Large amplitude, extremely rapid, predominantly perpendicular electric field structures at the magnetopause

F. S. Mozer,[1] S. D. Bale,[1] and J. D. Scudder[2]

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[1] Electric fields with amplitudes to 140 mV/m and average durations of 7.5 milliseconds have been observed at the magnetospheric side of the dayside magnetopause. These fields are predominantly perpendicular to B, they are electrostatic, and they occur inside local minima in the plasma density. Because they have been observed at each of approximately seven opportunities, they must be a common feature of the magnetopause. They may be associated with the magnetospheric separatrix because computer simulations suggest such structures. Their complete characterization requires time domain measurements of plasma and three component fields with better than a few millisecond time resolution. *INDEX TERMS:* 2712 Magnetospheric Physics: Electric fields (2411); 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 7815 Space Plasma Physics: Electrostatic structures; 7835 Space Plasma Physics: Magnetic reconnection. **Citation:** Mozer, F. S., S. D. Bale, and J. D. Scudder (2004), Large amplitude, extremely rapid, predominantly perpendicular electric field structures at the magnetopause, *Geophys. Res. Lett.*, *31*, L15802, doi:10.1029/2004GL020062.

1. Introduction

[2] The usual picture of the sub-solar magnetopause [*Birn et al.*, 2001] has been a static, two-dimensional, planar boundary containing an ion scale region (~100 km at the subsolar magnetopause) controlled by Hall MHD physics. Inside this ion diffusion region, there is a region within which $\mathbf{E} + \mathbf{U_e} \times \mathbf{B} \neq 0$, where $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields and $\mathbf{U_e}$ is the local average (bulk) velocity of the electron fluid. This region is thought to be the locale where a topological change of the magnetic field is made possible by the small-scale processes that are ignored in the Hall MHD approximation. It is thought to have a scale size the order of the electron skin depth, c/ω_{pe}, where c is the speed of light and ω_{pe} is the electron plasma frequency. Although $\mathbf{E} + \mathbf{U_e} \times \mathbf{B} \neq 0$ is a necessary condition for locating this region, it is not sufficient for its identification since there are additional terms, both parallel and perpendicular to $\mathbf{B}$ in the generalized Ohm's law that do not cause the requisite change of magnetic topology [*Scudder*, 1997]. These effects shape this inner region and are typified by electron pressure gradient drifts and incidental parallel electric fields of ambipolar origin. These deviations associated with electron pressure divergence drifts have been reported and measured in resolved magnetopause layers [*Scudder et al.*, 2002]. Outer region, ion scale, bipolar electric and magnetic fields predicted by Hall MHD simulations have been observed in a small percentage of magnetopause crossings [*Mozer et al.*, 2002]. These Hall dominated structures are not two-dimensional and static, and their post-reconnection $E \times B$ flows are sometimes towards rather than away from the separator [*Mozer et al.*, 2003a]. These effects do not require $\mathbf{E} + \mathbf{U_e} \times \mathbf{B} \neq 0$ [*Scudder*, 1997]. Within the magnetopause, hundreds of filamentary electron skin depth current layers have been observed and many have both parallel and perpendicular components of $(\mathbf{E} + \mathbf{U_e} \times \mathbf{B}) \neq 0$ [*Mozer et al.*, 2003b]. These regions involve non-ideal MHD and they may be topology changing in character.

[3] The previous measurements have been limited in their time resolution by the 40 samples/second electric field and 9 samples/second magnetic field measurements, such that the thinnest structures were several times the electron skin depth. Beginning in late January 2004, the telemetry format for the Polar satellite was modified to allow higher time resolution measurements of **E** and **B**. In the first several magnetopause crossings after this change, about seven examples containing $\leq$10 msec duration, predominantly perpendicular, electric field structures with amplitudes as large as 140 mV/m were observed. The purpose of this letter is to describe the properties of these events as seen in the field data. Because the time resolution of the particle measurements was not sufficient, the particle data are not discussed.

2. Data

[4] The top panel of Figure 1 presents 90 seconds of plasma density measured on January 31, 2004, when the spacecraft was at $-35°$ magnetic latitude and 1410 magnetic local time. This density estimate is obtained from the spacecraft potential, as calibrated from comparisons with the plasma density on slower time scales for similar densities [*Scudder et al.*, 2000]. Near the beginning and end of this interval, the spacecraft was in the magnetosphere, as is verified by the plasma density being $\sim$1 cm^{-3}. Through most of this figure the spacecraft was in the magnetosheath where the density was as large as 15 cm^{-3}. The pseudo-periodic variations in the plasma density are natural and not a multiple of the spacecraft spin period. The remaining three panels of Figure 1 present the three components of the electric field in GSE coordinates, as directly measured by the three-component electric field detector. Near the beginning and end of the figure, there were 80 points/sec of electric field data while there were 1600 points/sec in most of the region. At the feet of the density enhancements,

[1]Physics Department and Space Sciences Laboratory, University of California, Berkeley, California, USA.
[2]Physics and Astronomy Department, University of Iowa, Iowa City, Iowa, USA.

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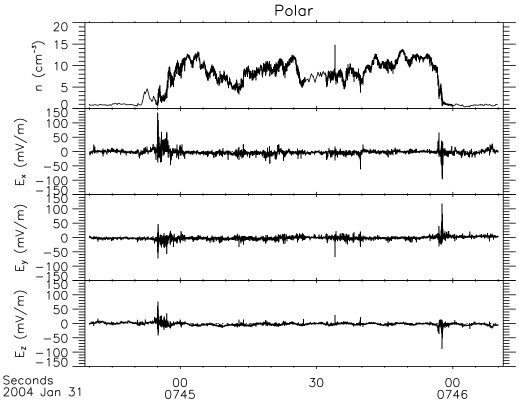

Figure 1. Plasma density determined from the calibrated spacecraft floating potential and the three components of the electric field measured during a 90 second interval on the Polar spacecraft as it crossed from the magnetosphere to the magnetosheath and back.

near 0744:55 and 0745:55 UT, electric fields as large as 140 mV/m were observed. These large fields were predominantly perpendicular to **B**, although a parallel electric field component as large as ~10% of the perpendicular component (which is significant for the electron physics in these structures) cannot be ruled out because the magnetic field data has not been calibrated and it does not have a time resolution sufficient to know the direction of the magnetic field on the required millisecond time scale. (For this reason, magnetic field data are not shown in this paper.)

[5] Figures 2 and 3 each present 300 milliseconds of plasma density and electric field data at the times of the two large field enhancements near the beginning and end of Figure 1, respectively. In either figure there are electric field enhancements as large as 140 mV/m lasting for times shorter than 10 msec (note that the time interval between horizontal tic marks in either figure is 10 msec). The largest electric fields correlate with minima in the plasma density, as is especially evident in Figure 2. These fields cannot have been produced by spatial gradients of plasma properties because such spurious fields would be bipolar.

[6] Magnetic field data during these events was low pass filtered at 11 Hz and transmitted at 54 samples/sec. The main magnetopause magnetic field variations associated with the magnetopause crossings of Figures 2 and 3 occurred during the six and four seconds surrounding the electric field data of these figures, respectively. We have not been able to determine a robust normal to the magnetopause in these events, but it is clear that the guide magnetic field was similar to or greater than the reconnection magnetic field in each case.

[7] Search coil magnetic field data (not shown) has structure near the boundaries of the big electric fields, suggestive of currents or wave fields at the walls of the density depression/electric field enhancement. Because the amplitude of the broad-band magnetic field fluctuations measured with the search coil magnetometer was a few tenths of a nT when the electric field was 140 mV/m, the ratio of E to B was greater than the speed of light, so the electric field structures were electrostatic.

[8] Further properties of these electric field structures are listed in Table 1, in which the 29 examples whose total field was greater than 50 mV/m during the interval of Figure 1 are listed. In this table, the temporal duration of each event is defined as the full width at half maximum.

3. Discussion

[9] Due to the non-linear Langmuir probe characteristic of the electric field sensors, it is possible that the observed signals could be the low frequency rectified envelope of higher frequency waves, which in this case would be Langmuir waves. This explanation is unlikely because the observed fields are mainly perpendicular to **B** while Langmuir waves are parallel to **B**. Also, these events are not the solitary wave structures reported previously [*Cattell et al.*, 2003] because the solitary wave fields are predominately parallel to the magnetic field.

[10] Data collection at 1600 samples/sec has been obtained at about seven magnetopause crossings in the first two weeks that the Polar spacecraft was in the high data rate mode. Because electric field signatures like those in Figures 2 and 3 were found at all of these crossings, it is concluded that large amplitude (to ~150 mV/m) short (<10 msec) variations of the predominantly perpendicular electric field are common features of magnetopause

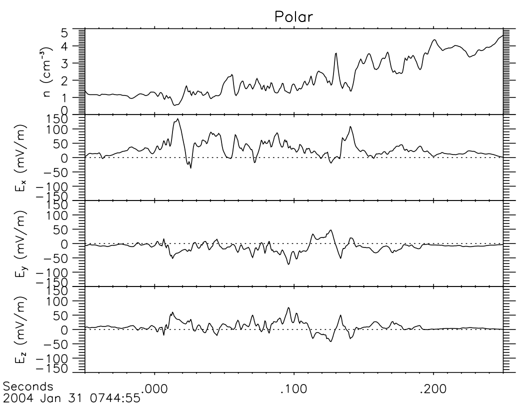

Figure 2. Plasma density and the three components of the electric field measured during a 300 msec interval on the Polar spacecraft as it entered the density increase in passing from the magnetosphere to the magnetosheath.

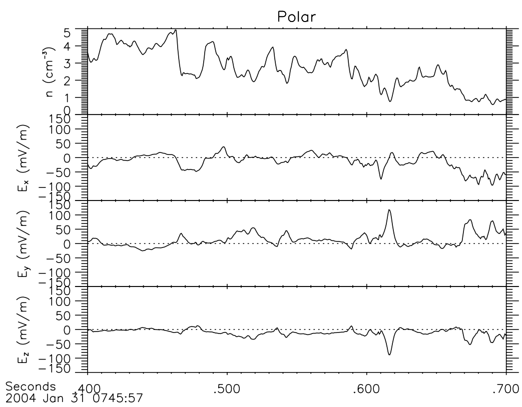

Figure 3. Plasma density and the three components of the electric field measured during a 300 msec interval on the Polar spacecraft as it passed through the density decrease from the magnetosheath to the magnetosphere.

Table 1. Properties of Electric Field Peaks

Time of Peak (sec)	Peak E (mV/m)	Duration (msec)	B (nT)	n (cm^{-1})	E/B (km/sec)
27895.01653	144.0	9.38	74.5	0.6	1930
27895.04028	91.3	10.25	72.9	0.9	1250
27895.05840	81.5	4.37	72.5	1.1	1120
27895.07028	72.8	5.00	71.8	1.5	1010
27895.07903	72.8	8.12	71.8	1.5	1010
27895.08778	94.8	8.13	71.6	1.3	1320
27895.09590	110.9	6.25	71.5	1.3	1550
27895.10153	80.6	7.50	71.5	1.5	1130
27895.12653	65.9	5.62	70.5	1.7	930
27895.14028	115.4	6.87	71.0	1.4	1620
27895.17340	52.3	10.63	68.6	2.4	760
27895.33340	51.7	8.12	69.6	2.5	740
27895.65028	50.5	9.37	71.0	1.9	710
27895.82590	69.0	4.38	70.6	1.7	980
27895.83715	54.6	7.50	70.8	1.5	770
27895.84903	58.6	9.38	71.2	1.5	820
27897.00340	66.8	9.38	66.1	2.6	1010
27897.01528	69.7	7.50	66.0	2.5	1060
27939.65652	64.5	9.38	62.0	3.7	1040
27939.67214	50.9	9.12	62.4	4.1	820
27956.93777	81.6	4.38	64.4	2.3	1270
27957.46714	57.0	5.00	63.2	3.9	900
27957.51839	65.0	8.12	63.1	1.9	1030
27957.54277	54.6	6.25	64.4	1.8	850
27957.59839	53.0	6.25	65.0	1.6	820
27957.61589	147.2	5.00	64.6	0.8	2280
27957.67527	117.9	10.63	66.2	0.7	1780
27957.69027	132.9	10.75	65.8	0.6	2020
27957.71652	57.8	4.37	65.6	1.0	880
Average	78.8	7.50	68.3	1.8	1150

crossings. Because the examples all occurred at the magnetospheric side of the crossing, they may be associated with the magnetopause separatrix, as has been observed in both simulations [*Shay et al.*, 2001] and earlier Polar data [*Mozer et al.*, 2003b]. This interpretation is also consistent with the anti-correlation of the plasma density and the large field structures because density minima within the separatrices has been predicted [*Shay et al.*, 2001].

[11] As given in Table 1, the average duration of the electric field structures was 7.5 msec. If the structures were approximately fixed in the electron frame such that they moved by the spacecraft at the average E/B speed within a structure, their average thickness was six km, which is about 1.5 electron skin depths. This estimate is uncertain because the actual speed of the structures is not known, this estimate neglects trigonometric factors that are present and, in the presence of other terms in the Generalized Ohm's law, the electron speed could be either larger or smaller than E/B.

[12] Another possible interpretation of the data is that the structures moved past the spacecraft at the typical magnetopause speed of a few tens of km/sec, in which case their thicknesses would be the order of the Debye length. This interpretation is discussed in a paper that includes computer simulations of such structures (J. D. Scudder et al., unpublished manuscript, 2004). Yet another possibility is that the field variations were temporal and not spatial, as assumed in the above examples. In this event, the durations of the structures are not related to their thicknesses. From the correlations of the signals from opposite sphere pairs, it has not been possible to determine which interpretation is more likely.

[13] To understand the possible role of these structures in the general framework of collisionless reconnection will require measurements of the electromagnetic field and electron moments with high accuracy and millisecond temporal resolution. Because such measurements are also required in regions where the magnetic field is small, their accuracy should be ~0.1 mV/m and ~0.1 nT in small field regions. A spacecraft this well instrumented should see interesting structures at most magnetopause crossings.

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S. D. Bale and F. S. Mozer, Space Sciences Laboratory, University of California, 7 Gauss Way, Berkeley, CA 94720-7450, USA. (fmozer@ssl.berkeley.edu)

J. D. Scudder, Physics and Astronomy Department, Room 203 Van Allen Hall, University of Iowa, Dubuque at Jefferson Streets, Iowa City, IA 52242-1479, USA.