Debye-Scale Plasma Structures Associated with Magnetic-Field-Aligned Electric Fields

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We report a new type of spatially coherent plasma structure that is associated with quasistatic, magnetic-field-aligned electric fields in space plasmas. The solitary structures form in a magnetized plasma, are multidimensional, and are highly supersonic. The size along $\mathbf{B}_0$ is a few λ_D and increases with increasing amplitude, unlike a classical soliton. The perpendicular size appears to be influenced by ion motion. We show that the structures facilitate ion-electron momentum exchange and suggest that an aggregate of structures may play a role supporting large-scale, parallel electric fields. [S0031-9007(98)06705-2]

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Quasistatic, magnetic-field-aligned (parallel) potentials are known to be the primary energy source for particle acceleration in the "upward" magnetic-field-aligned current region of the auroral zone where precipitating electrons create a visible display. Parallel electric fields have been inferred from satellite and sounding rocket observations, specifically, from examination of precipitating electron distributions [1], observations of antiearthward ion beams [2], and observations of large-amplitude electric fields perpendicular to the ambient magnetic field ($\mathbf{B}_0$) [3]. Direct observation of parallel electric fields recently has been reported [4]. Theoretical treatments on how a collisionless plasma supports quasistatic, parallel electric fields, however, have been largely inadequate. Treatments include anomalous resistivity [5,6], weak double layers [7], magnetic mirror force [8], and strong double layers [9].

The recent discovery of quasistatic, parallel potentials in the "downward" current region of the auroral zone [10,11] establishes that parallel electric fields are responsible for particle acceleration in two distinct plasma regimes, which suggests that they may be a fundamental particle acceleration mechanism in astrophysical plasmas. In the downward current region, ionospheric electrons are accelerated antiearthward to up to 10^4 times their initial thermal energy. It is in this region that a new type of plasma structure is found.

In this Letter, we report characteristics of a unique type of solitary structures that are associated with parallel electric fields and assess their role in supporting parallel electric fields. These structures are observed with energetic electron fluxes and are found to be within or near large-scale, quasistatic, parallel potentials [12]. Similar structures have been observed by other auroral spacecraft [13] and in space plasmas outside of the aurora [14]. The solitary structures had speeds far greater than the ion thermal speed ($v_{i\text{th}}$) and thus were interpreted [14] to be one-dimensional "electron phase space holes" [15,16]. We demonstrate here that the structures are three-dimensional, Debye-scale charge clouds moving at the electron drift velocity, that they are inconsistent with classical soliton solutions, and that they facilitate ion-electron momentum exchange.

The observations in this paper are from the Fast Auroral SnapshoT (FAST) satellite [17] which measures charged particle distributions and electromagnetic fields in the Earth's auroral zone from 350 to 4175 km in altitude in a near-polar orbit (83° inclination). We present data from the Northern aurora near local midnight and near apogee. The FAST instruments have significantly higher time resolution than previous efforts, sampling electromagnetic fields faster than the plasma period ($1/\nu_{pe}$), and compiling particle distributions in $10/\nu_{pe}$ to $100/\nu_{pe}$.

Figure 1 displays the electromagnetic fields of the solitary structures. Panels 1(a)–1(d) display the parallel electric field ($\Delta E_\parallel$), two components ($\Delta E_\perp$) perpendicular to $\mathbf{B}_0$, and one component of the perturbation to magnetic field ($\Delta B_\perp$). Panels 1(aa)–1(dd) are expanded views of panels 1(a)–1(d). A noticeable feature is that $\Delta E_\parallel$ is bipolar, always with the same sense. The first excursion of the electric field (negative is antiearthward) is always in the direction of the energetic electron drift. Both components of $\Delta E_\perp$ are unipolar. $\Delta B_\perp$ is also unipolar and small such that $\Delta E_\perp/\Delta B_\perp \gg c$.

The attendant electron distribution, compiled over a ~78 ms period, is displayed in Fig. 2. It shows energetic (~30 eV or ~3×10^6 m/s), field-aligned electrons ($T_{e\parallel} \gg T_{e\perp}$). Temperatures are derived as the second moment of the electron distribution (minus drift) as the distributions were clearly non-Maxwellian. The electrons moving antiparallel to $\mathbf{B}_0$ (180° is antiearthward) display a plateau extending to ~50 eV (~4×10^6 m/s) before sharply dropping. In this example, the antiparallel (to $\mathbf{B}_0$) distribution dominates over all other angles producing a substantial drift (-1.6×10^6 m/s). Strong variations

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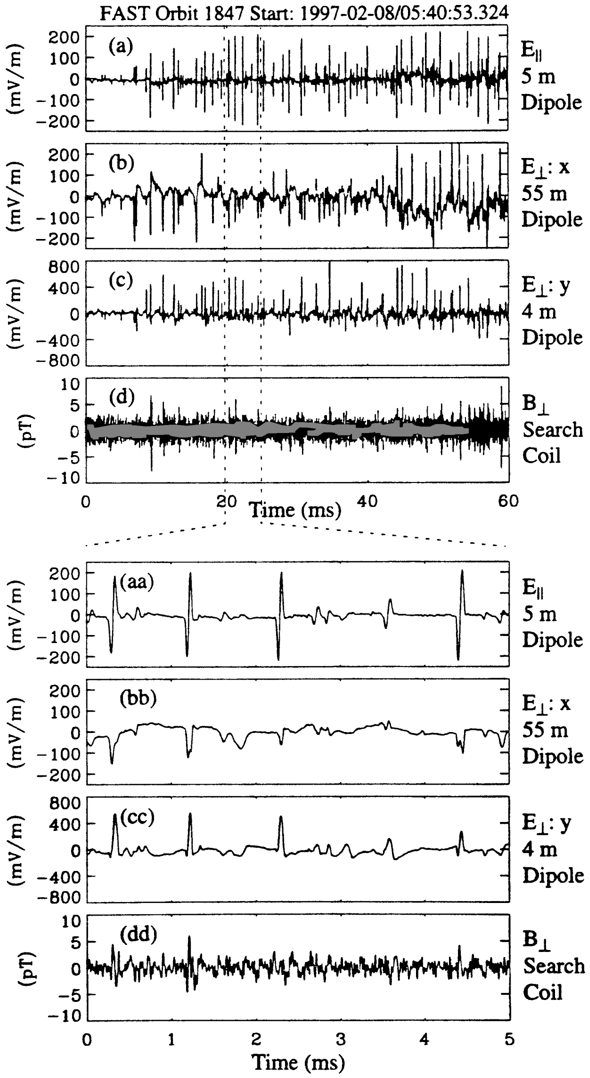

FIG. 1. (a) The electric field parallel to $\mathbf{B}_0$. (b) The electric field perpendicular to $\mathbf{B}_0$ ($\Delta E_\perp$) and in the spin plane of the satellite. This signal, measured by a 56 m dipole antenna, appears attenuated, indicating that the structure size may have been <112 m. (c) $\Delta E_\perp$ along the spin axis of the satellite. (d) A perturbation magnetic field perpendicular to $\mathbf{B}_0$ ($\Delta B_\perp$). $\Delta B_\perp$ was filtered to a pass band (3–16 kHz) to expose the weak signals and therefore may not appear unipolar in this figure. (aa)–(dd) An expanded view of the above data.

in the energetic electron fluxes are well correlated with the solitary structures [10,12]. The ion distribution (not shown) displays perpendicular heating with $T_{i\perp} > T_{i\parallel}$.

The velocity of the structures, derived from time delays between separated antennas (v_{delay}), are in the same direction as, and approximately equal to, the measured electron drift velocity,

$$\boldsymbol{v}_{ed} = \int f_e(\boldsymbol{v})\boldsymbol{v}\, d^3v/n\,, \qquad (1)$$

where f_e is the measured electron distribution and n is the plasma density. The ratio $\langle v_{\mathrm{delay}}/v_{ed}\rangle$ is 1.15 ± 0.87, where the brackets $\langle\ \rangle$ indicate an average over more than

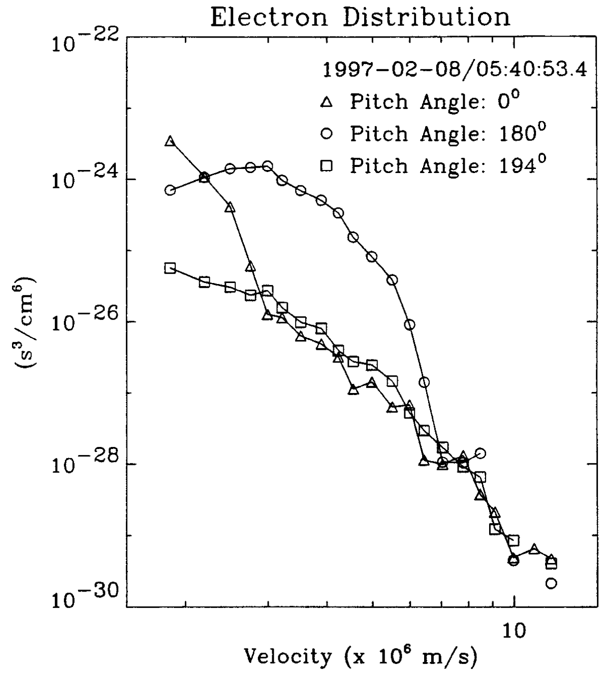

FIG. 2. The electron distribution at three angles from $\mathbf{B}_0$. The antiparallel distribution (180°) dominates over all other angles. The distribution at 194° does not show an enhancement, indicating the electron fluxes were nearly field aligned. This distribution had $v_{ed} \sim 1.6 \times 10^6$ m/s and a $T_{e\parallel} \sim 30$ eV. Measurements below $\sim 1 \times 10^6$ m/s could be affected by spacecraft charging.

1000 events. By contrast, ratio $\langle v_{\mathrm{delay}}/v_{eth}\rangle$ is 0.36 ± 0.30, where v_{eth} is the electron thermal velocity. Note that $v_{\mathrm{delay}} \gg v_{i\mathrm{th}}$, so the structures are supported by electrons. We also find that $\Delta B_\perp$ is consistent with the Lorentz field of a moving charge ($c^2\Delta B_\perp/\Delta E_\perp \cong v_{\mathrm{delay}}$), establishing that the solitary structures are electrostatic in the electron drift frame.

The electromagnetic signature is that of a two- or three-dimensional positive charge passing by the spacecraft at the electron drift velocity. $\Delta E_\perp$, however, shows no preferred direction which indicates that the structures are three-dimensional. Furthermore, $\Delta E_\parallel$ and $\Delta E_\perp$ are typically comparable and hodograms of $\Delta E_\parallel$ vs $\Delta E_\perp$ often conform to a spheroid such that $z_0 \leq r_0$, where z_0 is the parallel (to $\mathbf{B}_0$) scale size and r_0 the perpendicular scale size. We suggest later that the oblateness of the spheroids depends upon the ratio of ion gyroradius (ρ_i) and Debye length (λ_D) which typically satisfies $2 < \rho_i/\lambda_D \leq 20$ in regions where the structures are observed.

The parallel scale size of the solitary structures can be determined from their motion. Figure 3(a) is a greatly expanded view of $\Delta E_\parallel$. The time axis has been translated into Debye lengths ($\lambda_D = 82$ m) assuming a constant parallel velocity (v_{sol}). The displayed structure has a small $\Delta E_\perp$, which implies that it was almost centered about the spacecraft as it passed by or that it was a highly oblate structure. The measured signal fits remarkably well to the

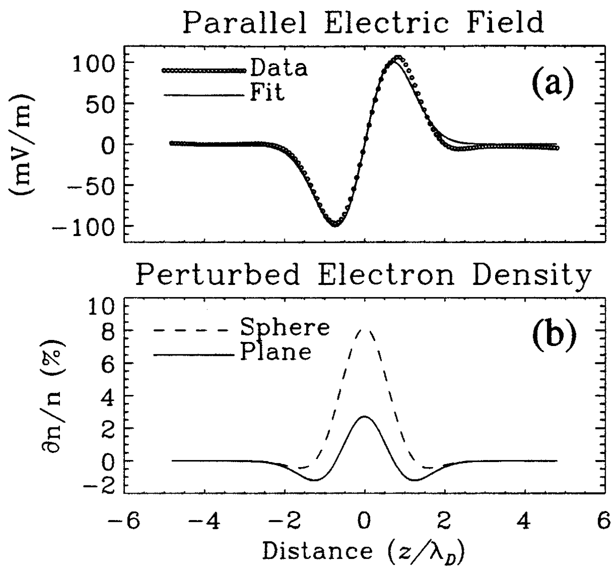

FIG. 3. (a) $\Delta E_{\|}$. The dots are the data at 0.5 μs resolution translated into Debye lengths assuming a constant parallel velocity, $v_{\rm sol} = 3.2 \times 10^6 \pm 1.1 \times 10^6$ m/s. The smooth trace is the fit to Eq. (2). The local plasma had $n_0 = 5.7 \pm 2.0$ cm^{-3}, $T_{e\|} = 704 \pm 145$ eV, $T_{i\perp} = 370 \pm 74$ eV, and $|\mathbf{B}_0| = 11\,481 \pm 10$ nT. $\lambda_D = 82 \pm 30$ m (f_e was non-Maxwellian) and was less than the H^+ gyroradius (241 $\pm$ 24 m). (b) Calculated charge densities assuming spherical and planar geometry.

derivative of a Gaussian,

$$E(z) = E_0 z e^{-1/2(z/z_0)^2}/z_0 \,. \tag{2}$$

The solid line in Fig. 3(a) represents a fit to the signal with $z_0 = 0.7\lambda_D$.

We use the fit to derive the charge density of the structure [Fig. 3(b)]. The actual charge density lay between the two traces which represent the extremes, spherical and planar geometry. The structure has a positive core of roughly $\sim 5\% n_0$ (more typical is $\sim 10\%$) surrounded by a negative halo. A close examination of $\Delta E_{\|}$ [Fig. 3(a)] reveals that it abruptly begins and ends (much faster than $1/z^2$) which implies that the total charge in the structure must be small.

We examined over 1000 events, chosen by an algorithm, to establish the characteristics of the solitary structures. The primary selection criteria isolated bipolar, parallel electric field signals with peaks exceeding the surrounding rms amplitude (averaged over ~ 2 ms) by a factor of 5. The perpendicular electric field had to be nearly unipolar. A spot check indicates $\sim 97\%$ of the structures identified by the search algorithm were as described above, but roughly $\frac{1}{2}$ of the structures discernible by eye were not identified, particularly those with low amplitudes.

The Gaussian half-widths (z_0) of the structures parallel to $\mathbf{B}_0$ are plotted in Fig. 4(a). λ_D was determined from the measured electron temperature and the ion density (non-Maxwellian distributions could lead to a small error). Typically, λ_D was determined to be better than 25% [18].

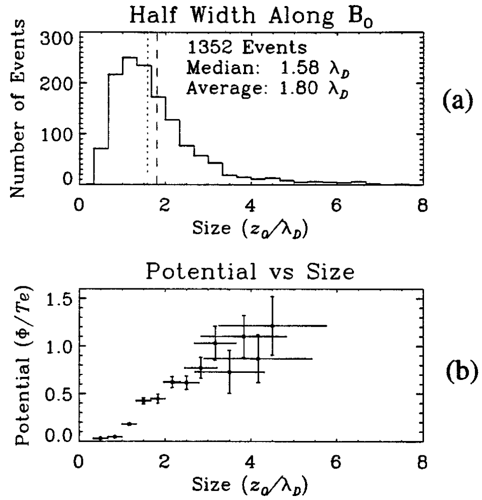

FIG. 4. (a) A histogram of the occurrence of solitary structures versus their size. The standard deviation in size is influenced by uncertainties in the velocity measurement. (b) The peak potential versus the structure size. Each point reflects the mean potential and size averaged over a size bin in panel (a).

The velocity of the structures, $v_{\rm sol}$, was not as accurately determined, often with uncertainties of $\pm 50\%$. The measured values ($v_{\rm delay}$) were used if the antennas were favorably oriented, whereas the Lorentz velocities ($c^2 \Delta B_\perp / \Delta E_\perp$) were used if $\Delta B_\perp$ was detectable. The average scale size is $1.80\lambda_D \pm 1.13\lambda_D$. The standard deviation is influenced by the uncertainty in $v_{\rm sol}$.

The relationship between maximum potential of the observed solitary structures (Φ_0) and size (z_0) is displayed in Fig. 4(b). Φ_0 clearly increases with size which indicates that the structures do not form through a simple self-focusing process. The general shape of the curve, when $z_0/\lambda_D < 2$, agrees with analytical results of a one-dimensional electron phase space hole solution [16]. Furthermore, the observed structures are predicted to be stable in one dimension [16] since their velocity was almost always less than twice the electron thermal speed.

The perpendicular scale size (r_0) has been difficult to establish. Theoretically, one expects ions to control r_0 since the electrons are strongly magnetized ($\rho_e \ll \lambda_D$), restricting their motion to one dimension. There also is observational evidence which suggests that r_0 scales with ρ_i. The structures are occasionally periodically spaced close to the proton cyclotron frequency. Figure 5 shows such an example. Furthermore, the spectral power density of the electric field waveforms almost always shows absorption at the ion cyclotron harmonics (not displayed).

It has not been established if the structures result from the sudden emergence of accelerated electrons or if they are directly associated with or, perhaps, carry the parallel electric field. Ion dynamics plays a critical role because resistance comes from momentum exchange between electrons and ions. The three-dimensional character of the solitary structures naturally provides such momentum exchange.

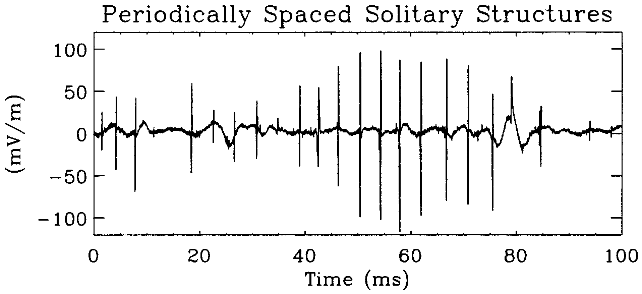

FIG. 5. The parallel electric field. The solitary structures in this example are evenly spaced at a frequency above the local H^+ gyrofrequency, and, within error, at the lower hybrid frequency.

In the frame of the solitary structure, ions are incident at very high velocity ($v_{\rm sol}$) relative to their thermal velocity, and will scatter from the positively charged core. Assuming that the perturbation to the ion trajectories is small and that the ions are unmagnetized (the ion transit time is far less than their gyroperiod), the perpendicular impulse from an ion passing through the solitary structure with an impact parameter of r is

$$M\Delta v_{i\perp}(r) = \int_{-\infty}^{\infty} eE_{\perp}[r, z(t)]\, dt\,, \qquad (3)$$

where M is the ion mass. The parallel velocity of the ion also will experience a perturbation. This perturbation can be estimated as $\Delta v_{i\parallel} \cong -\Delta v_{i\perp}^2/2v_{\rm sol}$ if there is a negligible recoil of the structure ($n\lambda_D^3 \gg 10^9$). The net result is a parallel momentum exchange between ions and electrons which acts to retard the electron drift.

The above analysis can be applied directly to the observations. There are two noteworthy results from this exercise. In the frame of the ions, the perpendicular energy gain is a significant fraction of the ion thermal energy. At the occurrence rate of the structures, ions undergo substantial perpendicular heating, consistent with the observations [12]. The heating of the ions, which results with ion temperatures comparable to the electron drift energy, must come from the drifting electrons. Furthermore, the parallel momentum imparted from the ions must be absorbed by electrons. Momentum balance requires a parallel electric field, acceleration (deceleration) of the solitary structures, or growth (decay) of the solitary structures.

In summary, $\sim 2\lambda_D$ solitary structures associated with quasistatic, magnetic-field-aligned electric fields were demonstrated to be three-dimensional electron phase space holes traveling at the electron drift velocity. The parallel profile fits very well to a Gaussian, the parallel size increasing with increasing potential. The structures are unique in that they exist in a strongly magnetized plasma and are multidimensional. Evidence suggests that ion motion influences the perpendicular scale size and organizes sets of the structures. The multidimensional nature of the structures can lead to a strong interaction with ions. Through scattering, the ions can receive considerable transverse heating and an appreciable exchange of parallel momentum with the electrons. These findings suggest that an ensemble of solitary structures may provide the means by which a collisionless plasma can self-consistently support a parallel electric field.

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[1] D. S. Evans, J. Geophys. Res. **79**, 2853 (1974).
[2] E. G. Shelley, R. D. Sharp, and R. G. Johnson, Geophys. Res. Lett. **3**, 654 (1976).
[3] F. S. Mozer, C. W. Carlson, M. K. Hudson, R. B. Torbert, B. Parady, J. Yatteau, and M. C. Kelley, Phys. Rev. Lett. **38**, 292 (1977).
[4] F. S. Mozer and C. A. Kletzing, Geophys. Res. Lett. **25**, 1629 (1998).
[5] M. K. Hudson and F. S. Mozer, Geophys. Res. Lett. **5**, 131 (1978).
[6] S. Ishiguro, T. Sato, H. Takamaru, and The Complexity Simulation Group, Phys. Rev. Lett. **78**, 4761 (1997).
[7] M. Temerin, K. Cerny, W. Lotko, and F. S. Mozer, Phys. Rev. Lett. **48**, 1175 (1982).
[8] S. Knight, Planet. Space Sci. **21**, 741 (1973).
[9] L. P. Block, Cosm. Electrodyn. **3**, 349 (1972).
[10] C. W. Carlson, J. P. McFadden, R. E. Ergun, M. Temerin, W. Peria, F. S. Mozer, D. M. Klumpar, E. G. Shelly, W. K. Peterson, E. Moebius, R. Elphic, R. Strangeway, C. Cattell, and R. Pfaff, Geophys. Res. Lett. **25**, 2017 (1998).
[11] R. E. Ergun, C. W. Carlson, J. P. McFadden, F. S. Mozer, G. T. Delory, W. Peria, C. C. Chaston, M. Temerin, R. Elphic, R. Strangeway, R. Pfaff, C. A. Cattell, D. Klumpar, E. Shelly, W. Peterson, E. Moebius, and L. Kistler, Geophys. Res. Lett. **25**, 2025 (1998).
[12] R. E. Ergun, C. W. Carlson, J. P. McFadden, F. S. Mozer, G. T. Delory, W. Peria, C. C. Chaston, M. Temerin, R. Elphic, R. Strangeway, R. Pfaff, C. A. Cattell, D. Klumpar, E. Shelly, W. Peterson, E. Moebius, and L. Kistler, Geophys. Res. Lett. **25**, 2041 (1998).
[13] F. S. Mozer, R. E. Ergun, M. Temerin, C. A. Cattell, J. Dombeck, and J. Wygant, Phys. Rev. Lett. **79**, 1281 (1997).
[14] H. Matsumoto, H. Kojima, T. Miyatake, Y. Omura, M. Okada, I. Nagano, and M. Tsutsui, Geophys. Res. Lett. **21**, 2915 (1994).
[15] H. Schamel, Phys. Scr. **T2/1**, 228 (1982).
[16] V. A. Turikov, Phys. Scr. **30**, 73 (1984).
[17] C. W. Carlson, R. Pfaff, and J. G. Watzin, Geophys. Res. Lett. **25**, 2013 (1998).
[18] C. W. Carlson and J. P. McFadden, in *Measurement Techniques in Space Plasmas: Particles*, Geophysical Monograph Vol. 102, edited by R. Pfaff (American Geophysical Union, Washington, DC, 1998).