MULTI-POINT ELECTRIC FIELD OBSERVATIONS IN THE HIGH-LATITUDE MAGNETOSPHERE

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ABSTRACT

We use multi-point electric field observations from the four Cluster satellites to study the dynamical behavior of the high-latitude magnetosphere on February 13-14, 2001, 20-02 UT. At 20:00 UT the vehicles enter the cusp where three satellites observe a 500-volt potential drop. It implies that at lower altitudes there likely exist some parallel electric fields that accelerate electrons downward and ions upward. In the following 2–3 hours the satellites move over the southern polar cap where all four satellites pass through a number of stationary, large-scale density enhancements that are associated with 200-volt potential drops. The observed events are possibly ionospheric ion outflows, occurring during enhancements of geomagnetic activity. At 23:20 UT, the satellites move in the distant plasma sheet, and an hour later they have a brief encounter with the auroral region where a density cavity of a few degrees wide is observed. At the equatorward edge of the cavity, large electric fields of 100 mV/m are observed, which are likely related to an auroral arc. Similar observations are collected from all four satellites within a few minutes, but a detailed comparison reveals plenty of differences, apparently due to small spatial and temporal scale sizes. Near the perigee pass, the vehicles traverse the plasma trough near local midnight, where they all detect a ULF wave event. A preliminary analysis of the event shows that it is a resonant mode of a 120-sec period. Surprisingly the observations from four satellites are not well correlated, which suggests a short spatial and temporal scale for the event. A possible source mechanism for ULF waves at this local time sector is drifting ring current protons.

1. INTRODUCTION

The structure and dynamics of the magnetosphere have been widely investigated with in-situ instrumentation on numerous satellites for forty years [*Stern*, 1995]. In many cases magnetospheric processes have short temporal and spatial scales, and therefore their proper monitoring requires a multi-satellite constellation with brief but variable separations [*Russell*, 2000]. One can expect that the four Cluster satellites, being the first real multi-satellite array, will play a central role in studying the Earth's magnetosphere during the following decade. There are plenty of important issues that are still poorly understood and that will immediately be studied with new Cluster observations, such as how the solar wind is coupled to the magnetosphere, or, how a substorm process is initiated in the magnetotail. Concerning the structure of the magnetosphere, the spatial variations of the plasma density and electric field are not yet modeled well enough, from a space weather point of view; for comparison, understanding of the magnetic field variations is in a much higher level. These are examples of problems where multi-point observations are necessary and which will be investigated with the electric field experiment EFW on the Cluster satellite.

The Cluster satellites carry a new type of double probe antenna that has turned out to provide us with quasi-static electric field observations of unprecedented quality [for more details of the experiment, see *Gustaffson et al.*, 2001]. The basic variables monitored by the EFW experiment are spacecraft potential and two-dimensional electric field. The third electric field component can be derived, by combining the electric field measurements and the 3-D magnetic field observations. Concerning spacecraft potential measurements, the variable monitored by EFW is a potential difference between a probe and the satellite, where the probe is biased to a constant potential, approximately +1 volt, for most of time. Therefore, in a good approximation, this parameter is the negative value of the spacecraft potential, which is directly proportional to the plasma density, while the spacecraft potential itself is inversely proportional to the plasma density [*Laakso and Pedersen*, 1998; *Pedersen et al.*, 2001].

This paper deals with dynamical processes of the high-latitude southern magnetosphere, using examples of multi-point electric field observations gathered by Cluster on February 13–14, 2001. Figure 1 shows a full 56-hour Cluster orbit over a sketch of the magnetosphere in the noon-midnight meridian. In this paper we will concentrate on a 6-hour interval during which the satellites move from the magnetosheath over the southern hemisphere towards the perigee near local midnight. In particular we will examine the cusp, polar cap, plasma sheet, and auroral oval. In addition, a ULF wave event is detected in the trough region, which will also be studied.

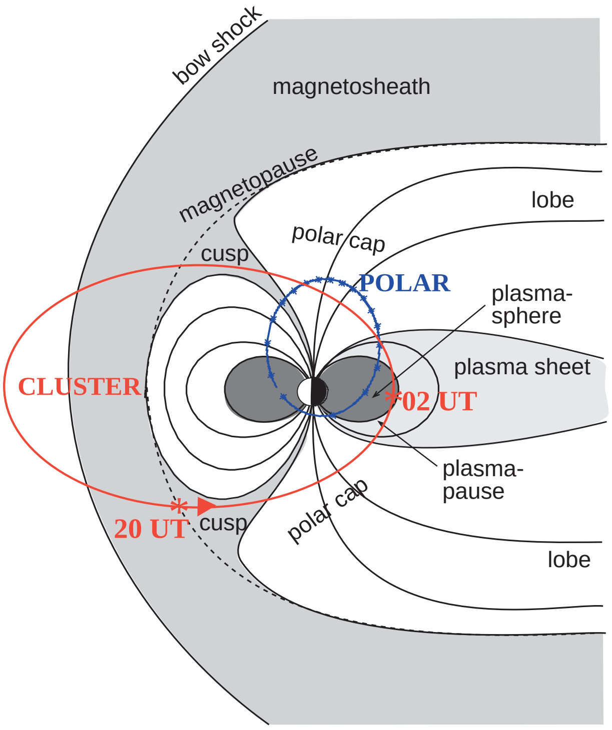

Figure 1. Sketch of the magnetosphere in the noon-midnight meridian with orbits of the Cluster and Polar satellites.

2. EFW OBSERVATIONS

Figure 2 summarizes EFW observations from Cluster 1 on February 13-14, 2001, 18:00–02:10 UT. The panels from top to bottom are the electric field x and y components in the GSE coordinate system, the spacecraft potential, and the plasma potential (the integrated electric field along the satellite trajectory). For the first two hours, the satellite is in the magnetosheath, where the vehicle potential is steady, implying that the plasma density is rather constant. At the same time the electric field is varying, which tells that either the interplanetary magnetic field or the solar wind velocity changes.

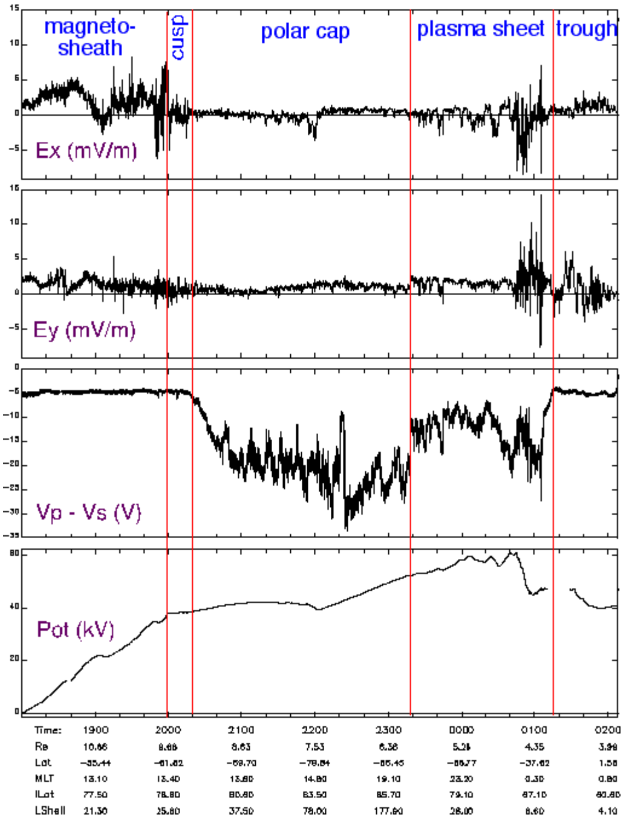

Figure 2. Spin-averaged (4-second) electric field observations from Cluster 1 on February 13-14, 2001.

Based upon magnetic field observations, the satellites enter the cusp at about 20:00 UT [*M. Dunlop*, private communication, 2001], which is in fact quite difficult to distinguish from the EFW data of Figure 2. Section 3 will deal with the cusp encounter in more detail. Tailward of the cusp, the satellites cross first the mantle and then the polar cap, where the latter is one of the most tenuous regions of the magnetosphere. In that region a rarefied medium forces the satellites to float at very high positive potentials, usually between 20-60 volts. Figure 2 displays a number of large-scale density enhancements in the polar cap at 20:40-23:10 UT, which will be studied in more detail in Section 4. About 23:20 UT, the satellites arrive at the plasma sheet, first they have an encounter with the distant plasma sheet and later with the near-Earth plasma sheet; the latter is often quite dynamic and is a source region of auroral precipitation. In the case of Figure 2, one can distinguish some auroral cavities and large electric fields at 00:40-01:10 UT. These observations will be discussed in more detail in section 5. The last issue to be considered in the present paper is a ULF wave event in the trough region (section 6); this event gives a faint signature in E_y between 01:40-02:00 UT in Figure 2.

3. CUSP

The magnetic field observations (data not shown here) display strong diamagnetic effects at 20:00-20:07 UT, revealing that the cusp is encountered. In addition some weaker magnetic field perturbations are detected until 20:15 UT, and soon afterwards the satellite likely enters the mantle. On the basis of the EFW observations of Figure 2, it is difficult to determine when the satellite goes in the cusp; in fact, one can barely recognize that the satellite has encountered the cusp. This is because the satellite moves directly from the magnetosheath into the cusp, and these two regions are somewhat similar as far as the plasma density and the plasma flow are concerned.

Figure 3 displays an overview of the cusp region, showing EFW measurements from Cluster 1. Before entering the cusp, the satellite detects high-frequency waves within a large-scale electric field pattern at 19:47-20:00 UT, which causes a negative excursion in the plasma potential (bottom panel). The other three satellites observe the same structure. One can speculate that these perturbations are related to an exterior cusp where the plasma flow is expected to be more irregular than in the magnetosheath [*Haerendel*, 1978]. However, rather than being a signature of an exterior cusp, these disturbances are possibly caused by a travelling solar wind structure [*M. Dunlop*, private communication, 2001].

During the high-altitude cusp pass at 20:00 – 20:15 UT, the plasma drift appears quite variable, as shown by the top two panels in Figure 3. Figure 4 compares the measurements from all four spacecraft so that the Cluster 1 data are delayed by 10 seconds. The E_y component and the spacecraft potential appear quite parallel between the four satellites. Notice that a positive E_y component is related to an antisunward flow velocity that is thus similar on all four satellites. Instead, some differences can be discerned in the E_x component and the plasma potential; especially these measurements by Cluster 1 seem to deviate quite significantly from those by Cluster 2-4.

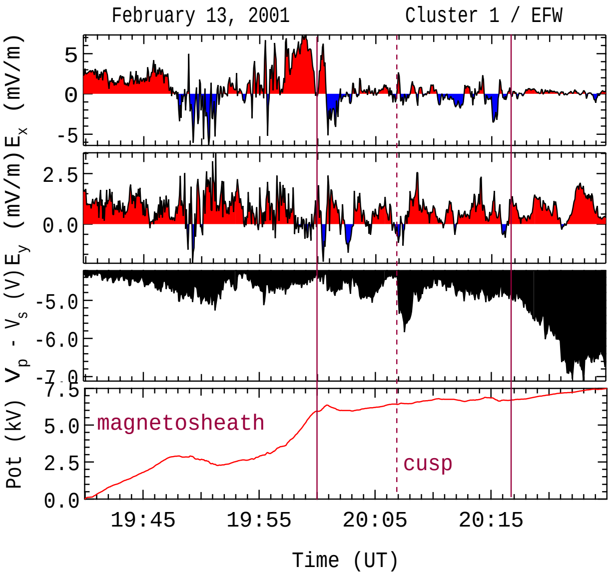

Figure 3. Spin-averaged EFW observations from Cluster 1 for a cusp region on Feb 13, 2001. The panels are the same as in Figure 2.

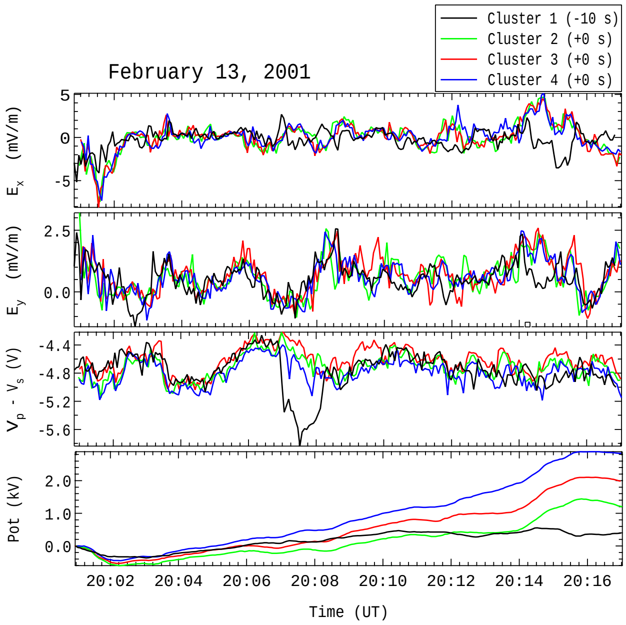

Figure 4. Spin-averaged EFW observations of the four Cluster satellites for a cusp crossing. The panels are as in Figure 3. The colors used are black, green, red, and blue for Cluster 1-4, respectively.

Notice particularly that Cluster 2-4 observe a potential drop of about 500 volts across the cusp at 20:01-20:15 UT, which corresponds in fact exactly to the interval where magnetic field perturbations are observed. Apparently, Cluster 1 encounters somewhat different field lines, as it detects no clear potential drop across the cusp. One may speculate that there may exist some parallel electric fields at lower altitudes, which accelerate electrons downward and ions upward by 0.5 kV within the cusp. This is in fact somewhat more than typically observed in the low-altitude cusp [*Newell and Meng*, 1988; *Smith and Lockwood*, 1996. The observed potential drop may be related to the occurrence of enhanced reconnection on the dayside magnetopause, causing some dayside auroras, as this is a particularly disturbed interval. After 19 UT, the preliminary AE index varies between 500 and 1500 nT for several hours.

4. POLAR CAP

The polar cap is defined as a region of open field lines, which map into the lobes of the magnetotail. As a result of an ambipolar electric field, the thermal electrons and ions can outflow from of the polar ionosphere [*Ganguli*, 1996]. As the cross section of the polar cap increases quickly with altitude, correspondingly the polar cap density steeply declines so that at an altitude of 3-4 R_E, the density is usually less than 0.1 cm^{-3} [*Persoon et al.*, 1983; *Laakso et al.*, 2001]. However, the polar cap density varies strongly with season and geomagnetic activity so that in winter during high geomagnetic activity the polar cap density can easily reach the summertime level [*Laakso et al.*, 2001].

Figure 2 displays enhancements in the spacecraft potential over the southern polar cap. Such events have been frequently observed, for instance, by the Polar satellite [*Laakso and Grard*, 2000] (for a typical Polar orbit, see Figure 1), and they typically occur during high geomagnetic activity.

Figure 5 shows a detailed overview of these density enhancements from the Cluster satellites. The time series are forwarded in time so that the structures occur simultaneously on the four satellites. The density and electric field variations are very similar between the four satellites and are observed with time delays related to the spacecraft separations and velocities. This suggests that the enhancements are quasi-stationary and are of ionospheric origin rather than from the solar wind. Weak electric field perturbations appear to be associated with the density enhancements, which suggest that the plasma drifts within these events are different from those in the surrounding polar cap. However, one cannot deduce from these data whether the particle velocities are parallel to the magnetic field, as such observations can be made with particle detectors only.

These density enhancements are also associated with magnetic field perturbations, which implies that some electric currents occur within the events [*M. Dunlop*, private communication, 2001]. Thus, both intensified plasma drifts and electric currents accompany the density enhancements.

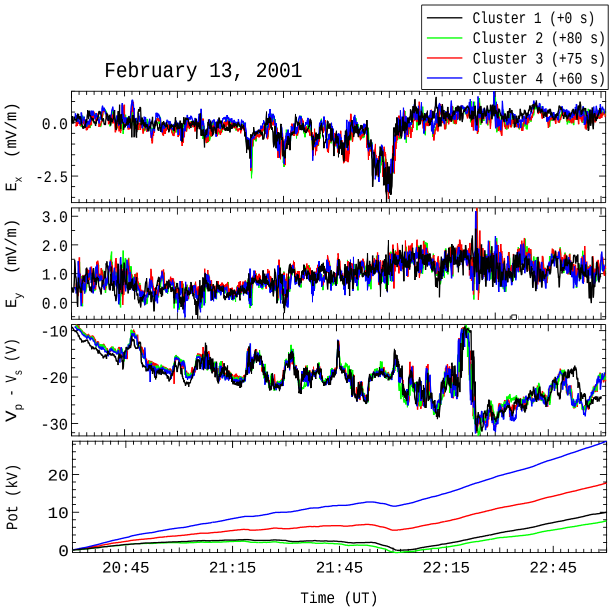

Figure 5. Spin-averaged EFW observations from the four Cluster satellites during a polar cap crossing. The measurements of Cluster 2-4 are forwarded in time as shown in the legend.

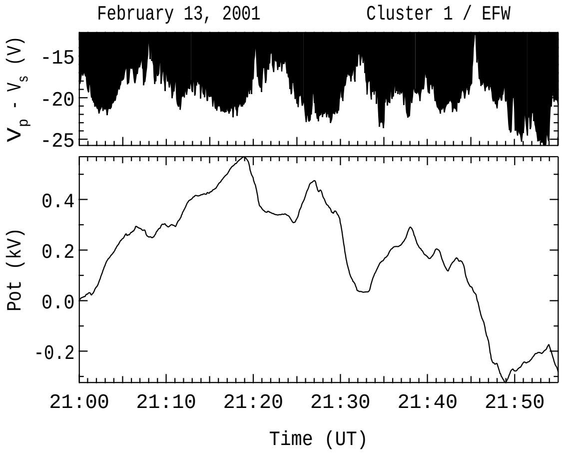

Figure 6. Density enhancements and potential drops in the polar cap.

Figure 6 displays the spacecraft potential and the space potential for a few enhancements, and there seems to be a good correspondence between the two time series. It implies that potential drops of a few hundred volts accompany the density enhancements. This gives an additional support to the interpretation that the events are enhanced outflowing ion events, where the ions are accelerated through a potential drop of a few hundred volts.

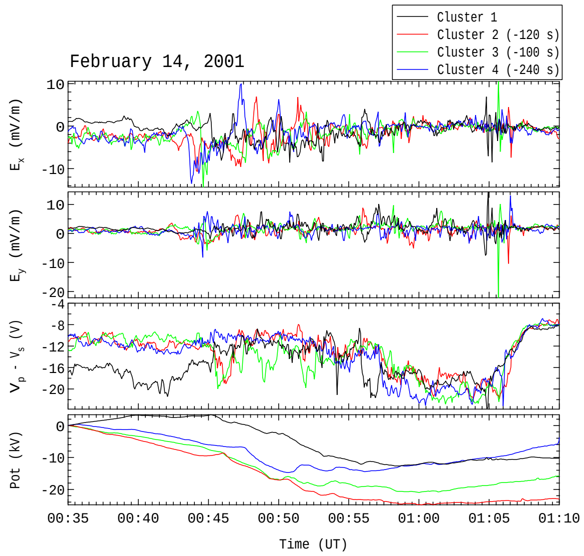

Figure 7. Spin-averaged (4-second) EFW observations from the four Cluster satellites during an auroral oval crossing.

5. PLASMA SHEET AND AURORAL OVAL

At about 23:20 UT the plasma density rises to a higher level and simultaneously electric field perturbations increase (see Figure 2), indicating that the satellites come in a new plasma region. Considering the Cluster orbit, the vehicles have likely entered the distant plasma sheet where the density is significantly higher and plasma drifts are more variable than in the lobes.

One and half hours later, the spacecraft potential decreases again, as the vehicles have arrived at an auroral region where particles effectively precipitate along magnetic field lines into the ionosphere, keeping the plasma density low. Figure 7 summarizes the EFW observations across the auroral region; the observations have been delayed so that all satellites enter the trough region at the same time, indicated by a rapid rise of the plasma density near 01:07 UT. One can notice that all satellites observe disturbances in the auroral region but hardly ever the same structures. Sometimes two satellites can encounter a comparable feature but the other two detect likely something quite different. It suggests that the scale sizes are usually of the order of or less than the satellite separation, 600 km, and the temporal scales are shorter, less than a few minutes.

The auroral observations are collected during a disturbed interval. According to ground-based magnetometers (data not shown), the auroral electrojets become weakly enhanced at 00:30-01:00 UT, and the Polar UVI imager shows a weakly brightened oval (not shown here). Figure 8 displays high-resolution electric field measurements from Cluster 1. The third panel from top presents the spacecraft potential data, which indicates that the auroral cavity is a few degrees wide. At the equatorward edge of the oval there occur large electric fields of the order of 100 mV m^{-1} that are possibly related to an auroral arc. A similar pattern, that is an auroral cavity with an arc, is observed on the other three satellites. However, a detailed comparison between the four satellites reveals plenty of differences in the magnitudes and directions of the electric fields, suggesting that the arc evolves quite significantly within a few minutes.

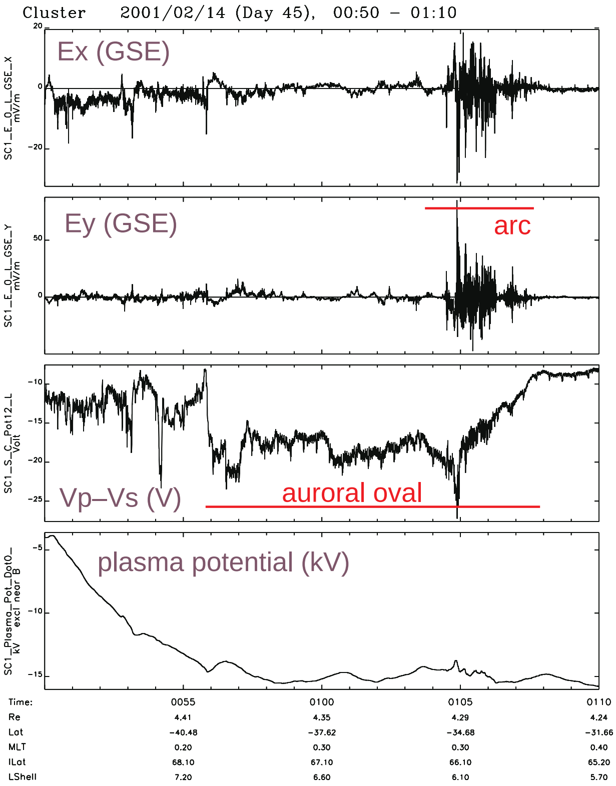

Figure 8. High-resolution EFW observations from Cluster 1 across the auroral oval.

The width of the region of the intense electric fields is 0.2-0.3° inv. lat., corresponding to 20-30 km, which is much more than a typical width of an intense arc [e.g., *Borovsky*, 1993]. In fact, a detailed examination of the structure reveals that there are plenty of structures with very small scales. In some cases the associated plasma potentials suggest the occurrence of downward-pointing electric fields that attempt to prevent electrons from precipitating into the ionosphere (see *Newell et al.* [1999] and references therein], leading to a formation of so-called black auroras [*Marklund et al.*, 1997].

6. ULF WAVES

Figure 7 shows that the satellites encounter the plasma trough region near 01:07 UT, as the plasma density rises and the plasma flow becomes coherent. These are indications of entering a dipolar magnetic field region. The observations are collected near midnight, and therefore it is somewhat surprising that the satellites detect a ULF wave event.

Figure 8 displays two electric field components together with the spacecraft potential from the four satellites. The electric field perturbations appear primarily in the east-west direction, that is, in the E_y component. Preliminary magnetic field data (not shown here) shows that the electric and magnetic fields are 90º out of phase, revealing that this is a standing mode. This is, however, no regular field line resonance [*Southwood*, 1974] that is triggered by earthward-propagating compressional waves, injected by traveling disturbances on the magnetopause [*Southwood*, 1979], because such a resonance cannot occur in the midnight sector [see e.g. *Laakso and Schmidt*, 1989]. A detailed analysis of the observed electric and magnetic field perturbations will be done in the future.

The ULF wave observations are collected during a disturbed interval, which suggests that these waves are possibly triggered by drifting ring current protons [see e.g. *Southwood*, 1981]. The time series are not shifted in Figure 8, as they are not very well correlated. Thus, this type of pulsation must have small spatial and temporal scales, although they may appear throughout a large longitudinal sector.

The period of the waves is about 100–120 second at L = 4.2. This period is about twice as large as the expected fundamental periods of the corresponding field lines if the flux tubes are loaded with protons. However, during disturbed intervals, the near-Earth magnetosphere is effectively filled by ionospheric, upflowing heavy ions [*Gloeckler and Hamilton*, 1987]. This will decrease the Alfvén speed on dipole field lines and increase the period of the fundamental mode of a field-line resonance [see e.g., *Laakso et al.*, 1998]. For the present case, a 20% percentage of O^+ ions are enough to explain the observed wave period.

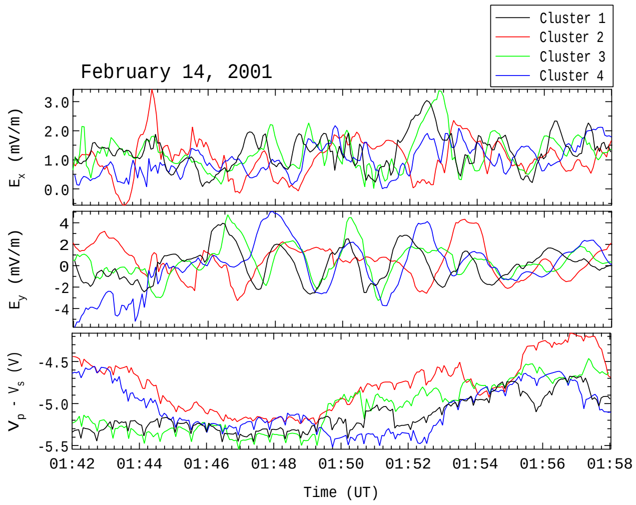

Figure 8. Electric field measurements during a ULF wave event observed near local midnight.

7. SUMMARY

The present study deals with multi-point electric field observations of the Cluster EFW experiment in the high-latitude magnetosphere during a 6-hour interval on February 13-14, 2001, 20–02 UT.

Before entering the cusp, the satellites observe strong electric field perturbations within a large flux vortex, which may be a signature of an exterior cusp. The actual entry into the cusp is quite difficult to detect in electric field data, as the satellites move from the magnetosheath directly into the cusp and the properties in the high-altitude cusp and the adjacent magnetosheath are somewhat similar. Within the cusp the density and the sunward flow velocity are quite well correlated between the four satellites, whereas some differences are distinguished in the east-west flow velocity. Across the cusp, three satellites observe a potential drop of 500 volts whereas the fourth one, Cluster 1, does not detect it. Such a potential drop may be explained by means of upward-pointing parallel electric fields at low altitudes that accelerate electrons downward and ions upward.

In the polar cap region, the Cluster satellites observe stationary large-scale density enhancements during a highly disturbed interval. These structures are coherent between the four satellites gathered within a few minutes, and all of them are associated with potential drops of a few hundred volts, suggesting that some upward-pointing parallel electric fields occur at low altitudes. The events are also associated with magnetic field perturbations. These all suggest that the events are possibly ion outflows from the polar ionosphere, occurring during enhancements in geomagnetic activity.

In the distant plasma sheet as well as in the auroral region, the basic features such as auroral cavities and regions of intense electric fields appear on all four satellites, but detailed features are not well correlated. Quite often two satellites can observe similar patterns for some time but the other two seem to miss them. This tells that the spatial and temporal scales are quite small, as expected. The satellites observe an auroral cavity of a few degrees wide and large electric fields of the order of 100 mV m^{-1} at the equatorward edge of the cavity. These electric fields are possibly related to the occurrence of an auroral arc. In fact, the arc is 0.2-0.3° wide, corresponding to a width of 20-30 km. A detailed investigation of the intense fields reveals that it consists of a large system of individual arcs, and some of them present downward-pointing electric fields that reduce precipitating electrons, causing the occurrence of black auroras.

At the end of the interval, near local midnight, the satellites enter the plasma trough, where the plasma flow appears coherent between the four satellites. Surprisingly, all satellites detect a ULF wave event, which is not common in this sector. A preliminary analysis shows that the oscillation period is 100–120 seconds, suggesting that the corresponding flux tubes are filled by heavy ions, as a typical period of a field line resonance at $L = 4$ is much smaller. In fact, the observations are collected during a disturbed interval, and therefore the near-Earth magnetosphere is likely filled with heavy ions of ionospheric origin. The ULF wave observations between the four satellites are not well correlated, implying a short temporal and spatial scale size for the waves. The appearance of the waves near midnight excludes a possibility that they are a regular field-line resonance caused by Kelvin-Helmholtz waves at the magnetopause, but they are rather triggered by drifting ring current protons.

8. REFERENCES

Borovsky, J. E., Auroral arc thickness as predicted by various theories, *J. Geophys. Res.*, **98**, 6101–6138, 1993.

Ganguli, S. B., The polar wind, *Rev. Geophys.*, **34**, 311–348, 1996.

Gloeckler, G. and D. C. Hamilton, AMPTE ion composition results, *Phys. Scr.*, **T18**, 73–84, 1987.

Gustafsson, G., M. André, T. Carozzi, A. I. Eriksson, C-G. Fälthammar, R. Grard, G. Holmgren, J. A. Holtet, N. Ivchenko, T. Karlsson, Y. Khotyaintsev, S. Klimov, H. Laakso, P-A. Lindqvist, B. Lybekk, G. Marklund, F. Mozer, K. Mursula, A. Pedersen, B. Popielawska, S. Savin, K. Stasiewicz, P. Tanskanen, and J-E. Wahlund, First results of electric field and density observations by cluster EFW based on initial months of operation, densities, *Ann. Geophys.*, submitted, 2001.

Haerendel, G., Microscopic plasma processes related to reconnection, *J. Atmos. Terr. Phys.*, **40**, 343–353, 1978.

Laakso, H. and R. Grard, The electron density distribution in the polar cap: its variability with seasons, and its response to magnetic activity, in *Space Weather Study using Multi-Point Techniques*, COSPAR Colloquia Series, Pergamon, submitted, 2000.

Laakso H. and A. Pedersen, Ambient electron density derived from differential potential measurements, in *Measurement Techniques in Space Plasmas: Particles*, edited by R. F. Pfaff, J. E. Borovsky, and D. T. Young, AGU Monogram 102, pp. 49–54, AGU, Washington, DC, 1998.

Laakso H. and R. Schmidt, Pc 4–5 pulsations in the electric field at geostationary orbit (GEOS 2) triggered by sudden storm commencements, *J. Geophys. Res.*, **94**, 6626–6632, 1989.

Laakso H., D. H. Fairfield, C. T. Russell, J. H. Clemmons, H. J. Singer, B. L. Giles, R. P. Lepping, F. S. Mozer, R. F. Pfaff, K. Tsuruda, and J. R. Wygant, Field-line resonances triggered by a northward IMF, *Geophys. Res. Lett.*, **25**, 2991–2994, 1998.

Laakso, H., R. Pfaff, and P. Janhunen, Polar observations of electron density distribution in the Earth's magnetosphere, 1. Statistical results, *J. Geophys. Res.*, submitted, 2001.

Newell, P. T., and C.-I Meng, The cusp and the cleft/LLBL: Low-altitude identification and statistical local time variation, *J. Geophys. Res.*, **93**, 14,549–14556, 1988.

Newell, P. T., R. A. Greenwald, and J. M. Ruohoniemi, The role of the ionosphere in aurora and space weather, *Rev. Geophys.*, **39**, 137–149, 1999.

Marklund, G., T. Karlsson, and J. Clemmons, On low-altitude particle acceleration and intense electric fields and their relationship to black aurora, *J. Geophys. Res.*, **102**, 17509–17522, 1997.

Pedersen, A., P. Decreau, C-P. Escoubet, G. Gustafsson, H. Laakso, P.-A. Lindqvist, B. Lybekk, F. Mozer, A. Vaivads, Cluster four-point high time resolution information on electron densities, *Ann. Geophys.*, submitted, 2001.

Persoon, A. M., D. A. Gurnett, and S. D. Shawhan, Polar cap electron densities from DE 1 plasma wave observations, *J. Geophys. Res.*, **88**, 10123–10136, 1983.

Russell, C. T., ISEE lessons for Cluster, in the Proceedings of the Cluster-II Workshop Multiscale/Multipoint Plasma Measurements, ESA SP-449, ESA, Noordwijk, 2000.

Southwood, D. J., Some features of field line resonances in the magnetosphere, *Planet. Space Sci.*, **22**, 483–491, 1974.

Southwood, D. J., Magnetopause Kelvin-Helmholtz instability, in *Magnetospheric Boundary Layers*, pp. 357–364, ESA SP-148, Noorwijk, The Netherlands, 1979.

Southwood, D., Low frequency pulsation generation by energetic particles, in *ULF Pulsations in the Magnetosphere*, edited by D. Southwood, pp. 75–88, Reidel, Dordrecht, 1981.

Smith, M. F. and M. Lockwood, Earth's magnetospheric cusps, *Rev. Geophys.*, **34**, 233–260, 1996.

Stern, D. P., A brief history of magnetospheric history during the space age, *Rev. Geophys.*, **34**, 1–31, 1995.