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Observations of large amplitude parallel electric field wave packets at the plasma sheet boundary

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ABSTRACT. We report the first observation of large amplitude electric fields parallel to the earth's magnetic field at radial distances of ~6 R_E on magnetic field lines linking the plasma sheet boundary to the auroral zone. The parallel fields, with magnitudes up to 40 mV/m, occur in three different electrostatic structures: unipolar wave packets with a net potential drop, bipolar wave packets, and solitary waves. Examples from one boundary crossing are presented which show that the wave packets have durations of <1s, are traveling at velocities of ≤100 k/s, and are consistent with ion acoustic waves. The waves can contribute to the acceleration of auroral electrons and modify the pitch angle distributions. The wave packets occur in a region of large-scale field-aligned currents and are often associated with perpendicular waves near the lower hybrid frequency with strongly modulated amplitudes. The velocities determined for the solitary waves are faster than those of the wave packets.

1. Introduction

The dynamic nature of the plasma sheet boundary has long been recognized. This region often contains ion and electron beams, field-aligned currents, spiky electric fields and strong waves. It is also believed to be on magnetic field lines which map to the poleward boundary of the night-side auroral zone. The structure of the boundary in the magnetotail has been explored in detail by the ISEE satellites [Eastman et al., 1984; Cattell et al., 1982; Parks et al., 1984] and by Geotail [Cattell et al., 1994; Hirahara et al., 1994; Matsumoto et al., 1994]. The Polar spacecraft offers the unique opportunity to examine the plasma sheet boundary at intermediate distances. We describe the first observations of large amplitude electric fields parallel to the Earth's magnetic field in this region. This discovery was enabled by the electric field instrument on the Polar spacecraft which is the first to make very high time resolution measurements of the full 3 components of the electric field in the magnetosphere. Large electric fields on time scales varying from milliseconds to tens of seconds are often observed by Polar while crossing the plasma sheet boundary in a region of field-aligned currents. In this letter, we present data from a single plasma sheet boundary crossing on May 20, at ~22 MLT and a radial distance of 6.16 Re.

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II. Instrumentation and Data Sets

The data for this study were obtained as the Polar satellite crossed the boundary of the plasma sheet at radial distances of ~6 Re. Electric and magnetic field data were utilized. The plasma sheet boundary was identified by examining the spacecraft potential as has been done in previous ISEE and Geotail studies. Measurements of the spacecraft potential(which depends on $\log(n_e T_e^{1/2})$) provide an estimate of the plasma density (see Pedersen [1995] for a discuss calibration and error sources, including the effects of temperature variations). Both the density and the boundary location, as identified by the spacecraft potential, are in good agreement with the values determined by the plasma instrument [C. Kletzing, private communication, 1997].

The electric field and spacecraft potential measurements were made by the double probe electric field instrument on the Polar satellite [Harvey et al., 1995]. In addition to its regular data rate of 40 samples/s, this instrument was designed to obtain bursts of high time resolution data. During the first 5 months of operation, a burst of 30s duration at a rate of 1600 samples per second was usually obtained as the satellite crossed the plasma sheet boundary at radial distances of ~5-7 Re. This sample rate allows us to study electric field variations on time scales ranging from the ion cyclotron period to the lower hybrid and ion plasma period. The electric field data are plotted in a magnetic field-aligned coordinate system in which the z axis is along the measured magnetic field, the x axis is in the plane of the magnetic field line at the satellite and radially inward, and the y axis is approximately westward. In addition to the electric field, the delay times between signals at opposing probes were examined, using a cross-correlation analysis, to estimate the propagation speed of electric field structures. Using the propagation speed, the net potential drops could be calculated.

AC magnetic field data were obtained from the search coils [Gurnett et al., 1995] which were sampled in the burst memory at the same rate as the electric field. DC magnetic field data were obtained from the fluxgate

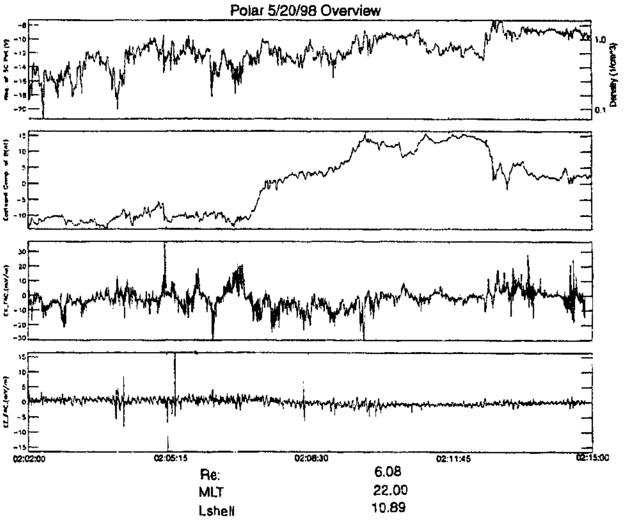

Figure 1. Overview of the plasma sheet boundary crossing on 5/20/1996: (a) Negative of the spacecraft potential (approximate density scale based on Pederson, 1995); (b) Eastward component of the magnetic field, indicative of field-aligned currents; (c) The Ex perpendicular component of the electric field; (d) The parallel component of the electric field. The time of the burst is marked with an arrow.

magnetometers [Russell et al., 1995]. For this study, the component along the spin axis (~eastward component) at a sample rate of ~8/s will be shown. If sheet currents are flowing along the magnetic field, this is the component in which the dominant signal will appear.

III. Example of 5/20/96

An overview of the period in which the high time resolution burst data occurred is shown in Figure 1 which contains 13 minutes of data obtained as the Polar satellite was moving from the lobes into the higher density plasma sheet at 22 MLT and a radial distance of ~6 Re. This density change can be seen in the negative of the spacecraft potential (panel a). An approximate equivalent logarithmic density scale (accurate to ~ a factor of 2) is shown on the right hand side of the figure and indicates a density change from the order of 10^{-1} to 1 cm^{-3}. The signature of several field-aligned current sheets can be seen in the eastward component of the magnetic field (panel b). A positive (negative) gradient corresponds to current out of (into) the ionosphere. A large-scale region of upward current, which is in the Region 1 sense for this magnetic local time sector, extends from ~0207 UT to ~0210 UT. This current is followed by a less intense downward current. There are also many small-scale changes in the eastward magnetic field , usually associated with density gradients. The perpendicular electric field (E_x which is radially inward is shown in panel c) was highly variable with many large amplitude spikes of the type previously reported on the plasma sheet boundary [Cattell et al., 1982; 1994]. In addition, there were several large amplitude, parallel electric field spikes (panel d). The 30s burst was triggered at 02:05:10 marked by the arrow, in a region of small currents just prior to the large upward current.

Figure 2 presents an example of a unipolar electric field wave packet. There were no associated magnetic fluctuations. The parallel component of the electric field (panel c) was very small (consistent with zero) outside of an ~ 0.4s pulse of ~ 70 Hz waves. The peak parallel electric field in the pulse was ~40 mV/m. The largest perpendicular perturbation within the packet was <6 mV/m (panels a and b). Therefore, using the fact that the waves were electrostatic, we can estimate that the ratio of the parallel to perpendicular wavelength, $k_{\parallel}/k_{\perp} \approx 7$. The spacecraft potential indicated that the background density (within ~factor of 2) was ~0.5 cm^{-3}. In addition, the wave packet was confined within a density cavity. The velocity of the structure was calculated to be ~ 95 km/s by examining the delay between two opposing probes which are aligned approximately along the magnetic field. This yields a parallel wavelength of ~1 km and a parallel scale size for the packet of ~35 km. In comparing the observed wave characteristics to physically significant ones, the largest uncertainty is in the values for the electron and ion temperatures, T_e and T_i. For the measured magnetic field magnitude, B_T=220nT, and estimated density, $n \approx 0.5$ cm^{-3}, the lower hybrid frequency, $f_{lh} \approx 100$ Hz, the ion plasma frequency, $f_{pi} \approx 150$ Hz and the ion cyclotron frequency, $f_{ci} \approx 3$Hz. Note that $f_{pe}/f_{ce} \approx 1$, so the exact expression for the lower hybrid frequency must be used. Assuming T_e= 100 eV, the Debeye length, λ_D, and the electron gyroradius, ρ_e , are both ~0.1 km. The measured parallel wavelength, therefore, is ~10 λ_D. The electron inertial length, λ_{ci}, is ~7 km. If $T_i = T_e$, the ion gyroradius, ρ_i , is ~5 km and the sound speed, c_S , is ~140 km/s. The observed wavelength, frequency, and wave speed are consistent with the dispersion relation for ion acoustic waves. The

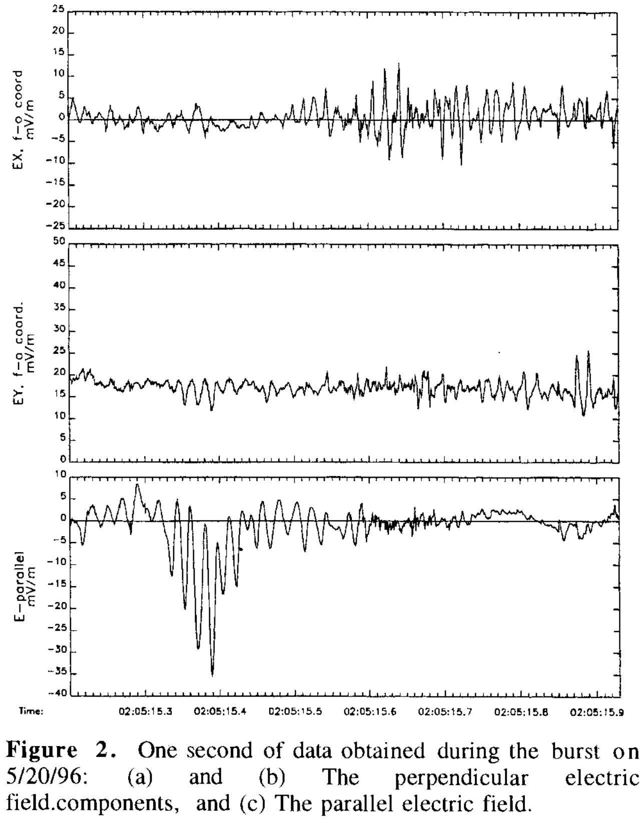

Figure 2. One second of data obtained during the burst on 5/20/96: (a) and (b) The perpendicular electric field.components, and (c) The parallel electric field.

uncertainties in the density and velocity values do not substantially change the results. Based on linear theory, however, one would not expect ion acoustic waves in a region with T_i larger than T_e. The electric field was anti-parallel to the geomagnetic field, resulting in a parallel potential drop of ~200 V which would accelerate electrons into the ionosphere. The electric field sampled at the usual data rate (panel d of Figure 1) also shows the occurrence of a net parallel potential drop. These observations suggest that the other parallel field spikes seen in Figure 1d may also be due to parallel wave packets whose detailed structure is not resolved.

A second type of parallel wave structure can be seen in Figure 3 which shows a large amplitude (up to 50 mV/m), short duration (~0.2s) wave packet parallel to the magnetic field (panel c) with a dominant frequency of ~20 Hz. Simultaneously waves at a higher frequency (~100 Hz) can be seen in the perpendicular components (panels a and b). There were no magnetic fluctuations at the frequency of the parallel packet; magnetic field fluctuations were associated with some of the perpendicular, higher frequency waves. The propagation velocity of the parallel wave was determined to be ~80 km/s. The parallel wavelength is ~4 km and the scale size for the packet is ~16 km. For this case, assuming all parameters but the density (~0.7 cm^{-3}) are the same as the previous packet, only f_{pi} (~175 Hz), f_{lh}(~110 Hz), and λ_{ei} (~4-5 km) are substantially different. The parallel wavelength would, therefore, be ~40 λ_D or ~λ_{ci}.

At the edge of the parallel packet, the perpendicular waves intensify and their amplitude is modulated, forming packets lasting <~0.1s (~3 ion gyroperiods). Each packet occurs in a small density cavity. The observed modulation and confinement of the packets to the density cavities suggests the waves are modified by the ponderomotive potential. Waves near the lower hybrid frequency with this type of modulation are commonly observed near the plasma sheet boundary and this topic is discussed elsewhere [Cattell et al., manuscript in preparation]. This modulation may be related to the bursty nature of the lower hybrid drift waves observed at the plasma sheet boundary and within the plasma sheet in the more distant tail [Cattell et al., 1994]. Large amplitude, modulated lower hybrid waves associated with density cavities have previously seen in the low altitude auroral zone and cusp on rockets and the Freja satellite [LaBelle et al., 1988; Dovner et al., 1994; Eriksson et al., 1994].

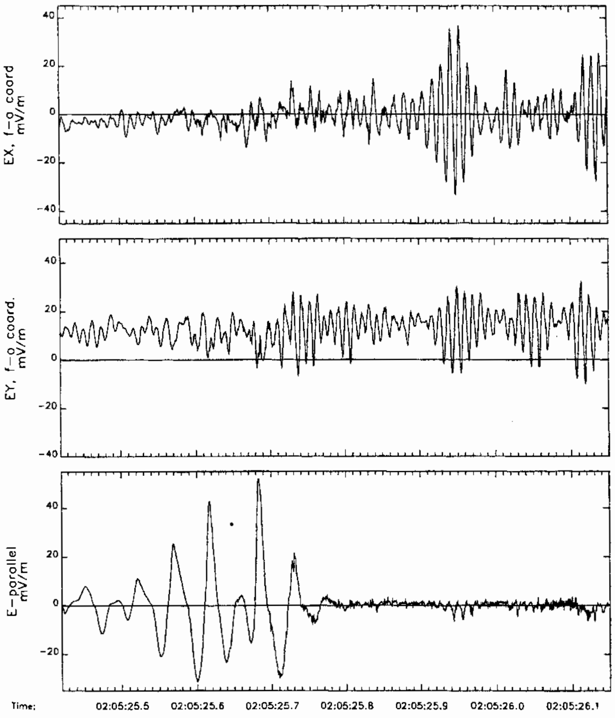

Figure 3. Another second of data obtained during the burst on 5/20/96: (a) and (b) The perpendicular electric field.components, and (c) The parallel electric field.

Solitary waves were also observed in the plasma sheet boundary during this burst. The amplitudes ranged from a few to 10's of mV/m, and the structures were associated with density depletions. No time delay could be seen between opposing sensors, indicating a propagation velocity faster than 100 km/s. Higher data rate bursts have provided examples which are consistent with velocities of 1000 km/s. At times, the solitary waves were observed as discrete structures with the interpulse spacing much longer than the duration of the solitary wave. At other times, the interpulse spacing is comparable to the pulse duration. This has also been observed at low altitudes by FAST [Ergun et al., 1997] and Polar [Mozer et al., 1997], and in the distant plasma sheet by Geotail [Matsumoto et al., 1994].

IV. Discussion and Conclusions

We have presented the first observations of large amplitude parallel electric fields in the plasma sheet boundary layer at radial distances of ~6 R_e. The parallel electric fields occur in three types of structures: (1) solitary waves similar to those observed at low altitudes in the auroral zone; (2) bipolar wave packets with small or zero net potential drops; and (3) unipolar packets with a net potential drop. All three types are electrostatic as indicated by the lack of magnetic fluctuations. Such structures are commonly observed in bursts obtained at the plasma sheet boundary within a large-scale region of field-aligned current. In addition, such fields often occur on the boundaries of high density regions in the polar cusp and dayside polar cap. Mozer et al. [1997] have reported the discovery of parallel wave packets in the low altitude, auroral zone Polar data. They showed an example of a bipolar 500 mV/m packet with a frequency comparable to the ion cyclotron frequency. The relationship between the wave packets observed at low altitudes in the auroral zone and the high altitude packets will be examined in a future study. The fact that parallel waves packets have been observed in all the regions with field-aligned currents which have been sampled by Polar suggests that they are a ubiquitous and important wave mode in space plasmas in boundary regions.

The unipolar wave packets are, to our knowledge, the first waves of this type to be reported in the magnetosphere. For the case described herein, the wave characteristics were most consistent with the ion acoustic mode, although the fact that the expected T_e/T_i in the plasma sheet boundary is <<1, is difficult to reconcile with the existence of ion acoustic waves. It may be the waves are not damped due to the existence of very short spatial gradients in the plasma parameters and/or highly non-Maxwellian features in the particle distributions. Such features would not be unexpected given the very large amplitude, small scale size density variations which were observed during the event. The net potential drop associated with wave packet was the order of 100 V which suggests that such packets provide a contribution to the acceleration of auroral electrons and will also modify the electron pitch angle distributions.

Solitary waves and double layers have been observed at altitudes ranging from ~1000 km to 10,000 km in the auroral zone [Temerin et al., 1982; Bostrom et el., 1988; Mozer et al., 1997] and, in the plasma sheet, to radial distances beyond 70 R_e [Matsumoto et al., 1994]. The solitary waves described herein which occur in the plasma sheet boundary at radial distances of ~6 Re are much larger amplitude than those in the distant tail and sometimes larger than those in the auroral zone. Their durations (~2 - 3ms) are comparable to both the other regions. Their estimated speed was faster than observed in the auroral zone. Mozer et al. [1997] and Ergun et al. [1997] have reported the discovery of large amplitude solitary waves which, in some cases, have both magnetic and electric field signatures, and which propagate at higher velocities than the previously reported electrostatic solitary waves.

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