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Direct observation of large, quasi-static, parallel electric fields in the auroral acceleration region

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Abstract. The three-axis electric field experiment on the Polar satellite provides direct observations of electric field components parallel and perpendicular to the local magnetic field with no arbitrary adjustment parameters. Approximately 750 perigee passes through each of the two southern auroral zones at a geocentric altitude of about two Earth radii have been computer-searched for parallel electric fields whose eight point (0.2 or 0.4 second) average exceeded 100 mV/m. After elimination of spurious events due to shadowing, saturation, and ten other effects, four events containing parallel fields of 200-300 mV/m, remain. These four events all occur in upward field aligned current regions, their parallel electric fields are all positive such that $\vec{j}\cdot\vec{E} > 0$, and they occur at boundaries between regions of active and quiet perpendicular electric fields. Up-going ion beams are observed in the active field regions, and the plasma density is higher in the quiet field regions than in the adjacent active field regions. These boundaries are interpreted in terms of model equipotentials, some of which are below the spacecraft in the large field regions and all of which are above the spacecraft in the quiet field regions. In this model, the expected location of large parallel electric fields is where they are observed. That the potential difference measured by the electric field instrument along the vehicle trajectory and the kinetic energy of the up-going ions are equal lends further credence to the data and its interpretation.

Discussion

It is generally agreed that electric fields parallel to the background magnetic field exist in the auroral acceleration region to produce up-going ion beams and down-going inverted-V electrons. If these parallel fields are quasi-static and small compared to the 100-1000 mV/m perpendicular fields that are present, they cannot be detected by the electric field experiment on the Polar satellite. This is because uncertainties in the measured parallel field, arising primarily from angular uncertainties in the detector orientations, are comparable to or larger than such fields. However, strong double layer or electrostatic shock theories [*Block,* 1972; *Kan,* 1975; *Swift,* 1975; *Swift,* 1979] predict parallel fields that are comparable to or larger than the perpendicular field. Such fields can be measured easily if the spacecraft flies through a region containing them. It is the purpose of this paper to report the positive results of a search for such large parallel fields.

The Polar satellite was launched in February 1996. Through October 1997, it made approximately 750 passes through each of the two southern auroral zones at a geocentric altitude of about two Earth radii. The three-axis electric field experiment on Polar is described elsewhere [*Harvey et al.,* 1995]. Polar electric field data have been combined with the measured magnetic field to produce 20 or 40 measurements per second of the three components of electric field in a magnetic coordinate system. It is emphasized that these components are computed with no arbitrary correction factors, gain adjustment, or offset corrections.

To look for large parallel electric fields in the southern auroral acceleration region, a computer search was made over a one hour interval centered at each perigee for parallel fields whose eight point (0.2 or 0.4 second) average exceeded 100 mV/m. This search eliminated parallel fields associated with ion cyclotron (~100 Hz) or higher frequency modes since their fields would average to near-zero. It produced about 250 events, of which all but four were eliminated by the following criteria:

- No Sun or magnetic field shadowing of the sensors. About 200 such events were identified by the spin periodicity of big field pulses.
- No detector saturation. About 20 such events were identified by their saturated signals, which were due to large electric fields.
- Spacecraft potential >5 volts (density <5/cc). About 20 events with big apparent fields were observed as being due to the sensors (which had a constant, negative, bias current) being on an inappropriate part of the Langmuir probe curve when the density was too high.
- No telemetry noise. A few apparent big field examples were caused by noise in the magnetometer or Sun pulse signals.
- Several of the six sensors must participate in the event.
- The spacecraft potential, as measured by the average potential of sensors 1 and 2 with respect to the spacecraft, is the same as that measured by sensors 3 and 4.
- No high frequency waves were rectified to produce DC offsets. (In Figs. 1 through 4, very small, apparent, parallel fields are due to this effect.)
- Spatial plasma gradients (including those described below in connection with Fig. 1) can produce apparent electric fields by causing different sensors to float at different potentials. No such gradient effects could account for more than 1% of the observed signals.

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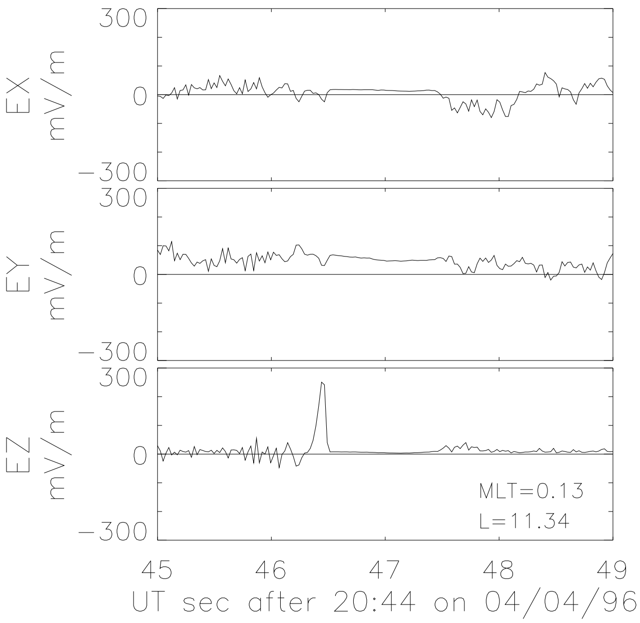

Figure 1. Electric field components in a magnetic field aligned coordinate system. Also shown are the spacecraft potential and the magnetic field component effected by field aligned sheet currents. The MLT value is the magnetic local time and L is the McIlwain L-value.

- The Plasma Source Instrument, which emits ions and electrons that perturb the local electric field, was not operating.
- The bias current and the guard and stub voltages were all nominal [see *Harvey et al.*, 1995].
- The observed parallel field did not depend significantly on the short on-axis measurement, which is less reliable than the long wire boom measurements.

Electric field components of the four events that survived the above criteria are illustrated in Figs. 1 through 4, in which the z-axis is parallel to the local magnetic field, the x-axis is perpendicular to B and pointing equatorward in the plane of the magnetic field line, and the y-axis is the third component of the ortho-normal set, pointing perpendicular to B in a westerly direction. It is noted that the parallel electric field is positive (upward) and it is observed near the boundary between relatively large, active, perpendicular fields and smaller, quiet fields in all four events.

Fig. 1 contains two panels in addition to the electric field data. The bottom panel is the spin-axis (roughly east-west) component of the magnetic field minus a model field. The slope of this component is a measure of the strength of field aligned current sheets. An essentially constant, upward directed, ~0.07 μA/m^2 field aligned current existed throughout the region of the parallel electric field and the quiet and active segments of the perpendicular field. This property is also observed, but not shown, in the events of Figs. 2 through 4. Comparisons of magnetometer signatures with the current carrying particle flux on FAST indicate that the field-aligned current obtained from the magnetometer is generally accurate to within 30% (McFadden, private communication). Ion cyclotron waves were observed during the time interval of Fig. 1. No wave measurements were made during the other events.

The second panel from the bottom of Fig. 1 is the spacecraft potential, which is an indicator of plasma density [*Pedersen,* 1995]. During the approximately 1.5 second quiet interval in the perpendicular field, the plasma density was about 5/cc, whereas it was less than 1/cc at all other times. That the plasma density is significantly greater in the region of the quiet perpendicular field is also observed in all the other examples.

Finding four large parallel electric field events in about 1500 auroral zone passes (and about six other large parallel fields in a second search described below). is consistent with statistical expectations, as the following discussion shows. A parallel electric field of 200-300 mV/m can extend over an altitude range of no more than about 10 kilometers to produce the several kilovolt potential drop expected from particle measurements. Because the auroral acceleration region is several thousand kilometers in altitude extent, the probability of passing through a 10 kilometer parallel field region in a single pass is the order of one percent. This estimate is not quantitative because many factors have been ignored. For example, the parallel field is primarily above the Polar spacecraft in the southern auroral zone so this is an overestimate. Also, the equipotential contours might be inclined at an angle different from 90 degrees with respect to the magnetic field, making them more extensive in altitude than they would be if they were inclined at 90 degrees. Thus, the number of observed parallel fields cannot be compared quantitatively with a model, but it is consistent with expectations.

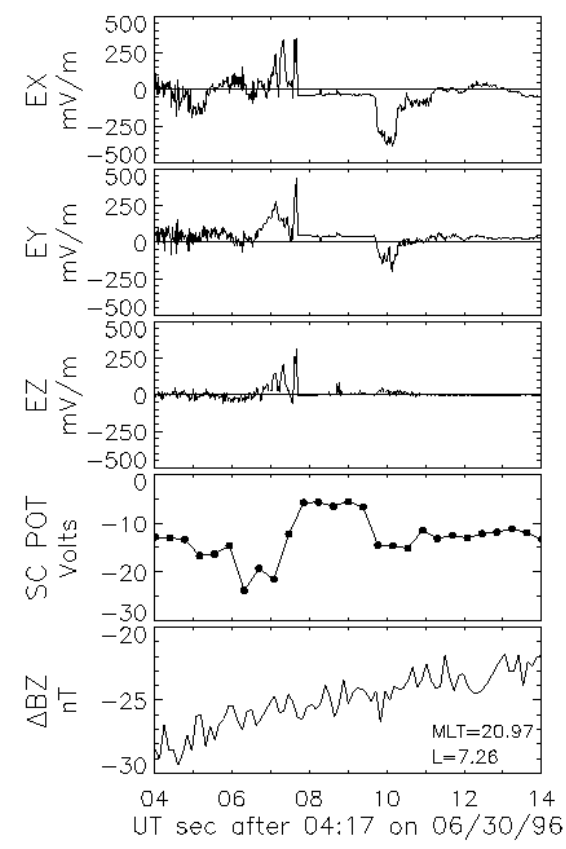

Figure 2. Electric field components in a magnetic field aligned coordinate system.

In a large sample of events having parallel electric fields with random signs, the probability that four events have parallel electric fields and field aligned currents of the same sign is less than 1/128 (less because many events in a random sample of parallel electric fields might have no field aligned current). Thus, the observations appear to be statistically significant.

Additional support for the reality of the observed events is associated with the fact that they all occur at the boundary between active, relatively large, perpendicular electric fields and quiet, small perpendicular fields. The characteristics of this boundary may be further studied by considering the particle fluxes in its vicinity, as illustrated in the two bottom panels of Fig. 4 which contain pitch-angle-averaged, energy-time spectragrams of up-going ions (pitch angle less than 30 degrees) and down-going electrons (pitch angle greater than 150 degrees) measured by the Hydra particle spectrometer (*Scudder et al.,* 1995). This instrument measures a spectrum every 1.15 seconds, alternating between electrons and ions. Because the Hydra detectors point in fixed directions and have narrow angular responses, some pitch angles are not measured during parts of a given energy sweep as the spacecraft rotates. Fig. 4 shows only those points where measurements are available, with a featureless grey background when there was no data. Throughout the time interval of this figure, the energy spectrum of down-going electrons peaked at 3-8 keV, consistent with an upward electric field above the spacecraft. In the quiet, perpendicular field region, no significant upward moving ions were observed, which is consistent with no parallel field below the spacecraft at these times. By contrast, in the active field region from about 26 to 34 seconds after 02:36, both of the ion measurements in the 1-2 keV energy range showed up-going ions and, in the active field region during the last 20 seconds of this figure, upgoing ion beams were observed in each of the 5 measurements made between 100 eV and 2 keV. These observations suggest that there is a parallel field below the spacecraft in the active perpendicular field regions and that the boundary between active and quiet fields is the site where equipotential contours move from above (below) to below (above) the spacecraft. This hypothesis can be tested by comparing the spatial integral of the electric field along the vehicle trajectory with the up-going ion energy. This comparison is made in the second panel from the bottom of Fig. 4, in which the dashed curve is the integrated potential less that due to an assumed uniform ionospheric field of 14 mV/m. That this integrated potential agrees so well with the ion energy is strong evidence in favor of the idea that the boundaries containing the parallel electric fields are the regions where lowest altitude portions of the equipotential contours move from above (below) to below (above) the spacecraft. This movement of equipotentials must be due to a spatial rather than temporal variation because, in the latter case, the plasma density would not recover in a time as short as that observed in Fig. 1 and the integrated potential would not agree with the ion energy.

The ion and electron fluxes during the events of Figs. 1, 2, and 3, are consistent with the above observations, although the time resolution is not sufficient for more detailed comparisons. Higher time resolution data from the FAST satellite have shown that the plasma characteristics of Fig. 4 frequently occur at the boundary between large, active perpendicular electric fields and quiet fields [*McFadden*, 1997]. No search of the type reported here has been performed on the FAST field data.

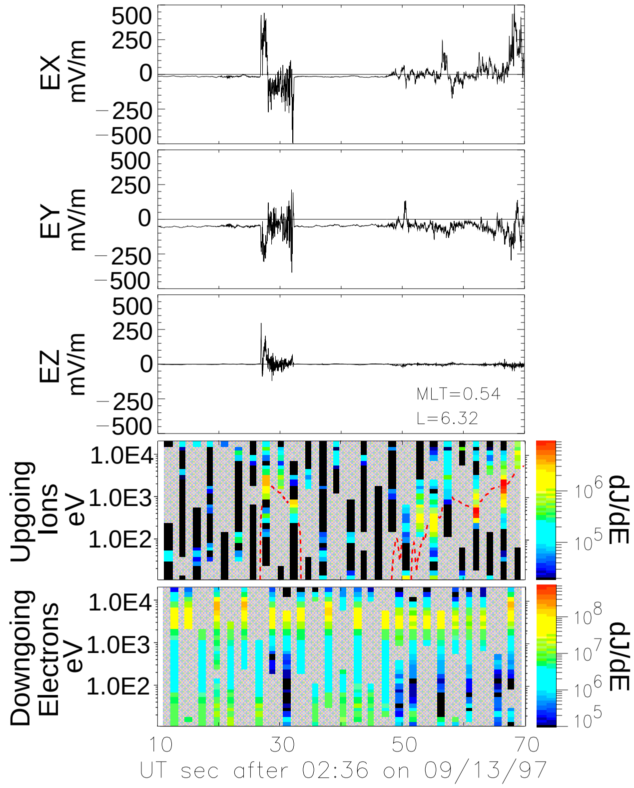

Figure 4. Electric field components in a magnetic field aligned coordinate system and down-going electrons and up-going ions observed by the Hydra instrument on Polar.

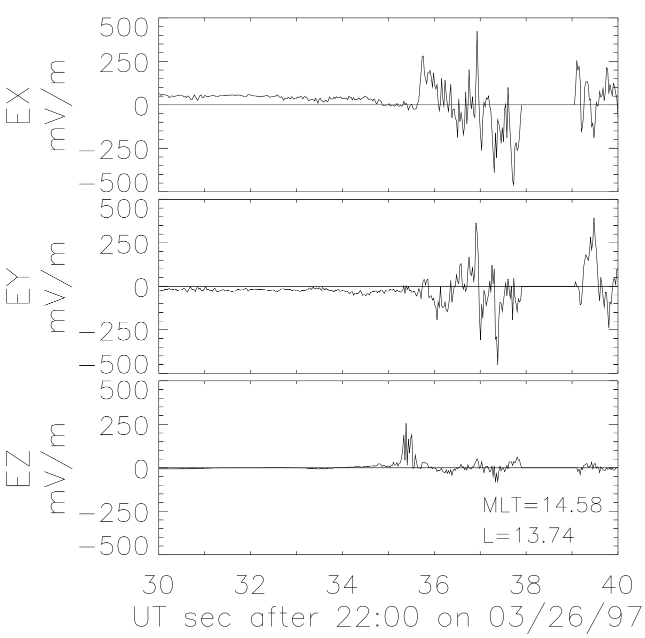

Figure 3. Electric field components in a magnetic field aligned coordinate system. The data between 38 and 39 seconds after 22:00 has been deleted due to detector saturation.

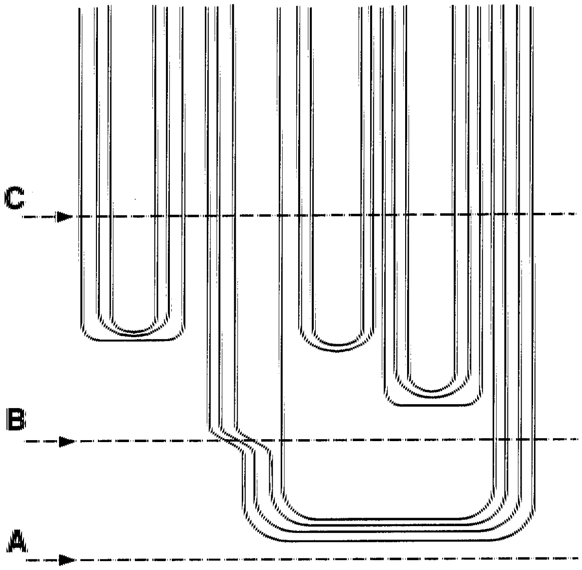

Figure 5. Equipotentials of a quasi-static electric field model in a uniform, vertical magnetic field, illustrating boundaries between quiet and large perpendicular electric fields and the parallel electric fields that might exist at such boundaries.

A model of equipotential contours consistent with the above description is given in Fig. 5. If the spacecraft moved along trajectory A of this figure, all of the parallel field would be above the spacecraft, so the perpendicular electric field would be quiet, the density would be high since particles are not being accelerated away, there would be no up-going ion beams, there would be down-going electron beams through the region, and the parallel electric field would be zero.

If the spacecraft moved along trajectory C of Fig. 5, all of the parallel field would be below the spacecraft, so that up-going ion beams would be observed throughout the region. There would be no down-going electron beams and the plasma density would be low because the plasma was accelerated away by the parallel field. The perpendicular electric field would be relatively large and variable, and the parallel electric field would be zero.

If the spacecraft moved along trajectory B of Fig. 5, it would cross the boundary where the spatial variation causes equipotential contours to move from above to below the spacecraft. Before this boundary is crossed, all of the properties of trajectory A would be observed. After the boundary is crossed, parallel fields would be both above and below the spacecraft so both down-going electrons and up-going ion beams would be observed. At the boundary, the density would decrease and the perpendicular electric field would become larger and variable. Depending on the detailed structure of the equipotential contours, parallel electric fields might be expected at this boundary. In the example of this figure, there is a large parallel electric field at the entrance boundary but not at the exit. The tilt of the equipotential contours at this entrance boundary is consistent with the data of Figs. 1 and 4 since the parallel and perpendicular fields are comparable and the perpendicular field points in the expected direction. The data of Figs. 2 and 3 require that the equipotentials be more horizontal since the parallel fields are large compared to the perpendicular fields in these examples. Also, in these cases, the perpendicular field points in the expected direction.

Given that the above analysis lends confidence to the observations of large, parallel, quasi-static electric fields at the boundaries between large, active, perpendicular electric fields and quiet regions, one may invert the original search and look for such boundaries to see if smaller but experimentally significant parallel electric fields exist at these locations. Although this search is not complete, several examples of parallel electric fields have been found in this way.

It is noted that the typical 0.1-0.2 second durations of the parallel electric fields translate to a 0.7-1.4 kilometer spatial size perpendicular to the magnetic field under the assumption that the spacecraft moved through a static structure. This dimension is comparable to the 0.6 kilometer gyration radius of a 1 kilovolt proton. It is also noted that the boundary of the equipotential contours is a new discontinuity in the magnetosphere, across which both the plasma density and $\bar{E} \times \bar{B}$ jump. Lastly, since physics is universal, it is possible that the parallel electric field physics of the auroral acceleration region operates in other current carrying locales such as reconnection sites, solar flares, collisionless shocks, and at other magnetospheric boundaries.

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