New Features of Time Domain Electric-Field Structures in the Auroral Acceleration Region

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The Polar Satellite carries the first three-axis electric field detector flown in the magnetosphere. Its direct measurement of electric field components perpendicular and parallel to the local magnetic field has revealed new classes and features of electric field structures associated with the plasma acceleration that produces discrete auroras and that populates the magnetosphere with plasma of ionospheric origin. These structures, associated with the hydrogen ion cyclotron mode, include very large solitary waves, spiky field structures, wave envelopes of parallel electric fields, and very large amplitude, nonlinear, coherent ion cyclotron waves. [S0031-9007(97)03793-9]

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The auroral acceleration region encircles the earth at magnetic latitudes of about $\pm 70°$ and at altitudes between a few thousand and 10 000 km. Within this region, large amplitude electric field structures have been observed [1,2]. These structures are best studied in the time domain since their main characteristic is their repetitive, spiky, nature. These "time domain" field structures and the free energy associated with magnetic field aligned currents flowing into and out of the ionosphere, accelerate the local plasma to produce magnetic-field-aligned electron and ion beams and perpendicular heated ion distributions that make the visible light of the aurora and that populate the magnetosphere with plasma of ionospheric origin [3]. The small scale plasma physics of this self-consistent field generation and particle acceleration are central to the study of auroral and magnetospheric physics as well as to the understanding of fundamental plasma processes in a parameter regime that encompasses much of astrophysics and that is not readily accessible for laboratory studies. Time domain electric field structures that have been observed previously include electrostatic shocks [1], solitary waves [2,4,5], double layers [2,4], and coherent ion cyclotron emissions [6].

The Polar Satellite [7] traverses magnetic field lines of the southern auroral acceleration region at altitudes of about 6000 km and the northern auroral region at altitudes of about 30 000 km. Its three-component electric [8] and magnetic [9] field measurements yield components of the *in situ* electric field that are parallel and perpendicular to the local magnetic field with time resolutions of 120 μs to 50 ms. New structures and new features of known time domain structures in the auroral acceleration region have been revealed by these first direct, three component electric field measurements in the terrestrial magnetosphere. It is the purpose of this Letter to describe these new structures and features.

Solitary waves with amplitudes larger than any previously reported are shown in Fig. 1. In this figure, 0.6 s of electric field measurements are presented in a magnetic-field-aligned coordinate system having the *z* axis parallel to the local magnetic field, the *x* axis in the plane of the magnetic field line, perpendicular to *B*, and pointing earthward, and the *y* axis completing the orthonormal set by pointing in the westward direction. The data were collected at a spacecraft altitude of about 5000 km in the southern, dawn, auroral zone during a time when there was an up-going ~1 keV ion beam that resulted from field-aligned acceleration below the satellite and a down-going ~800 eV electron beam, indicating acceleration above the satellite. During the first third of this figure, the main features of the data are the hydrogen ion cyclotron waves in the perpendicular field and the bipolar parallel electric field structures having amplitudes of between about 5 and 50 mV/m. The equal amplitude negative then positive going parallel field structures, such as that near 10:25:04.91, are the solitary waves that have been extensively studied by theories and computer simulations [10] and that are prevalent through this time

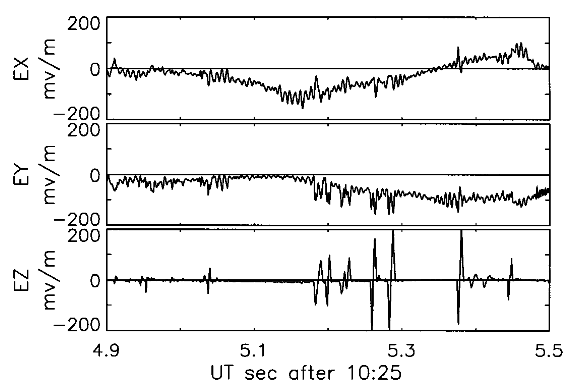

FIG. 1. Electric field measurements in a magnetic field aligned coordinate system in the auroral acceleration region illustrating small and large amplitude solitary waves and double layers during the 0.6 s interval after 1025:04.9 UT on 10 July 1996.

interval although they are difficult to discern because of the amplitude scale of the plot. The predominantly single polarity pulses, such as that near 10:25:04.95, are the double layers that have been shown theoretically to evolve from the solitary waves and to decay after a short lifetime [11].

In the latter half of Fig. 1, the parallel amplitudes of the solitary waves exceeded 200 mV/m, while the coherent ion cyclotron waves observed in the perpendicular electric field increased to more than 50 mV/m. Both the perpendicular and parallel field structures are predominately electrostatic since no magnetic field component greater than 0.03 nT was observed by the on-board search coil magnetometer [12]. By comparison of observation times at the individual elements of the electric field detector, it is concluded that these large amplitude solitary waves moved along the magnetic field line at a speed greater than 80 km/s.

Figures 2 and 3 show a new structure observed by the Polar Satellite consisting of spiky electric and magnetic fields whose individual spikes have durations between about 100 μs and 2 ms and repetition rates that, at least for the slower structures, are the order of the $\sim$100 Hz local hydrogen ion cyclotron frequency. Figure 2 shows few ms duration, 10-20 mV/m bipolar structures in the parallel electric field (third panel, plotted on a different amplitude scale than that for the other electric fields) in conjunction with 400 mV/m spikes in the perpendicular electric field (second panel) and $\sim$0.2 nT spikes in the magnetic field (bottom panel). These structures occur at a repetition rate that averages about 1.2 times the local hydrogen ion cyclotron frequency in a region containing perpendicular heated ion distributions (called ion conics) having energies of about 500 eV. The ratio of the electric to magnetic field averages about 10 times that of light. Assuming that these structures move past the spacecraft along the magnetic field line, comparisons of the responses of the individual spheres of the electric field detector show that this parallel velocity is in excess of 100 km/s.

Figure 3 is an example of much faster spikes for a 50 ms time interval during which the spacecraft was in an upward field aligned current region and the data collection rate was 8000 samples/s (instead of the 1600 samples/s of the other figures). The analog input data was unfiltered and the individual spikes lasted 1–2 points, so they were probably undersampled and had true durations approaching 100 μs. Because of the frequency response of the amplifiers and the differing lengths of the electric field baselines in the three orthogonal directions, the ratios of the components of the electric field in Fig. 3 cannot be trusted quantitatively. This is because the amplifiers have a diminished frequency response for voltage signals greater than about 10 V, and because a 10 V signal in the predominately y direction of Fig. 3 corresponds to a field that is about 10 times larger than similar voltage signals in the other directions. Thus it is not certain that the average ratio of x to y components in Fig. 3 was actually less than 1.

Similarly, the parallel electric field must have been the same order of magnitude as the 1500 mV/m perpendicular field. From this undersampled data it appears that the average parallel signature is bipolar with the positive spikes being larger than the negative spikes. Also observed in association with the electric field spikes were 0.1 nT pulses in the magnetic field (bottom panel of Fig. 3). The ratio of the electric to magnetic field in these pulses is greater than 30 times that of light.

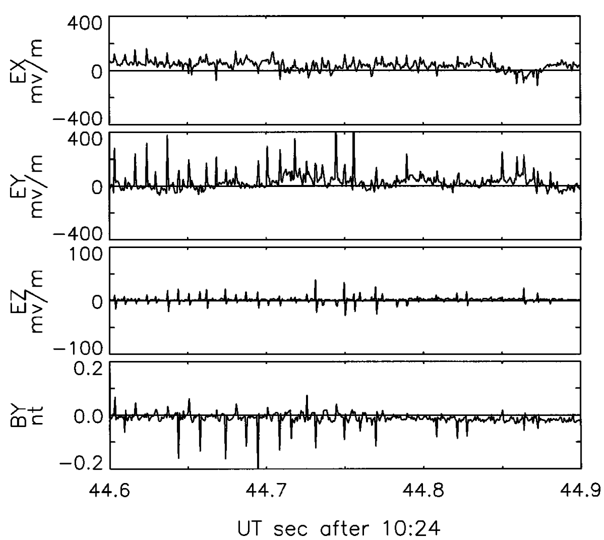

FIG. 2. Electric and magnetic field measurements in a magnetic field aligned coordinate system in the auroral acceleration region illustrating spikelike time domain structures in the fields during the 0.3 s after 1024:44.6 UT on 10 July 1996.

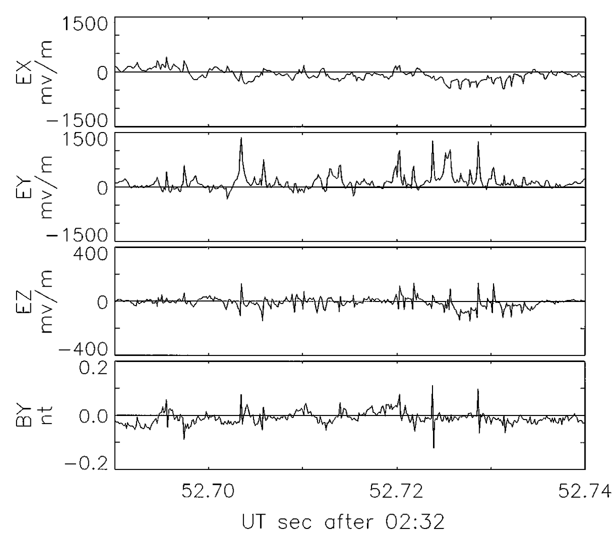

FIG. 3. Electric and magnetic field measurements in a magnetic field aligned coordinate system in the auroral acceleration region illustrating faster spikelike time domain structures in the fields during the 50 ms after 0232:52.690 UT on 29 March 1997.

Low energy ($\lesssim$100 eV) downgoing electrons and perpendicular ions were associated with this event. Accelerated particles have also been observed on the FAST satellite [13] in coincidence with electric field spikes such as those reported here.

The largest naturally occurring electric fields ever observed in the magnetosphere are shown in Fig. 4, which displays 0.5 s of ion cyclotron waves as large as 1500 mV/m. The perpendicular components of the electric field exhibit coherent, nonlinear oscillations at a frequency that is within a few percent of the local ion cyclotron frequency of 105 Hz. The major field perturbation is perpendicular to the local magnetic field and the parallel electric field exhibits solitary wavelike structures of smaller amplitude. The bottom panel gives one component of the magnetic field measured by the search coil magnetometer. Although a magnetic field signature is clearly present, the ratio of E to B is 5×10^{11} cm/s. The particles observed during this event included an up-going, heated, ion beam having a parallel beam energy of 2 keV and a perpendicular temperature of about 2 keV along with downward electrons accelerated to about 1 keV. Earlier observations and theoretical interpretations of nonlinearly steepened ion cyclotron waves have been reported [6]. Although waves of the amplitudes seen in Fig. 4 have not been observed previously, they were predicted from the observed acceleration of auroral electrons and of ^{3}He in impulsive solar flares [14].

A new time domain phenomenon, parallel electric fields occurring as modulated wave packets, is observed both at altitudes of about 5000 km in the southern auroral zone and 40 000 km in the northern plasma sheet boundary layer. Figure 5 presents an example of such a wave packet

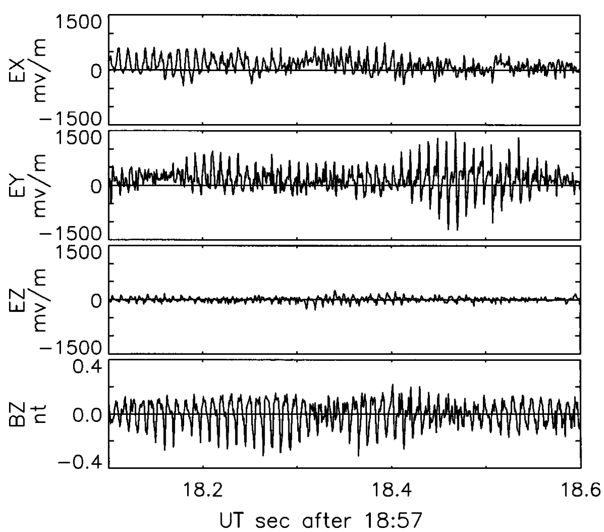

FIG. 4. Electric and magnetic field measurements in a magnetic field aligned coordinate system in the auroral acceleration region illustrating large amplitude, coherent, nonlinear hydrogen ion cyclotron waves during the 0.5 s interval after 1857:18.1 UT on 25 July 1996.

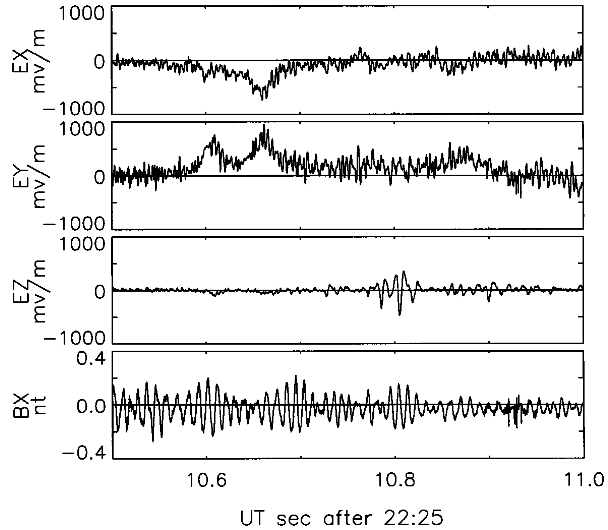

FIG. 5. Electric and magnetic field measurements in a magnetic field aligned coordinate system illustrating a wave packet in the parallel electric field during the 0.5 s interval after 2225:10.5 UT on 7 February 1997.

observed at the lower altitude. The parallel electric field was consistent with zero outside of a ~0.2 s interval centered at 22:25:10.8, in which it oscillated at a frequency within a few percent of the local hydrogen ion cyclotron frequency to produce a wave packet of amplitude as great as 500 mV/m. The magnetic field exhibited oscillations at this same frequency (bottom panel of Fig. 5), while the perpendicular electric field had a broader spectrum, except during the wave packet. This event occurred just within a region of upward accelerated ion beams of about 1 keV energy and downward 5 keV accelerated electrons.

In summary, the electric field experiment on the Polar Satellite has observed new classes and features of time domain electric field structures that are associated with the hydrogen ion cyclotron mode in the auroral acceleration region. Since these structures are partially responsible for the acceleration of the energetic plasmas that produce discrete auroras and that populate the magnetosphere with plasma of ionospheric origin, a follow-on task will be to understand the physics of the self-consistent production of these structures and the acceleration that they produce.

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