 2c and 2cc). The perpendicular electric field signal was unipolar as was the perpendicular magnetic field signal (Figure 2d-f and 2dd-ff). The data were consistent with $\Delta \boldsymbol{E} \bullet \Delta \boldsymbol{B} = 0$.

The parallel and perpendicular electric fields derived from the spin plane booms (Figures 2c, d, cc, and dd) were often saturated. The >~1 kHz saturation level was ~300 mV/m. The axial electric field signal (Figures 2e and ee) saturation level was ~2500 mV/m. Taking saturation into account, the amplitudes of the parallel and perpendicular electric field signals were comparable and $|\Delta \boldsymbol{E}|/|\Delta \boldsymbol{B}|$ was ~100 c.

Electric field signals recorded at 0.5 μs resolution from a different orbit are displayed in Figure 3. A small-amplitude event was chosen to remove any question of saturation. The waveforms were smooth on microsecond time scales and displayed little power above ~20 kHz. A map of $E_\perp$ versus $E_\parallel$ shows that the signal grew in the anti-earthward direction, rotated through perpendicular, and decayed as it was pointing earthward. This pattern is typical.

Fast solitary waves are often associated with strong modulations in both up-going and down-going electron fluxes (Figure 4). The typical 100 μs duration is much shorter than the electron integration time (1.6 ms), so a fine time resolution correlation between the structures and the election modulations cannot be seen.

The speed of the structures was calculated for over 1000 events during an orbit in which the electron energies were somewhat higher (~1 keV). The results are given in Figure 5 which displays a histogram of the time delays between two dipoles physically separated by 12 m along $\boldsymbol{B}$. The analysis shows a clear majority of the structures were moving anti-earthward at a significant fraction of the beam speed. Events that have been individually analyzed verify that the speed of the structures was comparable to, but usually less than, the energetic electron speed.

Discussion and Conclusions

Fast solitary waves have been observed predominantly in regions of up-going, energetic (>25 eV) electrons. The reverse cor-

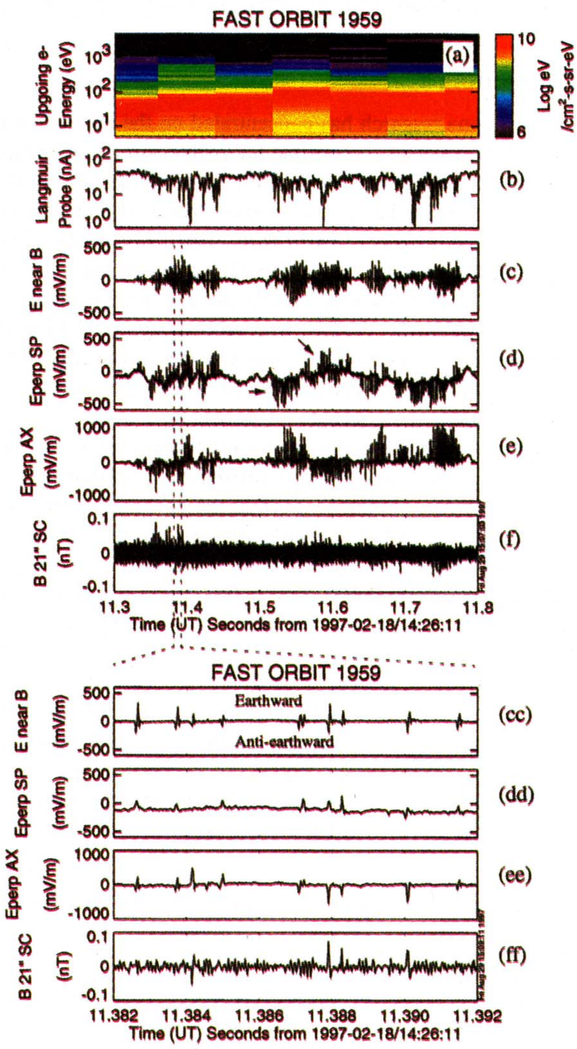

Figure 2. (a) Electron flux as a function of energy. (b) Langmuir probe current reflecting the plasma density. (c) The near-parallel electric field. (d-e) The perpendicular electric field in the spin plane (mostly North) and along the spin axis (mostly East). (f) The magnetic field signature from the 21" search coil. (cc-ff) Expanded views of (c-f).

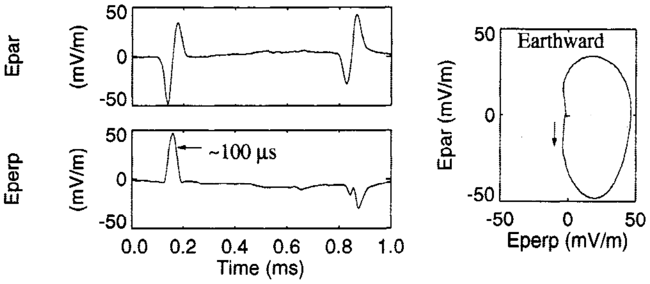

Figure 3. A fast solitary wave at 0.5 μs resolution. The right plot is $E_{\parallel}$ versus $E_{\perp}$ of the first structure. The speed of this structure was ~2000 km/s anti-earthward.

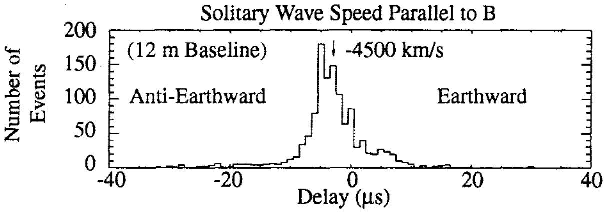

Figure 5. A histogram of the measured parallel delay between signals from dipoles separated by 12 m. There were 1196 solitary wave events greater that 50 mV/m in a 10 s period during orbit 1843. The average/median delay indicates a speed of ~4500 km/s anti-Earthward. The delay was calculated by correlating signal pairs (sampled at ~30 μs) over two spin periods to eliminate systematic errors. Random errors were typically ~2 μs. These speeds have been verified by individual event analysis with 0.5 μs resolution data.

relation is not the same. In a non-rigorous study of 20 orbits that had up-going electrons, the majority of the orbits had fast solitary wave emissions, but regions of fast solitary waves covered roughly 5%-10% of the time when energetic electrons were present. They tended to be at the boundaries of downward current regions.

The electromagnetic signature of a fast solitary wave is that of a positive charge or electron hole moving by the spacecraft at a significant fraction of the speed of the up-going, energetic electrons. A close examination (Figure 3) shows that $\Delta \boldsymbol{E}$ begins and ends suddenly indicating a small total charge, so the positive core may be surrounded by a negative halo. A speed of 5000 km/s and a duration of 100 μs implies a structure size of ~0.5 km parallel to $\boldsymbol{B}$. The signature of $E_{\perp}$ versus $E_{\parallel}$ (Figure 3) indicates that the perpendicular size should be roughly the same. A spherical structure that has ~0.5 km diameter requires a perturbed electron density of roughly - 0.6 cm^{-3} to produce a 1 V/m field. The above structure would carry a potential of ~100 V which is consistent with the observations of strong modulations of ~100 eV electron fluxes and the observation of weaker down-going electron fluxes. The parallel profile of these structures is similar to analytically predicted one-dimensional "electron phase space holes", also observed in laboratory plasmas [*Schamel*, 1982 and references therein].

A moving charge has $|\Delta \boldsymbol{E}|/|\Delta \boldsymbol{B}| \cong c^2/v_{str}$ (v_{str} is the speed of the charge). The perpendicular electric and magnetic field signatures (1 V/m, 0.05 nT) are consistent with a speed of 5000 km/s. $\Delta \boldsymbol{B}$ appears to be the Lorentz field of a moving charge.

Fast solitary waves were almost always accompanied by a decrease in Langmuir probe current (indicating a possible density decrease) and an increase in ion pitch angle, often to 90°. Ions in the downward current region can be trapped by the magnetic mirror force and the downward electric field. Such ions should have pitch angles extending to near 90° whereas escaped ions should have smaller pitch angles. We interpret the increase in ion pitch angles and decrease in density as evidence that fast solitary waves were in or near the electron acceleration region.

Fast solitary waves are often observed in groups with the same perpendicular polarity. In Figure 2d, for example, one sees a group in which the perpendicular electric field (which is nearly along the spacecraft velocity) is negative (11.50 s to 11.56 s, see arrow) then a group of positive signatures (11.56 s to 11.63 s, see arrow). The unipolar, perpendicular electric field ($\Delta \boldsymbol{E}_{\perp}$) of the solitary waves add to the existing D.C. electric field; $\Delta \boldsymbol{E}_{\perp}$ is positive if the D.C. field is positive and negative if the D.C. field is negative. The time-averaged electric field forms a structure like that of a diverging electrostatic shock, and a coincident increase in the electron energy is observed (Figure 2a, 11.56 s). A large group of fast solitary waves appear to statistically enhance an electrostatic shock. The above observation, coupled with observations of 90° pitch angle ions and the density depletions, strongly suggest that fast solitary waves play a role in supporting the downward parallel electric field.

Figure 6 summarizes the model that we propose. An external source (for example, a current or voltage driven from the magnetosphere) provides energy for electron acceleration. In the acceleration region, the solitary structures, which consist of positive charge clouds (electron holes) traveling anti-earthward, develop by drawing energy from the accelerating, up-going electrons, plateau the distribution, and accelerate some electrons earthward. In doing so,

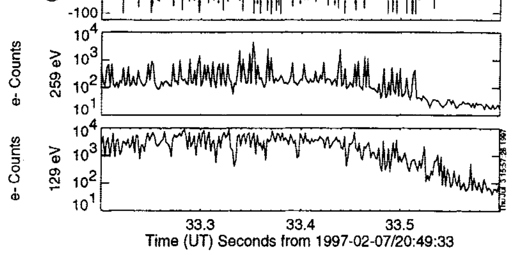

Figure 4. Strong modulations in up-going electron fluxes (bottom panels) are observed during a period of fast solitary waves (top).

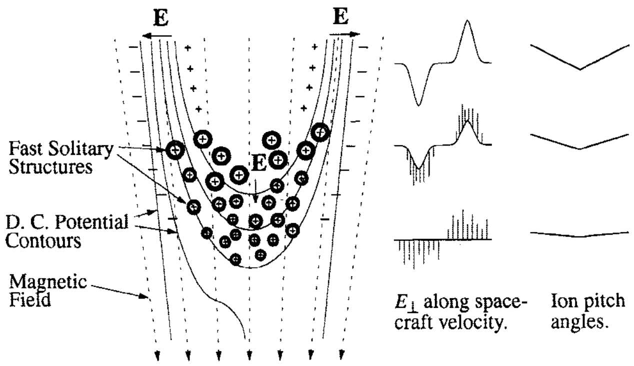

Figure 6. A model of the downward current region potential. Electron holes (positive charges) form in the acceleration region. They support a diverging electrostatic shock and a parallel electric field. To the right are diagrams of the expected electric field signals and the ion conic pitch angles above (top trace), in the middle, and in the lower (bottom trace) regions of the potential structure. The energy is carried by Poynting flux propagating along the magnetic field from the magnetosphere.

the fast solitary waves provide resistivity. It is not known, at this time, if the solitary waves are within the region of parallel electric field (for example, carry a small dipole moment supporting the electric field), or if they result from the sudden acceleration of electrons. Since large group of fast solitary waves are seen to statistically enhance a diverging electrostatic shock, the evidence somewhat supports the hypothesis that fast solitary waves are within the region of parallel electric field. The structures may self-consistently provide the needed resistivity, help support a parallel electric field, and realize the transition of the electrostatic shock into lower field strengths.

In summary, the following are observed properties of fast solitary waves. (1) Fast solitary waves are ubiquitous in the downward current region that was surveyed by FAST. They are most often seen in regions of energetic, up-going electron beams. (2) Strong electron modulations are associated with these structures. (3) Ion pitch angles increase toward 90° during intense emissions. (4) Solitary waves are often observed in large-scale regions of depleted density. (5) $|\Delta \boldsymbol{E}|$ is typically >50 mV/m, occasionally reaching 2.5 V/m. The parallel signal is bipolar, almost always in the electron beam direction then opposite and the perpendicular signal is unipolar. (6) The $\boldsymbol{E}_{\parallel}$ spectra have enhanced, broad band power at 1 kHz - 10 kHz. The $\boldsymbol{E}_{\perp}$ spectra have similar enhanced, broad band power and absorption at the ion cyclotron harmonics. Structure at H+ cyclotron harmonics indicates that ions play a role, which may be understood by considering that resistivity requires momentum exchange. (7) $\Delta \boldsymbol{B}$ is unipolar, perpendicular, and such that $|\Delta \boldsymbol{E}|/|\Delta \boldsymbol{B}| \sim 100\,c$ and $\Delta \boldsymbol{E} \bullet \Delta \boldsymbol{B} = 0$. (8) The typical duration is ~50 μs to ~200 μs, with a range of ~20 μs to ~500 μs (the ion cyclotron period). (9) The velocity of the structures is typically between 500 km/s and 5000 km/s anti-earthward, a significant fraction of the energetic electron velocity. (10) The structures are occasionally organized near the H+ cyclotron or lower hybrid frequency. (11) Large groups of the solitary structures with the same polarity may enhance a diverging electrostatic shock associated with electron acceleration.

We have inferred the following properties: (1) Fast solitary waves are in or near the region where a parallel electric field is accelerating electrons. (2) The electromagnetic signature is that of a positive charge (or electron hole) moving anti-earthward. (3) The vertical extent of the structures is hundreds of meters. The behavior of $\boldsymbol{E}_{\perp}$ and $\boldsymbol{E}_{\parallel}$ indicates the horizontal scale size roughly the same. (4) The inferred potentials can be up to hundreds of Volts. (5) The ratio $|\Delta \boldsymbol{E}|/|\Delta \boldsymbol{B}|$ is consistent with c^2/v_{str}

We propose that fast solitary waves may be pivotal in supporting large-scale parallel electric fields in the downward current region of the aurora.

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